Linköping Studies in Science and Technology
Dissertation No. 2519

Planning emergency mass evacuation in urban areas

Ahmad Jafarian

LINKÖPING UNIVERSITY

Linköping Studies in Science and Technology.
Dissertation No. 2519

Planning Emergency Mass Evacuation in Urban Areas

Ahmad Jafarian

Linköping University
Department of Science and Technology (ITN)

Norrköping 2026

Planning Emergency Mass Evacuation in Urban Areas
Ahmad Jafarian

Supervisor: Tobias Andersson Granberg
Co-supervisor: Krisjanis Steins

Linköping Studies in Science and Technology. Dissertation No. 2519

Cover designed by the author.

ISBN 978-91-8118-548-5 (Print)
ISBN 978-91-8118-549-2 (PDF)
ISSN 0345-7524

Printed by LiU Tryck, Linköping, Sweden 2026

Abstract

The increasing frequency and severity of natural and man-made disasters have intensified the need for effective emergency evacuation planning, particularly in densely populated urban areas. Mass evacuation involves the rapid movement of populations from hazardous zones to safe shelters, supported by the timely provision of essential relief commodities. However, evacuation operations face significant challenges, including route selection under disrupted infrastructure, shelter allocation, risk-aware decision-making, and the pre-positioning and distribution of humanitarian supplies under uncertainty.

This thesis investigates emergency mass evacuation from an operations management perspective through four interrelated studies. First, it provides a comprehensive analysis of evacuation planning and execution processes, identifying key operational bottlenecks across all evacuation phases. By adopting an interdisciplinary perspective, the study examines how technology-driven solutions—such as artificial intelligence, Industry 4.0 tools, big data analytics, and hybrid digital systems—can enhance coordination, reduce response time, and mitigate casualties. Second, the thesis develops a risk-aware emergency evacuation network design for flood-prone urban areas by explicitly incorporating geographical risk factors. A spatially informed risk assessment framework is proposed, and a Min–Max optimization model is developed to minimize the maximum risk across evacuation operations, including transportation, sheltering, and humanitarian logistics. This approach improves system resilience by strengthening the most vulnerable components of the evacuation network. Third, the thesis examines inventory pre-positioning under disaster uncertainty and evaluates flexible risk-sharing procurement contracts. The analysis highlights the roles of return permissions and order flexibility in reducing costs while maintaining high service levels during emergencies. Finally, the thesis compares alternative pre-positioning strategies in multi-stage humanitarian logistics networks under different disaster scenarios, considering disaster likelihood, product essentiality, and emergency transportation risk.

Sammanfattning

Det växande antalet och allvarlighetsgraden av både naturkatastrofer och människoskapade kriser har ökat behovet av välfungerande nödevakuering, särskilt i tättbefolkade städer. Massutrymningar handlar om att snabbt föra stora grupper från riskområden till säkra platser, där tillgång till viktiga resurser måste säkras omgående. Evakueringar kantas dock av flera svårigheter, såsom att välja säkra rutter när infrastrukturen är störd, fördela trygghetspunkter, fatta riskmedvetna beslut och planera och hantera lagring och distribution av humanitära förnödenheter.

Avhandlingen granskar nödevakuering ur ett operations management-perspektiv genom fyra sammankopplade delar. Via en litteraturstudie, analyseras först planerings- och genomförandeprocesserna för evakuering i sin helhet, med fokus på att identifiera de största flaskhalsarna i varje fas. Via en tvärvetenskaplig lins utforskas hur tekniklösningar som AI, Industri 4.0, big data och hybriddigitala system kan förbättra samordning, korta ledtider och minska skadeutfall. Därefter presenteras en riskmedveten design för evakuering i översvämningsutsatta stadsmiljöer, där geografiska risker beaktas direkt. En rumslig riskbedömningsmodell och en optimeringsmodell tas fram för att minimera den högsta risken vid transporter, inkvartering och logistik, vilket stärker motståndskraften i de svagaste delarna av evakueringssystemet. Den tredje delen undersöker lokalisering av lager vid osäkerhet och utvärderar flexibla riskdelningsavtal för upphandling. Studien visar att möjligheter till retur och flexibel beställning kan sänka kostnaderna och samtidigt hålla servicenivån hög vid nödlägen. Slutligen jämförs olika strategier för lagerhållning av kritiska förnödenheter i flerstegsnätverk för humanitär logistik, där hänsyn tas till sannolikheten för olika katastrofer, produkters nödvändighet och risker vid akut transport.

Acknowledgements

This PhD journey has been full of ups and downs, moments of challenge and achievement, all of which helped me grow both academically and personally. Completing this thesis would not have been possible without the support, guidance, and encouragement of many people who accompanied me throughout this journey. I am sincerely grateful to all those who, in different ways, contributed to the successful completion of my doctoral studies.

First and foremost, I would like to express my sincere gratitude to my supervisors. I am deeply thankful to Tobias Andersson Granberg for his constant support and mentorship throughout my PhD. Tobias has always been a reliable source of guidance and encouragement, and I am particularly grateful for his detailed, rigorous, and insightful comments on my papers and thesis. I would also like to thank Krisjanis Steins for his support and guidance during my doctoral studies. In addition, I am sincerely grateful to Reza Zanjirani Farahani, my supervisor at Rennes School of Business, France, for his invaluable guidance, support, and encouragement throughout my PhD journey. His motivation and high standards played a key role in strengthening the quality of my research ideas and publications.

I would like to express my deepest gratitude to my family, whose support has been essential throughout this journey. My sincere thanks go to my wife, Atieh, who, despite being a PhD student herself, took on greater responsibility in managing household duties and caring for our child to support me during this demanding period. Her patience, understanding, and unwavering support made it possible for me to focus on my research and complete this work. I am also deeply thankful to my son, Aron, who, at such a young age, showed remarkable understanding during times when my academic commitments required special focus and dedication. I am grateful to my parents, Mohammad and Adeleh, for their continuous support not only during my PhD but throughout my entire life. I would also like to thank my wife's parents, Amir and Sedigheh, for their unconditional support and encouragement. Without the help and support of my family, this thesis would not have been possible.

Finally, I would like to thank my colleagues at the Communications and Transport Systems (KTS) division for providing a supportive and friendly working environment. I am grateful to Niki for her valuable guidance during my PhD. I would also like to thank Rabii, Anna, and Wael. Although my physical presence in Norrköping was limited, the times I spent there—especially during Fika and doctoral meetings—were truly enjoyable and memorable.

Contents

Part I
Overview

1 Introduction

This section presents the background and motivation of the thesis, together with its study context, purpose, scope, and outline.

1.1. Background

The increasing frequency and severity of natural and man-made disasters, driven by climate change, rapid urbanization, and geopolitical instability, underscore the urgent need for effective disaster preparedness (Ibarrarán *et al.*, 2009). Statistical evidence highlights the growing threat: between 2000 and 2009, more than 4,000 disaster events were recorded worldwide, resulting in economic losses nearing $960 billion (Ray, 2011). Recent examples further illustrate the escalating impact of disasters: the 2017 floods in Sierra Leone led to over 1,000 fatalities; Hurricane Harvey caused $125 billion in damages and 107 deaths; and Hurricane Irma inflicted $65 billion in damages and claimed 134 lives (Sabbaghtorkan *et al.*, 2020). Since natural hazards are inevitable, it is crucial to focus on preparedness and structural resilience. Among these measures, evacuation has become a crucial strategy for mitigating human casualties during emergencies. In the United States alone, the Federal Emergency Management Agency (FEMA) reports between 45 and 75 disasters annually that require large-scale evacuations (Kimms and Maiwald, 2018).

Evacuation, defined as the organized relocation of individuals from hazardous areas to safer locations, serves as one of the most immediate and life-critical actions during the disaster response phase (Saadatseresht *et al.*, 2009). Its effectiveness can significantly reduce casualties and alleviate pressure on emergency services, especially in high-risk, densely populated urban areas (Nagarajan *et al.*, 2012). However, planning and executing large-scale evacuations involve complex operational and logistical challenges, including real-time decision-making, route optimization, coordination of transportation resources, and ensuring access to shelters (Afkham *et al.*, 2022). Poor evacuation planning or delayed decisions can significantly heighten casualty rates. For example, during Hurricane Katrina in 2005, severe flooding overwhelmed New Orleans' levee systems, submerging large portions of the city, damaging major roadways, and trapping thousands of residents who were unable to evacuate in time, thereby complicating rescue and relief efforts (Kazama and Noda, 2012).

Evacuation planning is one of disaster response's most complex and time-critical aspects, especially in densely populated urban areas. The inherent uncertainty of disaster events—such as unpredictable onset times, varying severity, and fluctuating population responses—combined with potential infrastructure disruptions and limited resources, makes evacuation a highly complex operational and logistical challenge (Bish *et al.*, 2014; Eriskin and Karatas, 2022). This uncertainty directly impacts evacuation efforts by making it difficult to assess how many people need to be evacuated, where shelters should be located, what resources are required, and how quickly they must be delivered (Anyidoho *et al.*, 2022). In particular, the first 72 hours following a disaster are critical, yet decision-makers often lack sufficient information to make optimal logistical choices (Van Wassenhove, 2006). Infrastructure disruptions, such as blocked roads, power outages, or collapsed bridges, can instantly render pre-planned evacuation routes unusable, requiring real-time adaptability and alternative solutions (Li *et al.*, 2021). This dynamic and uncertain context demands risk-aware evacuation planning that integrates sheltering, transportation strategies, and adaptive humanitarian logistics to protect affected populations effectively and ensure timely delivery of life-saving resources.

An effective evacuation strategy must ensure the safe relocation of individuals and ensure that critical support systems are in place to meet evacuees' immediate needs. Three key components—sheltering, emergency transportation, and humanitarian logistics—play an essential role. Sheltering involves the identification, preparation, and operation of safe locations where displaced individuals can access protection, food, water, and medical services (Bayram and Yaman, 2023). Emergency transportation involves the coordinated movement of evacuees from hazardous zones to shelters, often under severe time constraints and challenging infrastructure conditions (Stepanov and Smith, 2009). Humanitarian logistics supports the evacuation effort by managing the pre-positioning, delivery, and distribution of vital relief commodities (Seraji *et al.*, 2022).

However, the effectiveness of pre-positioning strategies depends heavily on how risk is accounted for. In humanitarian logistics, risk plays a critical role in the pre-positioning and distribution of relief supplies, as the uncertain likelihood and severity of disasters make it difficult to determine the optimal quantity and location of stockpiles (Fardi *et al.*, 2025). Without accurate risk assessments, organizations face the twin challenges of overstocking, which leads to wasted resources and higher costs, or understocking, which compromises their ability to meet urgent needs during an emergency (Zhang *et al.*, 2021). Given the dynamic and unpredictable nature of many hazards, implementing effective risk management policies is essential to balance these trade-offs and strengthen preparedness (Li *et al.*, 2023). One promising strategy is the adoption of risk-sharing mechanisms, such as option contracts, which allow humanitarian organizations to secure access to critical supplies without being obligated to purchase them until demand is confirmed fully (Shamsi *et al.*, 2018). By utilizing option contracts, organizations can minimize financial risk, improve the alignment of supply with actual needs, and enhance service levels by ensuring that essential commodities are readily available where and when they are most required.

1.2. Aim

The overall aim of this thesis is to develop a risk-based approach to emergency mass evacuation planning processes, supporting decision-making in evacuation operations, sheltering strategies, humanitarian logistics, and pre-positioning policies.

1.3. Scope

To contextualize the research, it is important to understand where emergency evacuation fits within the broader disaster management cycle. Disaster management refers to the systematic process of preparing for, responding to, and recovering from emergencies caused by natural or human-made hazards (Gupta *et al.*, 2016). It encompasses a range of coordinated actions aimed at minimizing the impact of disasters on human life, infrastructure, and the environment (Nappi and Souza, 2015). According to Waugh (2015), in disaster management, all actions are classified into four phases: (1) *mitigation*, which aims to reduce or eliminate the impact of disasters, for example, enforcing earthquake-resistant building codes in high-risk zones (Zhang *et al.*, 2022). (2) *preparedness*, focused on lessening or avoiding disaster effects, such as conducting community-wide evacuation drills before hurricane season (Wolshon *et al.*, 2005). (3) *response*, which seeks to preserve lives, property, and the environment, like deploying emergency medical teams and rescue units immediately after a flood (Yu *et al.*, 2020). (4) *recovery*, intended to return affected areas to their pre-disaster conditions—for instance, rebuilding damaged infrastructure and restoring public services after flood events (Amato *et al.*, 2020).

Emergency evacuation is positioned within the response phase of disaster management, which is activated immediately after a disaster strikes to protect lives, property, and the environment (Lovreglio *et al.*, 2016). Fig. 1 illustrates the research scope across the disaster management timeline, inspired by the framework proposed by Vanajakumari *et al.* (2016). As highlighted in blue in Figure 1, this thesis covers the entire emergency evacuation planning process. Although the primary emphasis is on decision-making during the response phase, certain preparedness activities, such as pre-positioning supplies and conducting vulnerability assessments, significantly influence the outcomes of the proposed model (Ma *et al.*, 2019). By bridging these two phases, the research aims to enhance evacuation efficiency, improve resource allocation, and increase the resilience of urban disaster response systems (Eriskin and Karatas, 2022).

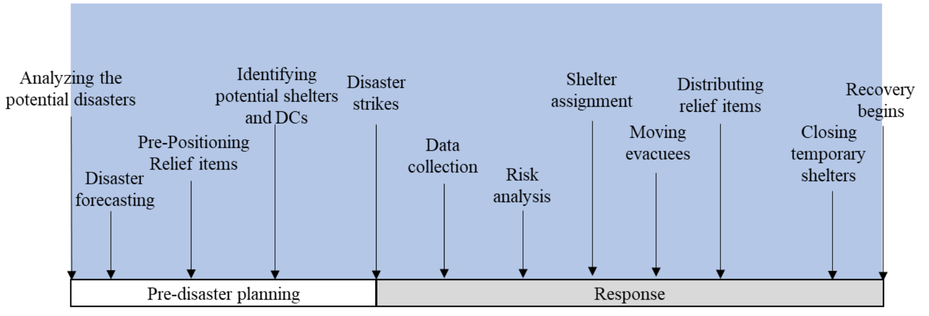

Figure 1. The timeline of disaster management.

This study focuses on Rennes Métropole as a representative urban area increasingly exposed to disaster risk. Located in the Brittany region of northwestern France, Rennes is particularly vulnerable to hydro-meteorological hazards, with flooding posing the most significant threat. The presence of the Ille and Vilaine rivers, which traverse the city, contributes to this vulnerability, especially during periods of heavy rainfall. The risk is further exacerbated by urban expansion, the prevalence of impermeable surfaces, and aging drainage infrastructure, all of which hinder natural water absorption and increase surface runoff into low-lying areas. Flooding has become a recurring issue in Rennes, with significant events recorded in 1995, 2000, 2018, and most recently in early 2021, when sustained rainfall led to river overflows that inundated homes, roads, and parts of the public transport system (metropole.rennes.fr). These events underscore the urgent need for more effective preparedness and response strategies.

1.4. Thesis outline

The structure of the thesis is organized as follows: Chapter 2 presents an overview of disaster management principles and evacuation management processes. Chapter 3 outlines the identified research gaps, the related research questions, and the research development process. Chapter 4 provides summaries of the research papers included. Finally, Chapter 5 offers a discussion of the papers and presents suggestions for future research directions.

2 Emergency Evacuation Planning

This section provides an overview of general concepts in emergency evacuation planning. It also reviews recent studies related to key components of the emergency evacuation network, including sheltering, emergency transportation, and humanitarian logistics.

2.1. Overview and key concepts

Emergency evacuation is a critical component of disaster risk management, aimed at ensuring the timely and safe movement of people from hazardous zones to safe shelters or locations (Lv *et al.*, 2013). Evacuation plans are designed to minimize casualties and disruptions while maximizing resource efficiency and safety (Sarvari *et al.*, 2018). This planning process involves an intricate interplay between evacuation route, transportation coordination, shelter allocation, and humanitarian logistics, typically carried out under high uncertainty and severe time constraints (Hu *et al.*, 2019).

Evacuation planning faces multiple challenges such as unpredictability of disasters, limited transportation and shelter capacity, dynamic human behavior, communication failures, and the need to address equity among diverse population groups (Kimms and Maiwald, 2018). In addition, the trade-off between speed and safety, especially in densely populated or infrastructurally constrained areas, makes planning a multidisciplinary problem. This inherent complexity gives rise to the need to integrate knowledge and methodologies from various fields.

Operations research contributes optimization models for route planning, shelter allocation, and resource distribution. Transportation engineering ensures the feasibility of evacuation flows given road capacities and network disruptions. Behavioral science and psychology help predict individual and group responses under stress and uncertainty. Urban planning provides insights into land use, infrastructure vulnerabilities, and population density patterns. Public policy and emergency management guide the coordination of institutional response frameworks, legal constraints, and communication strategies. Data science and artificial intelligence (AI) are increasingly used to analyze mobility data, simulate scenarios, and improve prediction accuracy.

Decision-making during disasters is often highly challenging due to time pressure, limited information, and rapidly evolving conditions (Lovreglio *et al.*, 2016). For example, during a severe flood, authorities may need to quickly decide which shelters to open and how to direct evacuees, even though some routes may be submerged, and the actual number of displaced people is still unclear (Sherali *et al.*, 1991). These conditions highlight the need for structured and resilient planning frameworks. To manage this operational uncertainty, emergency evacuation activities are commonly organized into two interdependent phases: pre-disaster and post-disaster operations. The pre-disaster phase focuses on preparedness activities, including risk assessment, identification of safe shelters, infrastructure evaluation, development of evacuation protocols, and implementation of early warning systems. Investment in preparedness has been shown to yield substantial returns; According to DFAT (2025), every US$1 invested in mitigation and preparedness can generate up to US$7 in post-disaster response and recovery savings. These proactive measures enhance system readiness and enable faster, more coordinated responses once a disaster occurs.

In contrast, the post-disaster phase involves the execution of evacuation plans under real-time constraints. Authorities must dynamically coordinate transportation resources, assign evacuees to shelters, and manage the distribution of essential relief commodities (Fardi *et al.*, 2025). Because infrastructure and communication systems may be partially or completely disrupted, the effectiveness of post-disaster response depends heavily on the robustness of pre-disaster planning (Besiou and Van Wassenhove, 2020). The 2011 Great East Japan

Earthquake illustrates this dependency, as widespread damage to railways, airports, bridges, and highways severely hindered evacuation efforts and delayed the delivery of critical supplies (Kazama and Noda, 2012).

Within this temporal structure, forecasting and inventory pre-positioning play a central role in strengthening preparedness. Accurate disaster forecasting improves the estimation of potential scale and impact, supporting more informed planning and resource allocation (Eftekhar *et al.*, 2022). Strategic pre-positioning of essential relief supplies prior to disaster onset reduces response time, enhances operational flexibility, and increases system resilience. Together, these mechanisms form a critical foundation for effective evacuation planning and humanitarian response.

2.1.1. Risk-aware evacuation planning

The risk associated with certain disasters, such as floods or wildfires, is dynamic, evolving rapidly over time as environmental conditions, hazard intensity, and infrastructure status change (Rana and Routray, 2018). Thus, unlike traditional models that rely on static assumptions, risk-aware planning dynamically adjusts decisions based on the likelihood and severity of disaster impacts in different areas (Guion *et al.*, 2007). These approaches incorporate hazard exposure, geographic vulnerabilities, infrastructure conditions, and population-specific risks into the design and execution of evacuation strategies (Nitheesh *et al.*, 2023). To improve the effectiveness of these strategies, there is a growing need for adaptive evacuation planning frameworks that can respond to the spatial and temporal variability of disaster impacts (Gama *et al.*, 2016). Integrating scenario-based analysis with geographic vulnerability assessments enhances operational readiness by enabling planners to anticipate various risk scenarios and make informed decisions about shelter locations, evacuation routes, and resource distribution. This risk management perspective supports the development of evacuation networks that are not only robust under uncertainty but also capable of minimizing human exposure to high-risk areas during rapidly unfolding emergencies.

2.2. Classification of evacuation scenarios

Evacuation scenarios vary widely and can be systematically categorized based on several key dimensions that shape planning strategies, resource allocation, and response coordination. These dimensions include factors such as the timing of evacuation (pre- or post-disaster), the nature of the hazard (sudden-onset versus slow-onset), the scale and complexity of the affected area, the availability of infrastructure, and the behavioral responses of the population. Understanding these variations is essential for designing context-sensitive evacuation models that align with the specific characteristics and constraints of each situation.

2.2.1. Type of disaster

Disasters are commonly classified into three main categories: natural, man-made, and Natech. i) *Natural disasters* include events such as floods, earthquakes, hurricanes, wildfires, and tsunamis, which arise from environmental or geological processes (Xie *et al.*, 2010). Readers are referred to FEMA (2010) for a comprehensive list of potential natural hazards and disasters. For example, the 2010 Haiti earthquake killed over 200,000 people and displaced more than a million (Na and Banerjee, 2015). ii) *Man-made disasters*, on the other hand, stem from technological failures (Error) such as industrial accidents, chemical spills, nuclear incidents, or human-caused hazards (Terror) such as acts of terrorism (Altay and Green III, 2006). These events may occur suddenly and often in densely populated or high-risk industrial areas, as seen in the 1986 Chernobyl nuclear disaster or the 2013 West Fertilizer Company explosion in Texas (Laboureur *et al.*, 2016). iii) *Natech disasters* arise when natural hazards trigger technological accidents, leading to cascading and compounded effects, such as explosions, fires, or toxic releases, particularly in facilities that store or process hazardous materials. Despite their potentially severe consequences, these events are often underrepresented in national risk assessments (Girgin *et al.*, 2019). For instance, the 2011 Great East Japan Earthquake triggered a tsunami that led to the Fukushima Daiichi nuclear disaster, a classic Natech event involving radioactive release (Ozbay *et al.*, 2019).

Moreover, evacuation planning is deeply influenced by the degree of predictability associated with different types of disasters. Predictable disasters, such as seasonal hurricanes or slow-onset floods, typically provide a short window of anticipation, enabling authorities to issue early warnings, mobilize transportation assets, and pre-position relief supplies (Van Wassenhove, 2006). For instance, during Hurricane Harvey in 2017, weather forecasts allowed officials in Texas to organize phased evacuations, although implementation challenges still emerged due to underestimated rainfall and public hesitancy (Anyidoho *et al.*, 2022). In contrast, unpredictable disasters—including earthquakes, industrial accidents, and terrorist attacks—occur with little or no warning, offering almost no time for structured planning (Sabouhi *et al.*, 2019). The 2011 Tōhoku earthquake and tsunami in Japan exemplify this sudden-onset chaos: infrastructure was rapidly overwhelmed, communication systems failed, and thousands were trapped before evacuation orders could be issued (Hu *et al.*, 2019).

2.2.2. Time of evacuation

Evacuations can be classified according to their timing in relation to the disaster event: i) *Pre-event evacuation* takes place when a hazard has not yet fully materialized, but forecasts or early warning indicators suggest a possibility of severe consequences. In such situations, although the exact path, timing, or intensity of the hazard may still be uncertain, authorities often decide to evacuate as a precautionary measure to avoid potential large-scale harm (Ng *et al.*, 2015). For instance, in 2008, ahead of Hurricane Gustav, officials in New Orleans initiated a large-scale pre-event evacuation, ordering more than a million people to leave the city in advance to prevent the catastrophic outcomes experienced during Hurricane Katrina. ii) *During-event evacuation* occurs while the disaster is actively unfolding, such as in the case of fires, floods, hurricanes, tornadoes, or wildfires, requiring rapid and often improvised responses (Sabouhi *et al.*, 2019). For example, in 2021, flash floods in Western Germany forced authorities to evacuate residents as rising waters suddenly overwhelmed communities. iii) *Post-event evacuation* is implemented after the disaster has occurred, typically in situations where continued risk remains or conditions have become uninhabitable, and people must be relocated until the area is deemed safe for return (Gupta *et al.*, 2016). For example, following the 2011 Fukushima Daiichi nuclear disaster in Japan, entire communities were evacuated days after the earthquake and tsunami due to radioactive contamination.

2.2.3. Type of planning

Evacuations can also be categorized based on the level of planning involved: i) *Urgent evacuation* occurs when there is little or no time to prepare, requiring immediate action in response to an unexpected and rapidly escalating threat (Rungta *et al.*, 2012). For example, the 2018 Camp Fire in Paradise, California, forced residents to flee with almost no warning as the wildfire spread rapidly through the town (Siam *et al.*, 2022). ii) *Planned evacuation* allows for more preparation time, enabling authorities and individuals to organize transportation, secure resources, and communicate clearly before the evacuation takes place (Zhang *et al.*, 2015). For example, before Hurricane Irma in 2017, Florida carried out a coordinated evacuation in which residents received advance notice and were instructed to evacuate in phases according to their geographic zones (Rahman *et al.*, 2021).

2.2.4. Scales of evacuation

The scale of an evacuation plays a critical role in determining the resources needed and the degree of coordination required among local, regional, and national authorities (Chiu *et al.*, 2018). A well-structured emergency response plan is essential to ensure that operations can be effectively scaled up or down according to the magnitude and severity of the event. Evacuations are commonly categorized into four levels based on their geographic coverage and the size of the affected population. i) *Local evacuation* involves a limited area, such as a neighborhood or small community, in response to localized incidents like fires or chemical spills (Leonard, 1985). For example, the evacuation of a neighborhood in Houston, Texas, after a chemical plant explosion in 2019. ii) *Regional evacuation* spans multiple neighborhoods or communities, often prompted by larger natural disasters such as floods or wildfires (Zhang *et al.*, 2015). An example is the evacuation of several towns during the 2018 Camp Fire in Northern California. iii) *Statewide evacuation* affects a significant portion of a state, usually due to major threats like hurricanes (Regnier, 2008). For instance, the evacuation orders issued across

Florida during Hurricane Irma in 2017. iv) *National (federal) evacuation* involves multiple states or the entire country and is reserved for extreme events such as nuclear threats or catastrophic disasters (Üster *et al.*, 2018). For example, in 2022, Ukraine conducted a nationwide evacuation in response to the Russian invasion, relocating millions of civilians from conflict zones through government-coordinated efforts across the country.

2.2.5. Individual preferences

Evacuations can be categorized into two main types based on individual decision-making and the involvement of authorities: i) *Voluntary evacuation* occurs when individuals decide to leave an area on their own initiative, either independently or in response to official recommendations, but without being legally required to do so. For example, during Hurricane Ian in 2022, many residents of central Florida evacuated voluntarily before any official orders were issued, based on forecast warnings (Zhao *et al.*, 2022). ii) *Mandatory evacuation* is ordered by the designated emergency authority, requiring all individuals in a specified area to evacuate due to imminent danger, often with legal enforcement to ensure compliance (Shahparvari and Abbasi, 2017). For instance, in 2021, authorities in California issued mandatory evacuation orders for communities near Lake Tahoe as the Caldor Fire advanced rapidly, posing severe risks to residents and property (wildfiretoday.com).

2.2.6. Type of relocation

In disaster response, relocation strategies generally fall into two main categories: i) *Evacuation* involves the organized movement of individuals from hazardous areas to designated safe zones, typically used when the threat poses an immediate and significant risk to life and infrastructure (Alam and Goulias, 1999). It is often implemented in response to large-scale hazards such as hurricanes, floods, or industrial accidents (Adjei *et al.*, 2022). ii) In contrast, *shelter-in-place* refers to the strategy of keeping people indoors, typically within their homes, workplaces, or designated safe buildings, to minimize exposure to external threats(Bayram and Yaman, 2023). This approach is commonly used during chemical spills, air quality emergencies, or active shooter incidents when moving people may increase their risk. The choice between evacuation and shelter-in-place depends on various factors, including the nature and speed of the hazard, available infrastructure, population density, and the capacity of emergency services.

2.2.7. Evacuation phases

Based on the operational model proposed by the City of London (Ingleby, 2014), the evacuation process can be divided into five phases: i) *Initiate evacuation* involves early disaster forecasting, preparedness, and analysis of human behavior to anticipate how the populations may respond. iii) *Alert population*, focuses on issuing timely warnings and clear instructions through multiple communication channels to inform residents of the need to evacuate (Regnier, 2008). iii) *Move people* addresses the physical relocation of individuals using well-coordinated transportation strategies and optimal routes to ensure safety and efficiency (Xie *et al.*, 2010). iv) *Sheltering and assistance* provide evacuees with secure temporary accommodation and essential services, integrating humanitarian logistics to meet basic needs (Shi *et al.*, 2025). v) *Return/recovery* involves planning and coordination for the reintegration of evacuees after the threat has passed, including collaboration with local transportation and service providers to support a smooth transition back to normal life (Bayram and Yaman, 2023).

Given the extensive body of literature on evacuation planning, Table 2 classifies previous studies according to their scenario and contextual characteristics. To facilitate this structured comparison, the coding scheme presented in Table 1 is applied in the review summarized in Table 2.

Table 1. Coding of evacuation management subjects.

Category	Subcategory	Code
Type of disaster	*Natural disasters*	ND
	Man-made disasters	MD
	Natech disasters	NT
Time of evacuation	*Pre-event evacuation*	PE
	During an evacuation	DE
	Post-event evacuation	PO
Type of planning	*Urgent*	UR
	Planned	PL
Scales of evacuation	*Local Evacuation*	LE
	Regional Evacuation	RE
	Statewide Evacuation	SE
	National Evacuation	NE
Individual preferences	*Voluntary evacuation*	VE
	Mandatory evacuation	ME
Type of relocation	*Evacuation*	EV
	Shelter-in-Place	SP
Evacuation Phases	*Initiate Evacuation*	IE
	Alert Population	AP
	Move People	MP
	Sheltering and Assistance	SA
	Return/Recovery	RR

2.3. Integrated emergency evacuation operations

In the mass evacuation literature, the effective design and operation of emergency evacuation operations require the integration of multiple components, including sheltering, emergency transportation, and humanitarian logistics. These elements work together to ensure the timely and safe relocation of affected populations and the delivery of essential relief supplies (Kimms and Maiwald, 2018). This section presents a comprehensive view of the evacuation process by exploring its three main operational pillars, which are critical to building a responsive and adaptive evacuation framework during disasters.

In a typical integrated emergency evacuation (IEE), evacuees are transported from urban zones to shelters, which receive and distribute relief commodities from designated distribution centers (Sabouhi *et al.*, 2019). The IEE encompasses two types of flow: i) *evacuee flow*, which involves the movement of people from city regions to designated shelters, and ii) *product flow*, which refers to the transportation of essential relief commodities from depots to shelters to meet the needs of evacuees (Amideo *et al.*, 2019).

Table 2. Classification of evacuation studies based on scenario and contextual characteristics.

Paper (Sorted chronologically)	Type of disaster	Time of evacuation	Type of planning	Scales of Evacuation	Individual preferences	Type of relocation	Evacuation Phases
Sherali *et al.* (1991)	ND	DE,PO	PL	LE	ME	EV	MP,SA
Chen *et al.* (2007)	MD	DE	UR	LE	ME	EV	IE,MP
Regnier (2008)	ND	PE	PL	SE	ME	EV	AP
Saadatseresht *et al.* (2009)	-	PE	PL	LE	ME	EV	IE,MP,SA
Stepanov and Smith (2009)	ND	PE	PL	LE	ME	EV	IE,MP,SA
Xie *et al.* (2010)	MD	DE	PL	LE	ME	EV	MP
Ng and Waller (2010)	-	DE,PO	PL	LE	ME	EV	MP
Huibregtse *et al.* (2011)	ND	PE,DE	UR	LE	VE	EV	IE,AP,MP
Kimms and Maassen (2011)	-	DE	PL	LE	ME	EV	MP,SA
Bish (2011)	ND	DE	PL	LE	ME	EV	MP
Duanmu *et al.* (2012)	-	DE	UR	LE	ME	EV	MP
Li *et al.* (2012)	ND	DE	PL	RE	ME	EV	MP,SA
Rungta *et al.* (2012)	-	DE	UR	SE	ME	EV	MP
Bish and Sherali (2013)	ND	PE	PL	RE	ME	EV	IE,MP
An *et al.* (2013)	ND	DE,PO	PL	LE	ME	EV	MP,SA
Hamacher *et al.* (2013)	-	DE	PL	LE	ME	EV	MP
Goerigk *et al.* (2013)	MD	DE	PL	LE	ME	EV	IE,MP
Hsu and Peeta (2014)	MD	PE	PL	LE	VE	EV	IE,MP
Bish *et al.* (2014)	ND	PE	PL	RE	ME	EV	IE,MP
Goerigk *et al.* (2015)	MD	DE	PL	LE	ME	EV	MP
Bayram *et al.* (2015)	ND	DE	PL	RE	ME	EV	IE,MP
Ng *et al.* (2015)	ND	PE	PL	LE	VE	EV	IE,AP
Zhang *et al.* (2015)	ND,MD	PE,DE	UR	SE	ME	EV	MP,SA
Kılcı *et al.* (2015)	ND	DE,PO	PL	LE	ME	SP	SA,
Goerigk *et al.* (2015)	MD	DE	PL	LE	ME	EV	IE,MP
Pillac *et al.* (2016)	ND	PE	PL	LE	VE	SP	IE,AP,MP
Wang *et al.* (2016)	ND	DE	PL	LE	VE	EV	IE,MP
Ndiaye *et al.* (2017)	MD	PO	PL	LE	ME	SP	RR
Yuan *et al.* (2017)	-	DE	PL	RE	ME	EV	MP,SA
Üster *et al.* (2018)	-	PE	PL	SE	ME	EV	MP,SA
Kimms and Maiwald (2018)	-	DE	PL	LE	ME	EV	MP
Bayram and Yaman (2018)	ND,NT	DE,PO	PL	LE	ME	EV	IE,SA
Yang *et al.* (2018)	-	DE	PL	LE	ME	EV	MP
Karabuk and Manzour (2019)	ND	PE,DE	UR	LE	ME	SP	IE,AP,MP
Golshani *et al.* (2019)	-	DE	UR	LE	VE	EV	IE,MP
Helderop and Grubesic (2019)	ND	DE	UR	LE	VE	EV	IE,AP,MP
Ozbay *et al.* (2019)	ND	DE,PO	PL	LE	ME	SP	SA
Mostajabdaveh *et al.* (2019)	ND	DE,PO	PL	LE	ME	SP	IE,MP,SA
Golshani *et al.* (2020)	-	DE	UR	LE	VE	EV	IE,MP
Wong *et al.* (2020)	ND	PE	PL	RE	VE,ME	EV	IE,MP,SA
Yabe and Ukkusuri (2020)	ND	PE	PL	LE	VE	EV	IE,MP
Zhang *et al.* (2020)	-	DE	UR	LE	ME	EV	MP
Zhao *et al.* (2020)	ND	DE	PL	RE	ME	EV	MP
Zhu *et al.* (2020)	ND	DE	PL	LE	ME	EV	MP
Dalal and Üster (2021)	ND	PE	PL	SE	ME	EV	IE,MP,SA
Jin *et al.* (2021)	ND	DE,PO	PL	LE	ME	EV	IE,MP,SA
Anyidoho *et al.* (2022)	ND	PE	PL	LE	VE	EV	IE,AP,MP
Adjei *et al.* (2022)	ND	PE	PL	LE	VE	EV	IE,SA
Grajdura *et al.* (2022)	ND	DE	UR	LE	VE	EV	IE,MP
Siam *et al.* (2022)	ND	PE,DE	UR	LE	VE	EV	IE,MP,SA
Seraji *et al.* (2022)	ND	PE	PL	LE	ME	EV	IE,MP,SA
Afkham *et al.* (2022)	ND	DE	UR	LE	VE	EV	MP
Chang *et al.* (2022)	ND	DE,PO	PL	LE	VE	EV	IE,MP,SA
Bayram and Yaman (2023)	ND,MD	PE	UR	RE	ME	EV,EP	MP,SA,RR
de Albuquerque *et al.* (2024)	ND	PE	PL	LE	ME	EV	MP,SA,RR
Sheu (2024)	ND	PE	PL	RE	VE	EV	IE,AP,MP
Shi *et al.* (2025)	ND	DE	UR	LE	ME	EV	AP, MP, SA
Ferreira and da Rocha (2025)	ND	DE	UR	LE	ME	DP	MP, SA

As noted by Homeland Security (2021), integrating humanitarian logistics into emergency evacuation planning significantly enhances the responsiveness and efficiency of disaster management efforts, ensuring that evacuees' immediate needs are met throughout the evacuation process. Moreover, effective planning also involves the coordination of transportation resources, including both public and private vehicles, to facilitate the orderly movement of people to safety (Samsonkin *et al.*, 2022).

2.4. Sheltering

Sheltering provides a safe and secure place for individuals and communities to seek refuge when forced to leave their homes due to disasters or other hazardous situations (Bayram and Yaman, 2023). The objective is to find safe and accessible locations to accommodate many people affected by the disaster (Chang *et al.*, 2022). Evacuation shelters (or emergency shelters) are designated locations where people can find immediate protection, essential services, and necessities until they can safely return home or transition to more permanent housing (Sherali *et al.*, 1991).

There are two types of shelters: permanent and temporary. *Permanent shelters* are already established facilities, but their capacity is insufficient for evacuees. *Temporary shelters* should be established to complement the permanent shelters when the demand is higher than the capacity of the shelters (Kılcı *et al.*, 2015). The operationalized temporary shelters are selected from available candidate locations. The candidate temporary shelters can be established in existing public buildings such as schools, educational centers, sports arenas, and municipal buildings with strong structures and suitable space before the disaster (Sheu and Pan, 2014).

Key factors influencing shelter location decisions during evacuation planning include: i) *Capacity*: shelters must have enough space to accommodate the projected number of evacuees (Üster *et al.*, 2018). ii) *Safety*: the shelter should be in a safe area, away from potential hazards such as flood zones or areas prone to landslides (Sherali *et al.*, 1991). iii) *Accessibility*: shelters should be in areas that are easily accessible, ideally near major transportation routes to facilitate the efficient movement of evacuees. In addition, these sites must allow for the timely delivery of humanitarian aid and emergency medical assistance (Stepanov and Smith, 2009). Allocating evacuees to shelters is a complex challenge, as it involves taking into account factors such as travel distance, demand, and shelter utilization levels (Na and Banerjee, 2015). Thus, effective sheltering is closely tied to broader disaster logistics, often planned in coordination with emergency transportation and evacuation strategies, such as route selection and vehicle scheduling (Seraji *et al.*, 2022).

2.5. Emergency transportation

Evacuation transportation (or evacuation routing) is defined as the movement of people from at-risk areas to safer locations (Stepanov and Smith, 2009). This process conducted just before, during, and immediately after the onset of a disaster to reduce casualties (Sabouhi *et al.*, 2019). Unlike normal daily traffic, evacuation traffic during an emergency is characterized by drastic oscillations and sudden flow breakdowns due to a significant increase in demand (Rahman *et al.*, 2021).

According to Homeland Security (2019), there are two types of evacuation transportation: i) *Hub and Spoke* (HAS): the evacuees are aggregated from numerous pickup locations to evacuation centers or safe areas by short trips. Then, they are distributed to shelters. For example, during large-scale hurricane evacuations in coastal regions such as Virginia, authorities use a HAS model in which evacuees are first transported from neighborhood pickup points to regional evacuation centers before being transferred to mass care shelters in safer inland areas. This model demonstrated strong performance in large-scale evacuations because it improves coordination, enables efficient resource staging, and facilitates prioritization of vulnerable populations before long-distance transport. ii) *Point-to-Point* (PTP): The evacuees are directly moved from the embarkation point to a shelter. For example, during wildfire evacuations in counties such as Larimer County, Colorado, a PTP model is applied, where evacuees are directly transported from designated embarkation points to specific shelters or host communities without intermediate aggregation hubs. This model showed effective performance in rapid-onset emergencies because it minimizes transfer delays, reduces operational complexity, and accelerates direct relocation to safe shelters.

A variety of transportation modes are employed during evacuations, with private vehicles being the most used by households (Sadri *et al.*, 2014). Public transit—especially buses—is crucial for relocating individuals without access to personal vehicles, as they offer high capacity and operational flexibility (Goerigk *et al.*, 2013). Several optimization models have been proposed to improve the efficiency of bus routing and scheduling during evacuations, addressing factors such as vehicle capacity, travel time, and pickup/drop-off coordination (Goerigk *et al.*, 2015; Shahparvari *et al.*, 2019; Zhao *et al.*, 2020). Other transportation options, such as helicopters, may be used for supply delivery or emergency rescues, and dedicated medical transport vehicles are essential for severely injured individuals. Effective evacuation planning must also accommodate the needs of vulnerable populations who require transportation assistance (Eriskin and Karatas, 2022). The choice of transportation often depends on the nature of the hazard and the available warning time—pedestrian evacuation may be necessary for sudden events like earthquakes, while hurricanes typically allow time for vehicle-based evacuations (Chang *et al.*, 2022).

Effective emergency transportation planning involves addressing several critical challenges. One of the primary issues is congestion on evacuation routes, which can significantly delay movement and reduce the number of evacuees who reach safety in time (Hajiali *et al.*, 2022). To manage evacuation traffic effectively, strategies are typically divided into two categories: demand management, which aims to optimize the use of the existing transportation network, and supply management, which focuses on increasing the network's capacity through additional resources or infrastructure (Sabbaghtorkan *et al.*, 2020). However, infrastructure disruptions—such as blocked roads or damaged bridges—and the inaccessibility of designated shelters further complicate the evacuation efforts. These issues demand flexible and adaptive routing and scheduling to ensure the safe and efficient movement of evacuees during emergencies (Stepanov and Smith, 2009). Additionally, vehicle capacity constraints can create bottlenecks, as each vehicle has limited space for passengers or goods (Zhao *et al.*, 2020). As a result, much of the research in this area is dedicated to developing models that support effective evacuation planning, vehicle routing, and scheduling under dynamic and uncertain conditions.

2.6. Humanitarian logistics

Humanitarian logistics involves efficiently managing and distributing necessary relief commodities to affected populations during and after emergencies (Kawase and Iryo, 2023). A critical component of this process is the pre-positioning of relief items, storing essential relief commodities in strategic locations before disasters occur (Fardi *et al.*, 2025). This approach enables rapid response, often within 24 to 48 hours, significantly reducing human suffering during emergencies (Salmerón and Apte, 2010). For instance, the United Nations Humanitarian Response Depot (UNHRD) operates a global network of hubs in locations like Brindisi, Dubai, and Accra, facilitating the swift deployment of aid by maintaining ready-to-ship inventories (unhrd.org). Effective distribution further relies on robust logistics systems that manage transportation, warehousing, and information flow, ensuring that aid reaches those in need efficiently (Balcik *et al.*, 2008). By integrating pre-positioning with coordinated distribution strategies, humanitarian organizations can enhance their responsiveness and effectiveness in disaster relief efforts (Hu *et al.*, 2019).

According to FEMA, humanitarian logistics facilities include: i) *Major Distribution Centers* (*MDCs*): permanent distribution centers strategically located around a country or province. The pre-position inventories are located at different MDCs to increase availability and reduce the risk of their loss during a disaster. For example, FEMA has established nine MDCs strategically positioned across the US to ensure nationwide coverage and rapid deployment of relief supplies, thereby strengthening preparedness capacity and reducing response time in large-scale emergencies. ii) *Staging Areas/Pre-Staging Areas* are temporary storage areas that act as hubs that receive the inventory from MDCs and send it to distribution points. For instance, the Reliant Stadium was considered by FEMA a Staging Area for the Houston area during Hurricane Earl, serving as a temporary logistics hub where relief supplies were received, sorted, and dispatched to ensure timely assistance to affected communities. iii) *Points of Distribution* (PODs): are sites where aid is distributed to affected people, such as shelters, parking lots, and stadiums. (Vanajakumari *et al.*, 2016). PODs should be chosen in areas exposed to minimal disaster risk and accessible to city regions and MDCs.

2.7. Classification of integrated emergency evacuation operations

Although emergency evacuation has been widely studied, there is no universally accepted classification framework from the operations management (OM) perspective that comprehensively addresses its key components, sheltering, transportation, and humanitarian logistics. Only a few review studies in OM journals have attempted structured categorizations. For instance, Caunhye *et al.* (2012) reviewed emergency logistics optimization models from 1976 to 2011, focusing on core operations such as shelter location, route selection, and relief distribution. Similarly, Amideo *et al.* (2019) proposed a classification based on disaster type, evacuation approach, sheltering, and modeling objectives.

Building upon these works, we propose an updated and more comprehensive classification of integrated emergency evacuation operations. It introduces a set of classification dimensions—including planning level, evacuation mode, route planning, timing of planning, disaster type, case country, modeling objective, uncertainty, and scenario planning—each comprising multiple categories to capture the diverse characteristics of evacuation research.

Integrated Emergency Evacuation Operations can be systematically analyzed using six key dimensions. i) *Type of planning* refers to the operational focus of the evacuation model, encompassing activities such as transportation of evacuees, assignment and location of shelters, and logistics operations like distributing relief commodities or locating distribution centers. ii) *Evacuation mode* describes the means of transport considered in the model, such as private vehicles, buses, pedestrian movement, or a general category that includes mixed or unspecified modes. iii) *The objective function* defines the main goal of the evacuation model, such as minimizing total evacuation time, cost, or travel distance, maximizing the number of evacuees reaching safety, or reducing risk and network clearance time. iv) *Uncertainty* accounts for unpredictable elements in the evacuation process, including fluctuations in demand, time windows, disaster effects, shelter, and route capacities, or the geographic location of the hazard. Additionally, I present the timing of planning and the type of disaster addressed in each study to further clarify and enrich the classification framework. These dimensions and their respective types are presented and coded in Table 3. Furthermore, to position my work in the broader research landscape, Table 4 compares relevant studies chronologically, highlighting how each addresses key operational aspects and the solution techniques employed.

Table 3. Coding of other features of emergency evacuation papers.

Subject	Type	Code
Type of planning	Evacuation transportation	ET
	Shelter assignment	SA
	Shelter locating	SL
	Commodity transportation	CT
	DC locating	DL
Evacuation mode	Bus	Bu
	Vehicle	Ve
	Pedestrian	Pe
	General	Ge
Objective function	Total no. evacuees/Flow of evacuees	TNE
	Total evacuation time	TET
	Network clearance time	NCT
	Total Cost	TCO
	Total travel distance	TTD
	Maximum/average shortest path to shelter	MSP
Uncertainty	Demand	De
	Time window	Tw
	Disaster effect	Df
	Disaster location	Lo
	Shelter capacity	Sc
	Route capacity	Rc

Table 4. Classification of evacuation studies from an operations management and modeling perspective.

Authors	Type of planning	Evacuation mode	Time of planting	Type of disaster	Case country	Objective function	Uncertainty
(Sherali *et al.*, 1991)	ET,SA,SL	-	PO	-	US	TNE	-
(Saadatseresht *et al.*, 2009)	ET,SA,SL	Ve	PO	-	Iran	TTD	-
(Xie *et al.*, 2010)	ET,SA,SL	Ve	PO	MD	US	TET, NCT	-
(Bish, 2011)	ET,SA,SL	Bu	PE	ND	-	TET	-
(Li *et al.*, 2011)	ET,SA,SL,CT,DL	Ve	PE,PO	ND	US	TCO	Df
(Li *et al.*, 2012)	ET, SA, SL	Ge	PE	ND	US	TET	De
(An *et al.*, 2013)	ET,SA,SL,CT,DL	Ve	PE,PO	ND	US	TCO	-
(Tuydes-Yaman and Ziliaskopoulos, 2014)	ET, SA, SL	Ve	PE	-	-	NCT	-
(Sheu and Pan, 2014)	ET,SA,SL,CT,DL	-	PO	ND	Taiwan	TCO	-
(Kılcı *et al.*, 2015)	ET,SA,SL	-	PO	ND	Turkey	MSP	-
(Pillac *et al.*, 2016)	ET,SA,SL	Pe	PO	ND	Australia	TNE	-
(Shahparvari and Abbasi, 2017)	ET,SA,SL	Bu	PO	ND	Australia	TNE	De, Tw
(Yuan *et al.*, 2017)	ET,SA,SL	Ve	PO	-	China	-	-
(Yang *et al.*, 2018)	ET,SA,SL	Ve,Bu	PO	-	US	TET	-
(Bayram and Yaman, 2018)	ET,SA,SL	Ve	PO	ND	Turkey	TET	Sc, Rc
(Üster *et al.*, 2018)	ET,SA,SL	ve	PO	ND	US	TCO	-
(Kimms and Maiwald, 2018)	ET,SA,SL	Ve	PO	-	Germany	TET	-
(Dalal and Üster, 2018)	ET,SA,SL,CT,DL	Ge	PE	ND	US	MSP	Df, Lo
(Yahyaei and Bozorgi-Amiri, 2019)	ET,SA,SL,CT,DL	Ge	PO	ND	Iran	TCO	De
(Sabouhi *et al.*, 2019)	ET,SA,SL,CT,DL	Ve	PO	ND	Iran	TET	-
(Shahparvari *et al.*, 2019)	ET,SA,SL	Bu	PO	ND	Australia	TNE	-
(Mostajabdaveh *et al.*, 2019)	ET,SA,SL	-	PO	-	Turkey	MSP	De, Df
(Hu *et al.*, 2019)	ET,SA,SL,CT,DL	-	PO	ND	China	TCO, TTD	-
(Helderop and Grubesic, 2019)	ET,SA,SL	Ve	PO	ND	US	-	-
(Golshani *et al.*, 2020)	ET,SA,SL		PO	-	US	-	-
(Wong *et al.*, 2020)	ET,SA,SL	Pe, Ve	PO	ND	US	-	-
(Zhu *et al.*, 2020)	ET,SA,SL	Ve	PO	ND	US	-	-
(Zhao *et al.*, 2020)	ET,SA,SL	Bu	PO	-	China	TET	-
(Jin *et al.*, 2021)	ET,SA,SL	Pe	PE	-	China	TTD	-
(Siam *et al.*, 2022)	ET,SA,SL	Ve,Pe,Bu	PO	ND	Greece	-	De
(Seraji *et al.*, 2022)	ET,SA,SL,CT,DL	Ge	PE	ND	Iran	MSP	De
(Grajdura *et al.*, 2022)	ET,SA,SL	Pe, Ve	PO	ND	US	-	-
(Dalal and Üster, 2021)	ET,SA,SL,CT,DL	Ge	PE	ND	US	TCO	Df, De
(Chang *et al.*, 2022)	ET,SA,SL	Pe	PO	ND	Taiwan	MSP	-

3 Research Gaps and Research Questions

This section identifies the key gaps in existing literature and formulates the research questions that guide this thesis. It begins by outlining the theoretical and practical limitations in current literature. Then, the main research questions are presented. Subsequently, the section explains how the four research papers included in this thesis were developed to address these gaps.

This thesis investigates emergency mass evacuation planning across its core operational components, including evacuation operations, sheltering, humanitarian logistics, and inventory pre-positioning. To systematically address these interconnected dimensions, research gaps within each area are identified and analyzed. Based on this structured gap analysis, four complementary research streams are developed, each corresponding to one of the included papers. As illustrated in Figure 2, these papers collectively address distinct yet interrelated components of the emergency evacuation system, contributing to a comprehensive and integrated understanding of evacuation planning and decision-making. Together, they encompass the full scope of this thesis.

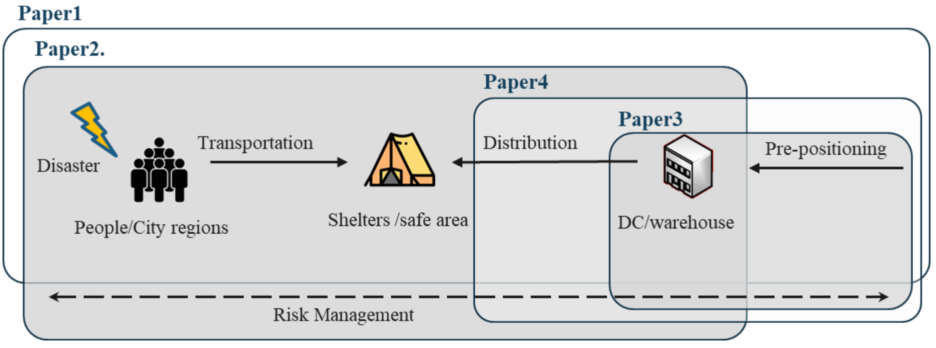

Figure 2. Coverage of the emergency evacuation network by different papers

3.1. Technology-driven approaches for evacuation planning

The existing literature on evacuation underscores several critical operational challenges, including disaster-related uncertainties, traffic congestion, high population density, limited shelter capacity, and the complex behavioral responses of evacuees. These challenges complicate evacuation planning and reduce overall operational efficiency (Gupta *et al.*, 2016). However, empirical evidence shows that emerging technologies—such as machine learning algorithms, real-time geospatial mapping, and monitoring systems—offer promising solutions. These tools enable rapid situational assessment and support informed decision-making, thereby improving the overall effectiveness of evacuation operations (Thangavel *et al.*, 2023). Although several studies have explored technology-driven approaches to enhance evacuation management, they often address isolated aspects of the process. For example, Ibrahim *et al.* (2016) developed intelligent evacuation systems for crowd control, and Bayram (2016) highlighted the use of macroscopic models to capture the complexity of evacuee behavior. Nguyen *et al.* (2021) investigated the role of machine learning algorithms in improving humanitarian pharmaceutical supply chains, and Shi *et al.* (2022) examined the use of social networks, such as Twitter and Facebook, in disaster response. Despite these advancements, a significant gap remains in the literature: there is no comprehensive study that systematically examines the entire evacuation process, identifies operational bottlenecks, and evaluates how emerging technologies can be effectively integrated across all phases of evacuation to enhance coordination, responsiveness, and efficiency.

3.1.1. Research question 1

RQ1: What are the key challenges in evacuation processes, and how can technology-driven approaches be used across the evacuation process to overcome these barriers, enhance efficiency, reduce casualties, and improve coordination?

3.2. Geographic risk assessment on disaster mass evacuation

Some disasters, such as floods and hurricanes, are inherently dynamic and geographically driven phenomena that evolve rapidly over time and space, making real-time decision-making and adaptive response strategies essential (Insani *et al.*, 2022; Karabuk and Manzour, 2019). Disaster management in these contexts faces two primary challenges: first, the uneven spatial distribution of risk, for example, low-lying regions being more vulnerable to flooding, and second, the evolving nature of risk over time. This dynamic risk landscape contributes to the unpredictability of hazard patterns, intensity, and frequency, particularly in the case of floods and wildfires (Benssam *et al.*, 2014). To address these challenges, several studies have adopted risk management approaches in evacuation planning that incorporate geographic vulnerability and scenario-based assessments. For instance, Dalal and Üster (2021) and An *et al.* (2013) defined risk in terms of facility availability, while Zhou *et al.* (2018) and Li *et al.* (2021) measured risk as the number of casualties. Apivatanagul *et al.* (2012) considered the risk to be the number of individuals left un-evacuated during a hurricane event.

Other researchers have proposed more spatially grounded approaches. Morel *et al.* (2011) introduced a geographical risk-based (GRB) method for towns vulnerable to storm surges and rising sea levels, using proximity to the coastline as a risk factor. *Quagliarini et al. (2018)* developed a seismic risk assessment framework that incorporates exposure, vulnerability, and path utilization in urban centers. Similarly, Hara *et al.* (2019) proposed a GRB approach that assesses road network risk based on the probability of segment blockages. Despite these contributions, there remains a significant gap in evacuation models that explicitly integrate geographical risk into route and shelter selection in a dynamic and comprehensive way: A GRB approach tailored to the emergency evacuation network (EEN) design problem—one that identifies high-risk zones and ensures evacuees are steered away from vulnerable shelters and routes—has yet to be fully developed.

3.2.1. Research question 2

RQ2: What is the optimal configuration of an EEN design in flood-prone urban areas when incorporating geographical risk assessments?

3.3. Risk-sharing contracts in the pre-positioning of disasters

Pre-positioning relief items is a widely used strategy among humanitarian organizations, such as the International Federation of Red Cross and Red Crescent Societies (IFRC), to enable rapid response in the critical hours following a disaster (Gupta *et al.*, 2016). While this approach enhances responsiveness, it also involves trade-offs in terms of cost, impact on beneficiaries, and potential waste. In their commitment to saving lives, humanitarian agencies often maintain high inventory levels, which increases the risk of overstocking and obsolescence due to the unpredictable nature of disasters (Emmons and Gilbert, 1997). The perishability of key supplies, such as food and medical products, further complicates storage and necessitates effective replenishment strategies to minimize waste and ensure timely availability (Ferreira *et al.*, 2018). For instance, it is estimated that FEMA could reduce its pre-positioned inventory losses by up to 10% annually by addressing perishability and logistical inefficiencies, potentially saving tens of millions of dollars (Plichta and Poole, 2023).

To address the challenges of pre-positioning, humanitarian organizations often adopt risk-sharing contracts that allow the return of unused items. However, humanitarian procurement differs fundamentally from commercial procurement. It involves two distinct decision-makers: a profit-driven supplier and a mission-driven humanitarian buyer focused on service levels, cost-efficiency, and human welfare (Holguín-Veras *et al.*, 2013). Unlike commercial supply chains that rely on predictable demand, humanitarian demand is event-driven and highly uncertain, influenced by the unpredictable timing and severity of disasters (Balcik and Ak, 2014). Procurement failures in this context can have severe consequences, shortages can cost lives, while overstocking leads to waste, social deprivation, and environmental harm (Eftekhar *et al.*, 2022). Given these complexities, procurement strategies and contract choices must be carefully tailored to balance flexibility, responsiveness, and cost-effectiveness under uncertain and time-sensitive conditions.

Some studies have explored the use of option contracts in the pre-positioning of relief items. For instance, Balcik and Ak (2014) proposed a framework agreement to facilitate rapid and cost-effective procurement for humanitarian organizations. Shamsi *et al.* (2018) examined option procurement contracts that allow buyers to reserve purchasing rights from multiple suppliers, enhancing flexibility. Wang *et al.* (2015) introduced a call option contract for pre-purchasing in relief supply chains, while Meng *et al.* (2023) developed bidirectional option contracts that combine call and put options, enabling buyers to adjust order quantities both upward and downward. However, these approaches face challenges, particularly in determining an appropriate wholesale price that accommodates both types of adjustments, often leading to inefficiencies and practical implementation issues. Notably, there remains a gap in designing risk-sharing contracts specifically tailored for humanitarian pre-positioning that explicitly incorporate disaster-specific features such as likelihood and severity into the contract mechanism.

3.3.1. Research question 3

RQ3: Which type of contract—wholesale, buyback, call option, or put options is most effective for inventory pre-positioning under different disaster scenarios?

3.4. Pre-positioning Strategies in Multi-stage Humanitarian Logistics

Pre-positioning relief items is a foundational preparedness strategy that enables agencies such as the IFRC and FEMA to deliver rapid and life-saving support during the critical hours following a disaster (Gupta *et al.*, 2016). Timely access to essential commodities—including food, water, and medical supplies—is central to effective humanitarian response efforts (Kovács and Spens, 2009). Because saving lives is the foremost mission of humanitarian organizations, they are often compelled to maintain substantial stockpiles to safeguard against uncertain and potentially high post-disaster demand. However, this practice also heightens the risk of overstocking and inventory obsolescence (Emmons and Gilbert, 1997). The inherently unpredictable nature of natural disasters in terms of both location and timing–combined with sudden surges in uncertain demand–creates substantial operational challenges for determining appropriate inventory levels and locations. Over-preparation may generate costly waste and social deprivation, while under-preparation can lead to critical shortages and reduced response effectiveness.

Humanitarian organizations can adopt different pre-positioning strategies—centralized, decentralized, or hybrid multi-echelon configurations— depending on the probability of disaster occurrence in various regions and the product essentiality. The centralized systems reduce holding and procurement costs; however, this strategy benefits from economies of scale and simplified procurement, but risks major disruptions if emergency shipping is delayed or infrastructure is damaged. For example, the IFRC hub located in Dubai's International Humanitarian City (IHC), and UNICEF's global warehouse in Copenhagen store essential supplies such as vaccines, medical kits, and therapeutic foods in a centralized hub for future emergencies (Hart and Ferguson, 2018; IFRC, 2025). In contrast, some use decentralized pre-positioning in regions and hence benefit from economies of scale and simplified procurement, but risk major disruptions if emergency shipping is delayed or infrastructure is damaged. For example, ASEAN supports member countries such as Indonesia, the Philippines, Malaysia, and Thailand by maintaining pre-positioned supplies across multiple locations rather than relying on a single hub. This approach enabled rapid distribution during the 2020 Indonesia floods and the 2013 Typhoon Haiyan in the Philippines (AHA Centre, 2024). Multi-echelon strategies, combining central and regional warehouses, allow organizations to exploit scale efficiencies centrally while maintaining rapid local response capability. These hybrid systems reduce shortages, mitigate cost volatility, and improve flexibility, especially when complemented by selective cooperation between regions. Thus, an appropriate multi-echelon design can significantly reduce overall cost while improving service levels under uncertainty.

Existing research in humanitarian logistics highlights the critical role of inventory pre-positioning in enhancing disaster preparedness and response efficiency. Early studies such as Taskin and Lodree Jr (2010), Mete and Zabinsky (2010), and Alem *et al.* (2016) primarily focused on determining optimal stock quantities based on disaster probabilities and cost trade-offs. Subsequent work broadened this perspective by incorporating multi-echelon network design, including facility location decisions (Campbell and Jones, 2011), inter-regional shipment capabilities (Morrice *et al.*, 2016), and service-level requirements (Rawls and Turnquist, 2010). Other scholars, including Howard *et al.* (2015), Tofighi *et al.* (2016), and Uichanco (2022), examined the advantages and limitations of centralized, decentralized, and hybrid logistics systems, emphasizing trade-offs between economies of scale, responsiveness, and vulnerability to disruptions. More recent contributions Ye *et al.* (2020); Zbib *et al.* (2024) underscore the growing importance of horizontal and vertical coordination among humanitarian actors, demonstrating how shared depots, inter-regional transfers, and integrated planning enhance demand fulfillment and cost efficiency. However, despite substantial advances in inventory sizing, facility location, and coordination mechanisms, existing studies still lack a unified, risk-informed framework that systematically compares pre-positioning strategies while jointly accounting for disaster likelihood, transportation disruption risk, product essentiality, and inter-regional collaboration.

3.4.1. Research question 4

RQ4: Which pre-positioning strategy performs best under varying disaster probabilities, product essentiality levels, and risks of emergency shipment delays?

3.5. Research development

This dissertation is structured around a research project comprising four research gaps and four core studies, each addressing a specific research question. Table 5 provides an overview of the identified research gaps, the corresponding research questions, the methodological approaches employed, and the resulting outputs.

This thesis is closely aligned with the Rennes Métropole project, which focuses on enhancing disaster preparedness and emergency response within the metropolitan region. Specifically, the research addresses challenges in mass evacuation, risk-aware network design, and humanitarian logistics, all of which are central to local resilience planning. Through collaboration with regional stakeholders, the studies integrate real-world data and contextual risk factors relevant to Rennes, such as flood-prone zones and urban infrastructure constraints. By grounding its models and technological frameworks in the specific needs and characteristics of Rennes Métropole, the thesis offers practical, data-driven solutions that support both current emergency management strategies and long-term policy development. Figure 3 presents a schematic timeline of the project and papers, illustrating the progression from data gathering through the "As-Is" analysis in Phase I to the "To-Be" modeling in Phase II, along with the development periods of Papers I through III. Also, it shows that the four sub-studies were conducted sequentially, each building on the findings and insights of the preceding one.

Table 5: An overview of the thesis's research gaps, research questions, method choice, and output.

RG	RQ	Purpose	Method	Output
RG1	RQ1	Using technology-driven approaches in the evacuation process to improve it	Systematic literature review with structured classification analysis	Paper1
RG2	RQ2	Designing the EEN for floods with minimum risk	Stochastic optimization, Mixed integer programming, metaheuristics	Paper2
RG3	RQ3	Finding the best contract for pre-positioning humanitarian products	Game-theoretic modeling with analytical equilibrium analysis	Paper3
RG4	RQ4	Identifying the best pre-positioning strategy in multi-echelon humanitarian logistic	Multi-echelon mathematical modeling with analytical performance evaluation	Paper4

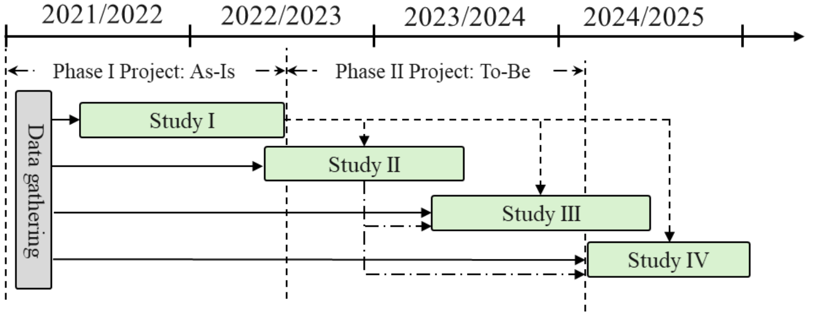

Figure 3: The timeline of the thesis and the connection between papers.

4 Summary of Papers

This section provides a summary of the four included papers, outlining their research methodologies and key contributions.

4.1. Paper I: Technology-Driven Emergency Mass Evacuation: An Operations and Engineering Management Perspective

Paper I provides a comprehensive operations management review of technology-driven solutions for evacuation planning and execution. Drawing on interdisciplinary fields, such as disaster response, information systems, and decision sciences, the paper first classifies evacuation processes and identifies key challenges and bottlenecks. It then examines how emerging technologies are applied to improve response time, communication, and casualty reduction. Given the lack of a universally agreed-upon definition of "technology-oriented tools", we identified a set of technologies frequently discussed in the literature under the umbrella of Industry 4.0, AI, drones, big data, and emerging technologies. The study classified relevant technologies under four main categories: (i) AI and learning systems, (ii) decision support and data analytics, (iii) sensing and autonomous technologies, and (iv) spatial and visualization tools. Also, beyond the four main categories, several widely used technologies were identified as hybrid systems that integrate AI with industrial and digital innovations. For example, drones combine AI with engineering components, representing application-level solutions that span multiple technological domains rather than fitting neatly into a single category.

To systematize insights, the paper introduces a structured framework comprising five research themes that encapsulate the core dimensions of evacuation management: (1) Forecasting and Initial Warning, (2) Social Behavior Analysis, (3) Evacuation Planning and Strategy Development, (4) Emergency Transportation, and (5) Sheltering and Assistance. These themes support a system-level understanding of the evacuation process, recognizing interdependencies across phases and offering a bridge between theoretical research and operational complexity. The study also highlights several gaps, such as the need for dynamic behavioral modeling, integration of multimodal transport, technological accessibility, and infrastructure resilience. By aligning technology adoption with operational needs, this work offers actionable insights for policymakers and emergency planners aiming to design more intelligent, adaptive, and equitable evacuation systems.

Research methodology: The methodology of this paper is grounded in a rigorous, structured literature review, designed to systematically identify, categorize, and analyze existing research, while revealing critical gaps in the field. The process began with a two-level aspect inclusion strategy, where comprehensive search was conducted in the Scopus database using carefully selected and iteratively refined keywords. These keywords were grouped into three main categories: evacuation management, technology-driven approaches, and an exceptions category to filter out irrelevant studies (e.g., animal evacuations or facility-specific contexts). The search was limited to the title, abstract, and keywords fields and covered publications from journal inception through December 31, 2024. To enhance the quality and relevance of the review, the second step involved strict journal quality filtration. The selected journals came from three major domains: operations management, technology-driven disciplines, and disaster and risk management. The third and fourth steps involved a detailed screening of titles and abstracts. In the final step, full-text screening further narrowed the focus to high-quality studies that aligned with the research scope.

Research contributions: Previous studies on the effect of using technologies in mass evacuation typically suffer from two key limitations: they either concentrate on specific technologies, such as information systems, AI solutions, machine learning algorithms, drones or intelligent transportation, or focus narrowly on a particular evacuation context, like flood evacuation, humanitarian logistics, or terrorist threats. As a result, there is a lack of comprehensive reviews that holistically assess the influence of technology across the broader evacuation process. This paper addresses that gap by making two key contributions: first, it presents a detailed, micro-level analysis of problem characteristics, modeling approaches, and solution methods found in the literature; second, it offers a critical synthesis of emerging trends, existing research gaps, and opportunities for future studies. The overarching contribution lies in its structured classification and evaluation of technology-driven solutions aimed at improving evacuation management.

Paper I has been accepted for publication and is available in Early Access in IEEE Transactions on Engineering Management (Jafarian et al., 2026).

The thesis author was responsible for the literature review; the research methodology; collecting and preparing the data; developing the model; performing visualization and presentation of results; interpreting the findings; and writing and editing the manuscript.

4.2. Paper II: The effect of geographic risk factors on disaster mass evacuation strategies: a smart hybrid optimization

Paper II examines the optimal configuration of an EEN by incorporating geographical risk factors into evacuation planning for an urban area affected by flooding. Recognizing that flood risk varies across different regions of a city, a spatially-informed risk assessment method is proposed to analyze the disaster risk imposed on each area. Accordingly, the paper models an EEN with three interconnected layers: city regions, shelters, and distribution centers. Shelters are classified into two categories: permanent shelters, which are pre-existing facilities with limited capacity, and temporary shelters, selected from a pre-identified list of candidate locations. The study adopts a PTP evacuation strategy, in which evacuees are moved directly from city regions to designated shelters. A risk-aware EEN model is developed to minimize the highest level of risk across all evacuation operations, including movement, sheltering, and commodity transportation. The paper proposes a Min-Max optimization approach inspired by reliability engineering, which focuses on improving the weakest component to enhance the resilience of the entire system. Specifically, the model aims to minimize the maximum risk imposed on geographical grid zones by optimally configuring the EEN, selecting paths and shelter sites away from high-risk areas.

To better capture real-world emergency conditions, the model integrates four critical components: (i) *combinatorial scenario planning*, which jointly considers disaster severity and evacuee demand to reflect the scale and urgency of evacuation under diverse scenarios; (ii) *uncertainty in evacuee demand*; (iii) *multimodal evacuation transportation*; and (iv) *spatial risk-based prioritization*, recognizing the flood impact varies across urban zones. This last element employs spatial analysis to identify high-risk areas, helping to steer evacuees away from hazardous routes and shelters. This comprehensive modeling approach enables a deeper, context-aware understanding of evacuation dynamics and strengthens the decision-making capacity of emergency managers. It is validated through a case study in Rennes, France—an urban area vulnerable to flooding. The city is divided into grid zones with distinct geographic risk levels. Using various disaster severity and demand scenarios, the model determines optimal shelter allocations, evacuation routes, and supply distributions.

Research methodology: A two-stage stochastic mixed-integer programming (SMIP) model is developed to optimize shelter selection, evacuation routing, and relief commodity distribution under uncertainty in evacuee demand. The model incorporates a Min-Max objective to minimize the highest geographical risk, which might lead to serious casualties. Three types of risk are considered in the model: the risk of moving evacuees, the risk when sheltering evacuees, and the risk associated with transporting essential commodities. A weighted normalization method is applied, where each normalized risk component is multiplied by a corresponding weight to reflect its relative importance in the overall objective function. To solve the computationally complex EEN design problem, a novel AI-based meta-heuristic approach is proposed that uses a fuzzy inference system (FIS) for dynamic self-tuning of parameters. The proposed method also incorporates a heuristic-based neighborhood search process, which significantly reduces computational time and enhances the quality of the response. The proposed method is validated through numerical experiments for the case study in Rennes.

Research contributions: The main features that distinguish this study from the previous research are: (i) *presenting a new risk assessment approach* for the EEN design problem that uses a min-max formulation to reduce the maximum induced risk in a geographical grid zone. This approach balances the risk between geographical grid zones, and the probability of a casualty happening in the riskiest grid zones is reduced. (ii) *Presenting a combinatorial scenario planning* that enhances emergency evacuation planning by considering the interaction of disaster severity and the number of evacuees. This approach allows anticipation and preparation for many outcomes, from minor incidents with few evacuees to major disasters impacting large populations. (iii) *Developing a novel solution method*: a metaheuristic approach called the smart hybrid optimization approach (SHOA) is developed to solve the problem. SHOA employs a FIS algorithm, an AI-based technique, for dynamic parameter tuning, along with a heuristic-driven local search tailored to the EEN design problem, to enhance the algorithm's efficiency and effectiveness.

Paper II is published in Transportation Research Part E: Logistics and Transportation Review (Jafarian *et al.*, 2025).

Parts of this work were presented by the author at the 2023 POMS International Conference in Paris, in the session titled Wildfire Response and Risk Management.

The thesis author was responsible for the literature review; methodology development; data collection; data preparation; model implementation; data analysis; visualization and presentation; interpretation of findings; manuscript writing and editing.

4.3. Paper III: Sustainable inventory pre-positioning in disasters: flexibility and risk-sharing in option contracts

This paper aims to develop and evaluate flexible contract mechanisms that enable humanitarian organizations (as buyers) and suppliers (as sellers) to better manage demand uncertainty in disaster scenarios. The objective is to improve three key sustainability performance metrics: economic efficiency, waste generation, and service levels. Two critical features influencing contract performance are return permission—the ability to return unused goods—and order flexibility, which allows adjustment of quantities based on actual needs. Specifically, wholesale and buyback contracts are categorized as fixed-order contracts, while call and put options offer flexible ordering. In wholesale contracts, buyers take on all inventory risk by committing to a fixed quantity at a set price. Buyback contracts reduce this risk by allowing returns at a predetermined price, shifting some liability back to the seller. Call option contracts grant buyers the right—but not the obligation—to purchase additional quantities later, enhancing responsiveness and minimizing overstocking. Put options, on the other hand, let buyers return a portion of goods for a fee, helping reduce excess inventory and waste. The study examines how different contract types impact the three performance metrics. Thus, a game-theoretic model is developed to analyze these contract types under various conditions, demonstrating that the optimal contract choice depends on disaster likelihood, product perishability, and salvage value, highlighting that no single contract is superior in all contexts.

Research methodology: For each prevalent contract type, a Stackelberg game model is developed to capture the interaction between a profit-maximizing supplier and a cost-minimizing buyer. To model this uncertainty, the study adopts a general probability distribution function (PDF), offering the flexibility needed for complex, high-variability scenarios. Furthermore, a continuous inventory policy is used to reflect the urgency of disaster response, ensuring that inventory is replenished within the product's perishability window. The models are solved analytically, and their effectiveness is assessed from the perspective of humanitarian organizations based on the three key conflicting criteria: total cost (economic efficiency), waste generation, and service level (the maximum demand that can be fulfilled). In addition, to demonstrate the applicability of the model in different situations, the study applies a uniform PDF for demand across all contract types. Additionally, a sensitivity analysis is conducted to evaluate contract performance under varying disaster likelihoods and levels of product essentiality, helping to identify the most suitable contract type for each scenario.

Research contributions: This paper proposes option contracts as tailored risk-sharing tools for inventory pre-positioning in humanitarian logistics. Unlike earlier studies, it incorporates disaster-specific factors, such as the likelihood of occurrence and severity of disaster, enabling more adaptive and context-aware procurement strategies. The research systematically evaluates the effectiveness of various contract types across different disaster scenarios, distinguishing between predictable and unpredictable events to guide better decision-making. Additionally, the study highlights how well-designed contracts can significantly reduce waste from perishable relief items. By explicitly modeling the interaction between humanitarian organizations and suppliers, and factoring in the salvage value of unused goods, the paper offers an analytical framework for identifying contracts that minimize expiration-related losses without compromising service levels. This approach provides practical guidance for promoting sustainability and efficiency in disaster preparedness operations.

This paper has been submitted to Production and Operations Management Journal and is currently under revision.

The thesis author was responsible for the literature review; methodology development; data preparation and analysis; model implementation; visualization and presentation; interpretation of findings; manuscript writing and editing.

4.4. Paper IV: Pre-positioning Strategies in Multi-stage Humanitarian Logistics

This paper aims to evaluate pre-positioning strategies for humanitarian operations to better manage demand uncertainty in disaster scenarios. The objective is to reduce total cost and improve the service levels. Pre-positioning strategies in multi-stage humanitarian logistics can be categorized into four main groups, each reflecting a different level of centralization and inter-regional coordination. Anchor Hub represents a highly centralized structure in which central main hub holds the majority of pre-positioned inventory and supplies all regions during a disaster, offering strong economies of scale but limited regional autonomy. Region-Led Response decentralizes inventory by allowing each region to independently manage its own stock and response operations, improving responsiveness but potentially increasing redundancy and cost. In this strategy, emergency transportation to other regions is also permitted as part of a collaborative response. The Hub-and-Spoke model blends these two approaches: regional facilities maintain limited stock, while central main hub provides additional support when local capacity is insufficient, enabling a balance between efficiency and flexibility. In this structure, the regions do not engage in collaborative response, and all emergency transportation is carried out solely from the central hub. Finally, the Collaborative Network represents a fully coordinated system where multiple regions and hubs share resources, exchange inventory, and support one another dynamically. This strategy enhances adaptability and resilience through inter-regional cooperation; however, its Achilles' heel is the risk of transportation delays caused by road damage after disasters, which can significantly slow emergency shipments and lead to regional shortages. Accordingly, quantitative models are developed to analyze these strategies under various conditions, demonstrating that the optimal choice depends on regional disaster likelihood, product essentiality, and the risk of emergency transportation delays, highlighting that no single strategy is universally superior.

Research methodology: We classify existing pre-positioning strategies in multi-stage humanitarian logistics along two dimensions—inter-regional cooperation and the structure of the logistics network—resulting in four types: Anchor Hub, Region-Led Response, Hub-and-Spoke, and Collaborative Network. For each strategy, a corresponding quantitative model is developed. To capture uncertainty in disaster demand, the study employs a general PDF, providing the flexibility needed to represent complex and highly variable scenarios. A continuous inventory policy is incorporated to reflect the urgency of disaster response, ensuring that replenishment aligns with the perishability constraints of relief items. For comparative analysis, a uniform PDF is also used as a specified demand distribution. All models are solved analytically and evaluated from the perspective of humanitarian organizations using two keys—and often conflicting—performance criteria: total cost (economic efficiency) and service level (maximum demand satisfied). Finally, a comprehensive sensitivity analysis examines how strategies perform under varying disaster likelihoods, levels of product essentiality, and risks of delay in emergency shipments, enabling the identification of the most appropriate strategy for different operational conditions.

Research contributions: This paper offers several theoretical and practical contributions. First, it integrates risk-informed decision-making with an analytical mathematical formulation, introducing a framework for optimizing inventory allocation across multiple logistics echelons under predictable disaster scenarios. Second, it provides a classification of pre-positioning strategies, presenting and analyzing four distinct strategies—Anchor Hub, Region-Led Response, Hub-and-Spoke, and Collaborative Network. This taxonomy offers a structured lens through which to understand how alternative humanitarian logistics architectures balance cost efficiency, responsiveness, and coordination requirements. Third, the study advances the understanding of coordination among distribution centers by evaluating both cooperative and non-cooperative structures. It demonstrates how enhanced inter-regional coordination can strengthen system resilience, reduce spatial imbalances, and support more adaptive and equitable humanitarian logistics networks.

Paper 4 is a working paper.

5 Discussion: Insights and Contributions

This section integrates the findings of the included papers to highlight their collective contributions and demonstrate how they advance emergency evacuation planning.

This thesis addresses a broad spectrum of processes within urban mass evacuation management. It begins by examining evacuation systems, their operational challenges, and the multiple dimensions of risk embedded within them. Building on this foundation, four complementary studies are developed, each focusing on a distinct aspect of emergency mass evacuation planning. However, the primary contribution of the thesis emerges when these studies are considered jointly. Together, they establish an integrated framework that spans disaster identification and risk assessment in the preparedness and pre-positioning phase, potential shelter identification, and geographic risk-informed operational decision-making in the post-disaster phase.

5.1. Integration across decision layers

A central insight emerging from this thesis is that emergency evacuation planning operates across multiple interconnected decision layers. These layers include (i) information and technological support, (ii) operational network configuration, (iii) procurement and contractual flexibility, and (iv) strategic inventory positioning. Each paper addresses one of these layers, but their real value lies in how they collectively enhance coordination and resilience across the entire evacuation system.

Paper I demonstrates how emerging technologies—such as AI, drones, Internet of Things (IoT) sensors, spatial analytics, and mobile platforms—can enhance the speed and quality of decision-making throughout the evacuation process. By adopting an interdisciplinary perspective that integrates insights from disaster management, logistics, and information systems, the study establishes the informational backbone required for effective planning and execution. However, technological capability alone is insufficient without structured operational design to translate information into coordinated action. Paper II addresses one of the identified operational challenges by incorporating geographic risk identification during disaster events. Specifically, it integrates geographic risk assessments into the design of the EEN. By embedding spatial vulnerability and infrastructure disruption risk into routing and shelter selection decisions, the proposed model moves beyond traditional cost-minimization approaches and introduces a risk-informed operational optimization framework. This contribution demonstrates that evacuation routing and shelter allocation strategies must explicitly account for spatial heterogeneity and hazard exposure to reduce casualties and enhance overall system efficiency.

Paper III takes disaster occurrence uncertainty and demand variability in humanitarian logistics supply as the cornerstone of this study. Building on this foundation, it extends the system perspective to the procurement layer by examining how risk-sharing contracts can mitigate both financial and operational risks in the pre-positioning process under disaster uncertainty. The study demonstrates that contractual mechanisms are not merely financial arrangements; rather, they function as strategic instruments that shape preparedness levels, enhance service performance, and contribute to waste reduction within humanitarian supply chains. Paper IV considers two fundamental operational challenges in humanitarian preparedness and relief distribution: uncertainty in disaster occurrence and the risk of transportation disruptions during emergency response. It complements this by analyzing multi-echelon pre-positioning strategies in humanitarian logistics networks. By comparing centralized, decentralized, and hybrid configurations under varying disaster probabilities, product essentiality levels, and transportation disruption risks, it shows that structural preparedness decisions significantly shape system resilience and cost efficiency. Taken together, these four layers form coherent architecture: technology improves information accuracy; risk-aware network design improves emergency transportation and sheltering; contract mechanisms enable flexible inventory decisions; and multi-echelon strategies determine structural preparedness. Thus, this thesis contributes an integrated system perspective, demonstrating that evacuation effectiveness depends on coordinated decision-making across technological, operational, contractual, and structural dimensions.

5.2. Multi-dimensional risk integration

One of the main cross-paper insights concerns the nature of risk in mass evacuation management. Across the four papers, risk is conceptualized and modeled in multiple forms: geographic risk (Paper II), demand uncertainty and disaster probability (Papers III and IV), infrastructure disruption (Papers II and IV), and informational uncertainty (Paper I). While each study focuses on a particular dimension, their integration reveals that evacuation risk is inherently multi-dimensional and cannot be effectively managed through isolated optimization efforts.

For example, Paper II demonstrates that geographic risk affects not only route selection but also shelter feasibility and the positioning of pre-disaster inventories. Papers III and IV show that disaster probability influences both contract design and overall network configuration decisions. Moreover, infrastructure disruption risk significantly shapes the relative performance of centralized versus decentralized pre-positioning strategies. These interdependencies indicate that evacuation planning requires a holistic risk management approach that integrates spatial, probabilistic, behavioral, and supply-chain considerations. Accordingly, this thesis advances the literature by demonstrating that risk-informed evacuation planning must jointly consider preparedness and response phases. Post-disaster operational performance is strongly conditioned by pre-disaster contractual, structural, and network design decisions. In this sense, preparedness and response should not be treated as separate domains, but rather as interconnected components of a unified decision-making system.

5.3. Managerial and policy implications

From a managerial and policy perspective, the integrated findings of this dissertation provide actionable guidance for emergency authorities and humanitarian organizations seeking to design more resilient evacuation systems. First, investment in emerging technologies can significantly enhance evacuation planning and response. Advanced forecasting tools, real-time disaster monitoring systems, and behavioral tracking technologies can provide more accurate predictions of disaster occurrence and up-to-date information on evolving hazard conditions and evacuee behavior. These technological capabilities enable decision-makers to take more precise and timely actions, while improving coordination across all layers of the decision-making hierarchy.

Second, geographic risk criteria must be explicitly incorporated into evacuation network design. Given the dynamic nature of hazards such as floods and hurricanes, and the potential inaccessibility of critical infrastructure, including roads and shelters, evacuation plans should prevent directing evacuees toward vulnerable routes or unsafe shelters. Risk-aware routing and shelter allocation mechanisms are therefore essential to avoid secondary exposure and cascading failures. Third, logistics strategies should be aligned with disaster characteristics. Flexible contractual mechanisms, such as option contracts, may be preferable in highly uncertain, low-probability disaster scenarios, where risk-sharing is critical. In contrast, alternative procurement and supply mechanisms may perform better in frequent or recurrent disaster settings. Aligning contractual design with disaster probability enhances both cost efficiency and service reliability.

Finally, pre-positioning strategies should be selected based on disaster probability, transportation disruption risk, and product criticality. Hybrid multi-echelon systems often provide a balanced trade-off between cost efficiency and responsiveness, particularly under infrastructure uncertainty. Importantly, these decisions should not be made in isolation. The overall system performance depends on the synergy among technological tools, risk-aware routing and location design, contractual flexibility, and inventory structure. Therefore, policymakers should adopt a system-thinking approach when designing evacuation frameworks, recognizing the interdependence between preparedness and response decisions.

5.4. Theoretical contributions

Beyond its practical implications, this thesis advances the theoretical understanding of emergency evacuation and humanitarian logistics through an integrated, risk-informed perspective. It conceptualizes emergency evacuation, sheltering, and humanitarian logistics as interconnected components of a unified multi-layer decision system rather than independent operational problems. Within this architecture, risk-aware routing influences shelter demand and inventory allocation, while logistics structures determine system resilience under transportation disruptions. This systemic perspective shifts the analytical focus from isolated optimization toward coordinated evacuation system design.

A central contribution lies in the treatment of risk as a multidimensional construct encompassing geographic vulnerability, disaster probability and severity, demand uncertainty, and transportation disruption. By embedding these dimensions across preparedness and response phases, the thesis demonstrates that post-disaster performance is structurally conditioned by pre-disaster contractual and inventory decisions. In doing so, it advances evacuation theory beyond static, phase-specific optimization toward holistic risk balancing across temporal stages.

Furthermore, the thesis integrates resilience, efficiency, and sustainability within evacuation system design. Rather than prioritizing cost minimization or routing efficiency alone, the framework jointly considers casualty reduction, service performance, cost efficiency, and waste minimization. It shows that resilience emerges not from redundancy alone, but from alignment between risk assessment, contractual flexibility, and multi-echelon logistics configuration. By analytically linking these elements, the thesis establishes a structured foundation for designing evacuation systems that are operationally robust and resource-efficient under uncertainty.

6 Conclusion and Future Research

This section outlines the conclusions drawn from the studies and based on the findings, provides directions for further research.

6.1. Conclusions

This thesis contributes to the growing body of literature on disaster response by developing a risk-based approach for planning mass evacuations in urban areas. By adopting an operations management and decision science perspective, the research addresses key challenges in emergency evacuation through four complementary studies. First, it offers a comprehensive classification of technology-driven solutions across different evacuation phases, identifying opportunities for improved coordination, decision-making, and equity. Second, it introduces a novel emergency evacuation network design model that incorporates geographic risk factors to optimize shelter selection, evacuation routing, and humanitarian logistics under flood scenarios. Third, it evaluates flexible, risk-sharing contract mechanisms, such as buyback, call option, and put option, for sustainable inventory pre-positioning, balancing responsiveness, cost-efficiency, and waste reduction in humanitarian logistics. Fourth, it classifies and evaluates pre-positioning strategies in multi-echelon humanitarian logistics.

Thus, it provides a practical framework that compares these strategies based on regional disaster likelihood, product essentiality, and the risk of emergency transportation delays. Collectively, these studies underscore the importance of integrating behavioral dynamics, spatial risk variability, and contract flexibility into evacuation planning. The proposed models and strategies not only enhance theoretical understanding but also provide actionable insights for disaster managers, humanitarian agencies, and policymakers working to build more resilient and adaptive urban emergency response systems. Through its interdisciplinary approach and practical orientation, the thesis lays a solid foundation for future advancements in evacuation management, risk-aware humanitarian logistics, and sustainable disaster preparedness.

6.2. Further research

From an operations management and decision science perspective, future research should aim to solve the critical challenges and bottlenecks in the evacuation process by developing intelligent, behaviorally aware systems that integrate socio-technical dimensions. First, the integration of emerging technologies such as IoT, AI, satellite imagery and smart sensors can significantly enhance disaster evacuation systems. By using AI models combined with real-time disaster and environmental data, the geographical risk level of each region (e.g., floods, storms, wildfires) can be dynamically calculated. Hence, evacuation priorities, shelter selection, and routing decisions can be adjusted in real time. Second, evacuation route recommendations can be communicated directly to citizens through navigation applications, where suggested paths are dynamically updated according to calculated risk levels. Also, the development of an integrated DSS is a critical future direction. A decision support system that integrally assesses risk, prioritizes regions for evacuation, and selects suitable shelters and routes, can enhance evacuation efficiency.

Third, one of the key challenges posed by the widespread use of social networks during disasters is their influence on public behavior. Social connections and shared content can distort risk perception, triggering evacuations that do not align with the actual severity of a disaster, either through exaggerated fears or, conversely, underreaction to serious disasters. Overstated portrayals may cause unnecessary mass evacuation, while minimizing critical situations could lead to non-compliance and reduced cooperation. Future research should explore how social networks and mass notification systems can shape the behavior of different population segments during emergencies, particularly those prone to misinformation or impulsive responses. Research should also emphasize socially inclusive evacuation frameworks that address mobility impairments, income disparities, and access limitations, ensuring equitable outcomes. Integrating participatory platforms into post-evacuation phases can align recovery efforts with community needs, boosting resilience and long-term sustainability.

Fourth, future research could develop a multi-period pre-positioning model that updates disaster probabilities across different seasons or periods. For example, wildfire probability increases during dry seasons, while flood risk may be higher in rainy periods. By updating occurrence probabilities dynamically, inventory ordering quantities can also be adjusted accordingly, improving preparedness and reducing waste. Another limitation of this study is the assumption of symmetric information between stakeholders. In practice, information is often asymmetric. For example, local authorities (buyers) may possess more accurate information regarding disaster likelihood than suppliers. This creates strategic decision-making questions regarding when and whether such information should be shared.

Fifth, capacity constraints of local authorities represent a practical limitation. Shelter capacity is often limited, and while temporary shelters (e.g., reinforced buildings or sports halls) can increase capacity, their reliability and operational costs (e.g., generator maintenance) may exceed their practical benefits. Some cities address this challenge by reserving hotel rooms or guesthouses in neighboring cities. Therefore, local authorities could adopt a hybrid capacity strategy combining permanent shelters, temporary potential shelters, and hotel reservations to achieve optimal capacity at minimum cost.

Sixth, in remote regions, or in areas expected to face limited accessibility after a disaster, local community contributions and NGO support may serve as valuable sources of emergency supply. Moreover, future research could examine collaboration between local authorities—such as municipalities with distribution capabilities but constrained budgets—and large humanitarian organizations. Using local operational capacities can enhance responsiveness during disasters and reduce overall network costs.

References

Adjei, E., Murray-Tuite, P., Ge, Y., Ukkusuri, S., & Lee, S. (2022). Estimating hurricane evacuation destination and accommodation type selection with perceived certainty variables. *Transportation Research Part D: Transport and Environment*, *105*, 103235.

Afkham, M., Ramezanian, R., & Shahparvari, S. (2022). Balancing traffic flow in the congested mass self-evacuation dynamic network under tight preparation budget: An Australian bushfire practice. *Omega*, *111*, 102658.

AHA Centre. (2024). Rising through the moments: Aha centre annual report 2023. *ASEAN Coordinating Centre for Humanitarian Assistance on disaster management*. https://ahacentre.org/publication/annual-report-2023

Alam, S. B., & Goulias, K. G. (1999). Dynamic emergency evacuation management system using geographic information system and spatiotemporal models of behavior. *Transportation Research Record*, *1660*(1), 92-99.

Alem, D., Clark, A., & Moreno, A. (2016). Stochastic network models for logistics planning in disaster relief. *European Journal of Operational Research*, *255*(1), 187-206.

Altay, N., & Green III, W. G. (2006). OR/MS research in disaster operations management. *European Journal of Operational Research*, *175*(1), 475-493.

Amato, A., Gabrielli, F., Spinozzi, F., Magi Galluzzi, L., Balducci, S., & Beolchini, F. (2020). Disaster waste management after flood events. *Journal of flood risk management*, *13*, e12566.

Amideo, A. E., Scaparra, M. P., & Kotiadis, K. (2019). Optimising shelter location and evacuation routing operations: The critical issues. *European Journal of Operational Research*, *279*(2), 279-295.

An, S., Cui, N., Li, X., & Ouyang, Y. (2013). Location planning for transit-based evacuation under the risk of service disruptions. *Transportation Research Part B: Methodological*, *54*, 1-16.

Anyidoho, P. K., Davidson, R. A., Rambha, T., & Nozick, L. K. (2022). Prediction of population behavior in hurricane evacuations. *Transportation research part A: policy and practice*, *159*, 200-221.

Apivatanagul, P., Davidson, R. A., & Nozick, L. K. (2012). Bi-level optimization for risk-based regional hurricane evacuation planning. *Natural hazards*, *60*, 567-588.

Balcik, B., & Ak, D. (2014). Supplier selection for framework agreements in humanitarian relief. *Production and Operations Management*, *23*(6), 1028-1041.

Balcik, B., Beamon, B. M., & Smilowitz, K. (2008). Last mile distribution in humanitarian relief. *Journal of intelligent transportation systems*, *12*(2), 51-63.

Bayram, V. (2016). Optimization models for large scale network evacuation planning and management: A literature review. *Surveys in Operations Research and Management Science*, *21*(2), 63-84.

Bayram, V., Tansel, B. Ç., & Yaman, H. (2015). Compromising system and user interests in shelter location and evacuation planning. *Transportation Research Part B: Methodological*, *72*, 146-163.

Bayram, V., & Yaman, H. (2018). Shelter location and evacuation route assignment under uncertainty: A benders decomposition approach. *Transportation science*, *52*(2), 416-436.

Bayram, V., & Yaman, H. (2023). A Joint Demand and Supply Management Approach to Large Scale Urban Evacuation Planning: Evacuate or Shelter-in-Place, Staging and Dynamic Resource Allocation. *European Journal of Operational Research*.

Benssam, A., Bendjoudi, A., Yahiaoui, S., Nouali-Taboudjemat, N., & Nouali, O. (2014). Towards a dynamic evacuation system for disaster situations. 2014 1st International Conference on Information and Communication Technologies for Disaster Management (ICT-DM),

Besiou, M., & Van Wassenhove, L. N. (2020). Humanitarian operations: A world of opportunity for relevant and impactful research. *Manufacturing & Service Operations Management*, *22*(1), 135-145.

Bish, D. R. (2011). Planning for a bus-based evacuation. *OR spectrum*, *33*(3), 629-654.

Bish, D. R., & Sherali, H. D. (2013). Aggregate-level demand management in evacuation planning. *European Journal of Operational Research*, *224*(1), 79-92.

Bish, D. R., Sherali, H. D., & Hobeika, A. G. (2014). Optimal evacuation planning using staging and routing. *Journal of the Operational Research Society*, *65*(1), 124-140.

Campbell, A. M., & Jones, P. C. (2011). Prepositioning supplies in preparation for disasters. *European Journal of Operational Research*, *209*(2), 156-165.

Caunhye, A. M., Nie, X., & Pokharel, S. (2012). Optimization models in emergency logistics: A literature review. *Socio-Economic Planning Sciences*, *46*(1), 4-13.

Chang, K.-H., Wu, Y.-Z., & Ke, S.-S. (2022). A simulation-based decision support tool for dynamic post-disaster pedestrian evacuation. *Decision Support Systems*, *157*, 113743.

Chen, H. K., Chou, H. W., & Chiu, Y. C. (2007). On the modeling and solution algorithm for the reverse logistics recycling flow equilibrium problem. *Transportation research part C: emerging technologies*, *15*(4), 218-234.

Chiu, Y.-P., Shiau, Y.-C., & Lai, Y.-H. (2018). Study on evacuation simulation under crowd-diversion condition. *Advances in mechanical engineering*, *10*(7), 1687814018785092.

Dalal, J., & Üster, H. (2018). Combining worst case and average case considerations in an integrated emergency response network design problem. *Transportation science*, *52*(1), 171-188.

Dalal, J., & Üster, H. (2021). Robust emergency relief supply planning for foreseen disasters under evacuation-side uncertainty. *Transportation science*, *55*(3), 791-813.

de Albuquerque, N. L. B., da Silva, L. B. L., Alencar, M. H., & de Almeida, A. T. (2024). A multicriteria decision model to improve emergency preparedness: Locating-allocating urban shelters against floods. *International Journal of Disaster Risk Reduction*, *111*, 104695.

DFAT. (2025). *Australia-indonesia facility for disaster reduction - phase 2*.

Duanmu, J., Chowdhury, M., Taaffe, K., & Jordan, C. (2012). Buffering in evacuation management for optimal traffic demand distribution. *Transportation Research Part E: Logistics and Transportation Review*, *48*(3), 684-700.

Eftekhar, M., Jeannette Song, J.-S., & Webster, S. (2022). Prepositioning and local purchasing for emergency operations under budget, demand, and supply uncertainty. *Manufacturing & Service Operations Management*, *24*(1), 315-332.

Emmons, H., & Gilbert, S. M. (1997). The role of returns policies in pricing and inventory decisions for catalogue goods. *JOT-Journal fur Oberflachentechnik*, *37*(5), 276.

Eriskin, L., & Karatas, M. (2022). Applying robust optimization to the shelter location–allocation problem: a case study for Istanbul. *Annals of Operations Research*, 1-47.

Fardi, K., Ghasemzadeh, F., Farahani, R. Z., Asgari, N., Laker, B., & Ruiz, R. (2025). The impact of frequency and magnitude of natural disasters on inventory prepositioning. *European Journal of Operational Research*, *322*(2), 511-540.

FEMA. (2010). Comprehensive Preparedness Guide (CPG) 101 Version 2.0. *Federal Emergency Management Agency: Washington, DC, USA*, 17.

Ferreira, G. O., Arruda, E. F., & Marujo, L. G. (2018). Inventory management of perishable items in long-term humanitarian operations using Markov Decision Processes. *International Journal of Disaster Risk Reduction*, *31*, 460-469.

Ferreira, M. J., & da Rocha, H. R. (2025). Hazard classification, social and economic losses in flooded urban areas. *International Journal of Disaster Risk Reduction*, *120*, 105395.

Gama, M., Santos, B., & Scaparra, M. (2016). A multi-period shelter location-allocation model with evacuation orders for flood disasters. *EURO Journal on Computational Optimization*, *4*(3-4), 299-323.

Girgin, S., Necci, A., & Krausmann, E. (2019). Dealing with cascading multi-hazard risks in national risk assessment: The case of Natech accidents. *International Journal of Disaster Risk Reduction*, *35*, 101072.

Goerigk, M., Deghdak, K., & T'Kindt, V. (2015). A two-stage robustness approach to evacuation planning with buses. *Transportation Research Part B: Methodological*, *78*, 66-82.

Goerigk, M., Grün, B., & Heßler, P. (2013). Branch and bound algorithms for the bus evacuation problem. *Computers & Operations Research*, *40*(12), 3010-3020.

Golshani, N., Shabanpour, R., Mohammadian, A., Auld, J., & Ley, H. (2019). Evacuation decision behavior for no-notice emergency events. *Transportation Research Part D: Transport and Environment*, *77*, 364-377.

Golshani, N., Shabanpour, R., Mohammadian, A., Auld, J., & Ley, H. (2020). Modeling evacuation demand during no-notice emergency events: Tour formation behavior. *Transportation research part C: emerging technologies*, *118*, 102713.

Grajdura, S., Borjigin, S., & Niemeier, D. (2022). Fast-moving dire wildfire evacuation simulation. *Transportation Research Part D: Transport and Environment*, *104*, 103190.

Guion, D. T., Scammon, D. L., & Borders, A. L. (2007). Weathering the storm: A social marketing perspective on disaster preparedness and response with lessons from Hurricane Katrina. *Journal of Public Policy & Marketing*, *26*(1), 20-32.

Gupta, S., Starr, M. K., Farahani, R. Z., & Matinrad, N. (2016). Disaster management from a POM perspective: Mapping a new domain. *Production and Operations Management*, *25*(10), 1611-1637.

Hajiali, M., Teimoury, E., Rabiee, M., & Delen, D. (2022). An interactive decision support system for real-time ambulance relocation with priority guidelines. *Decision Support Systems*, *155*, 113712.

Hamacher, H. W., Heller, S., & Rupp, B. (2013). Flow location (FlowLoc) problems: dynamic network flows and location models for evacuation planning. *Annals of Operations Research*, *207*(1), 161-180.

Hara, T., Sasabe, M., & Kasahara, S. (2019). Geographical risk analysis based path selection for automatic, speedy, and reliable evacuation guiding using evacuees' mobile devices. *Journal of Ambient Intelligence and Humanized Computing*, *10*, 2291-2300.

Hart, M., & Ferguson, S. (2018). In times of emergency, unicef stepsu. https://www.unicefusa.org/stories/times-emergency-unicef-steps

Helderop, E., & Grubesic, T. H. (2019). Streets, storm surge, and the frailty of urban transport systems: A grid-based approach for identifying informal street network connections to facilitate mobility. *Transportation Research Part D: Transport and Environment*, *77*, 337-351.

Holguín-Veras, J., Pérez, N., Jaller, M., Van Wassenhove, L. N., & Aros-Vera, F. (2013). On the appropriate objective function for post-disaster humanitarian logistics models. *Journal of operations management*, *31*(5), 262-280.

Homeland Security. (2021). Federal evacuation support annex to the Response and Recovery Federal Interagency Operational Plans (FEMA RD Federal Evacuation Support Annex No. FEMA-RD-Federal-Evacuation-Support-Annex_042025). Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_rd_federal-evacuation-support-annex_042025.pdf

Homeland Security. (2019). Planning considerations: Evacuation and shelter-in-place: Guidance for state, local, tribal, and territorial partners (FEMA document). Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/2020-07/planning-considerations-evacuation-and-shelter-in-place.pdf

Howard, C., Marklund, J., Tan, T., & Reijnen, I. (2015). Inventory control in a spare parts distribution system with emergency stocks and pipeline information. *Manufacturing & Service Operations Management*, *17*(2), 142-156.

Hsu, Y.-T., & Peeta, S. (2014). Behavior-consistent information-based network traffic control for evacuation operations. *Transportation research part C: emerging technologies*, *48*, 339-359.

Hu, Q.-M., Zhao, L., Li, H., & Huang, R. (2019). Integrated design of emergency shelter and medical networks considering diurnal population shifts in urban areas. *IISE Transactions*, *51*(6), 614-637.

Huibregtse, O. L., Hoogendoorn, S. P., Hegyi, A., & Bliemer, M. C. (2011). A method to optimize evacuation instructions. *OR spectrum*, *33*, 595-627.

Ibarrarán, M. E., Ruth, M., Ahmad, S., & London, M. (2009). Climate change and natural disasters: macroeconomic performance and distributional impacts. *Environment, development and sustainability*, *11*, 549-569.

Ibrahim, A. M., Venkat, I., Subramanian, K., Khader, A. T., & Wilde, P. D. (2016). Intelligent evacuation management systems: A review. *ACM Transactions on Intelligent Systems and Technology (TIST)*, *7*(3), 1-27.

IFRC. (2025). International Federation of Red Cross and Red Crescent Societie. *United arab emirates – ifrc*. https://www.ifrc.org/taxonomy/term/1383

Ingleby, A. (2014). London resilience partnership communicating with the public framework v1. *London. http://doi. org/10.1577/1548-8659 (1971)*, *100*, 389.

Insani, N., Akman, D., Taheri, S., & Hearne, J. (2022). Short-notice flood evacuation plan under dynamic demand in high populated areas. *International Journal of Disaster Risk Reduction*, *74*, 102844.

Jafarian, A., Granberg, T. A., & Farahani, R. Z. (2025). The effect of geographic risk factors on disaster mass evacuation strategies: A smart hybrid optimization. *Transportation Research Part E: Logistics and Transportation Review*, *193*, 103825.

Jafarian, A., Zanjirani Farahani, R., Andersson Granberg, T., & Steins, K. (2026). Technology-driven emergency mass evacuation: An operations and engineering management perspective. *IEEE Transactions on Engineering Management*. Advance online publication.

Jin, J. G., Shen, Y., Hu, H., Fan, Y., & Yu, M. (2021). Optimizing underground shelter location and mass pedestrian evacuation in urban community areas: A case study of Shanghai. *Transportation research part A: policy and practice*, *149*, 124-138.

Karabuk, S., & Manzour, H. (2019). A multi-stage stochastic program for evacuation management under tornado track uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, *124*, 128-151.

Kawase, R., & Iryo, T. (2023). Optimal stochastic inventory-distribution strategy for damaged multi-echelon humanitarian logistics network. *European Journal of Operational Research*, *309*(2), 616-633.

Kazama, M., & Noda, T. (2012). Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage). *Soils and Foundations*, *52*(5), 780-792.

Kılcı, F., Kara, B. Y., & Bozkaya, B. (2015). Locating temporary shelter areas after an earthquake: A case for Turkey. *European Journal of Operational Research*, *243*(1), 323-332.

Kimms, A., & Maassen, K.-C. (2011). Optimization and simulation of traffic flows in the case of evacuating urban areas. *OR spectrum*, *33*, 571-593.

Kimms, A., & Maiwald, M. (2018). Bi-objective safe and resilient urban evacuation planning. *European Journal of Operational Research*, *269*(3), 1122-1136.

Kou, G., Ergu, D., & Shi, Y. (2014). An integrated expert system for fast disaster assessment. *Computers & Operations Research*, *42*, 95-107.

Kovács, G., & Spens, K. (2009). Identifying challenges in humanitarian logistics. *International journal of physical distribution & logistics management*, *39*(6), 506-528.

Laboureur, D. M., Han, Z., Harding, B. Z., Pineda, A., Pittman, W. C., Rosas, C., Jiang, J., & Mannan, M. S. (2016). Case study and lessons learned from the ammonium nitrate explosion at the West Fertilizer facility. *Journal of hazardous materials*, *308*, 164-172.

Leonard, R. (1985). Mass evacuation in disasters. *The Journal of Emergency Medicine*, *2*(4), 279-286.

Li, A. C., Nozick, L., Xu, N., & Davidson, R. (2012). Shelter location and transportation planning under hurricane conditions. *Transportation Research Part E: Logistics and Transportation Review*, *48*(4), 715-729.

Li, J., Hu, Y., & Li, J. (2021). Rapid risk assessment of emergency evacuation based on deep learning. *IEEE Transactions on Computational Social Systems*, *9*(3), 940-947.

Li, L., Jin, M., & Zhang, L. (2011). Sheltering network planning and management with a case in the Gulf Coast region. *International Journal of Production Economics*, *131*(2), 431-440.

Li, M. K., Sodhi, M. S., Tang, C. S., & Yu, J. J. (2023). Preparedness with a system integrating inventory, capacity, and capability for future pandemics and other disasters. *Production and Operations Management*, *32*(2), 564-583.

Lovreglio, R., Fonzone, A., & dell'Olio, L. (2016). A mixed logit model for predicting exit choice during building evacuations. *Transportation research part A: policy and practice*, *92*, 59-75.

Lv, Y., Huang, G., Guo, L., Li, Y., Dai, C., Wang, X., & Sun, W. (2013). A scenario-based modeling approach for emergency evacuation management and risk analysis under multiple uncertainties. *Journal of hazardous materials*, *246*, 234-244.

Ma, Y., Xu, W., Qin, L., & Zhao, X. (2019). Emergency shelters location-allocation problem concerning uncertainty and limited resources: a multi-objective optimization with a case study in the Central area of Beijing, China. *Geomatics, Natural Hazards and Risk*.

Meng, Q., Kao, Z., Guo, Y., & Bao, C. (2023). An emergency supplies procurement strategy based on a bidirectional option contract. *Socio-Economic Planning Sciences*, *87*, 101515.

Mete, H. O., & Zabinsky, Z. B. (2010). Stochastic optimization of medical supply location and distribution in disaster management. *International Journal of Production Economics*, *126*(1), 76-84.

Morel, G., Hissel, F., & Jia, X. J. (2011). Support for preventive mass evacuation planning in urban areas. IET International Conference on Smart and Sustainable City (ICSSC 2011),

Morrice, D. J., Cronin, P., Tanrisever, F., & Butler, J. C. (2016). Supporting hurricane inventory management decisions with consumer demand estimates. *Journal of operations management*, *45*, 86-100.

Mostajabdaveh, M., Gutjahr, W. J., & Sibel Salman, F. (2019). Inequity-averse shelter location for disaster preparedness. *IISE Transactions*, *51*(8), 809-829.

Na, H. S., & Banerjee, A. (2015). A disaster evacuation network model for transporting multiple priority evacuees. *Iie Transactions*, *47*(11), 1287-1299.

Nagarajan, M., Shaw, D., & Albores, P. (2012). Disseminating a warning message to evacuate: A simulation study of the behaviour of neighbours. *European Journal of Operational Research*, *220*(3), 810-819.

Nappi, M. M. L., & Souza, J. C. (2015). Disaster management: hierarchical structuring criteria for selection and location of temporary shelters. *Natural hazards*, *75*, 2421-2436.

Ndiaye, I. A., Neron, E., & Jouglet, A. (2017). Macroscopic evacuation plans for natural disasters: A lexicographical approach for duration and safety criteria: Lex ((Q| S) Flow). *OR spectrum*, *39*, 231-272.

Ng, M., Diaz, R., & Behr, J. (2015). Departure time choice behavior for hurricane evacuation planning: The case of the understudied medically fragile population. *Transportation Research Part E: Logistics and Transportation Review*, *77*, 215-226.

Ng, M., & Waller, S. T. (2010). Reliable evacuation planning via demand inflation and supply deflation. *Transportation Research Part E: Logistics and Transportation Review*, *46*(6), 1086-1094.

Nguyen, A., Lamouri, S., Pellerin, R., Tamayo, S., & Lekens, B. (2021). Data analytics in pharmaceutical supply chains: state of the art, opportunities, and challenges. *International Journal of Production Research*, 1-20.

Nitheesh, K., Bhavathrathan, B., Manoj, M., & Rahul, T. (2023). A risk minimization based approach for planning evacuation trip distribution. *International Journal of Disaster Risk Reduction*, *97*, 104051.

Ozbay, E., Çavuş, Ö., & Kara, B. Y. (2019). Shelter site location under multi-hazard scenarios. *Computers & Operations Research*, *106*, 102-118.

Pillac, V., Van Hentenryck, P., & Even, C. (2016). A conflict-based path-generation heuristic for evacuation planning. *Transportation Research Part B: Methodological*, *83*, 136-150.

Quagliarini, E., Bernardini, G., Santarelli, S., & Lucesoli, M. (2018). Evacuation paths in historic city centres: A holistic methodology for assessing their seismic risk. *International Journal of Disaster Risk Reduction*, *31*, 698-710.

Rahman, R., Hasan, S., & Zaki, M. H. (2021). Towards reducing the number of crashes during hurricane evacuation: Assessing the potential safety impact of adaptive cruise control systems. *Transportation research part C: emerging technologies*, *128*, 103188.

Rana, I. A., & Routray, J. K. (2018). Integrated methodology for flood risk assessment and application in urban communities of Pakistan. *Natural hazards*, *91*, 239-266.

Rawls, C. G., & Turnquist, M. A. (2010). Pre-positioning of emergency supplies for disaster response. *Transportation Research Part B: Methodological*, *44*(4), 521-534.

Ray, C (2011). UN concerned with severe financial losses to natural disasters worldwide. /http://www.helium.com/items/2161177-un-concerned-withsevere-financial-losses-to-natural-disasters-worldwide/print.

Regnier, E. (2008). Public evacuation decisions and hurricane track uncertainty. *Management Science*, *54*(1), 16-28.

Rungta, M., Lim, G. J., & Baharnemati, M. (2012). Optimal egress time calculation and path generation for large evacuation networks. *Annals of Operations Research*, *201*, 403-421.

Saadatseresht, M., Mansourian, A., & Taleai, M. (2009). Evacuation planning using multiobjective evolutionary optimization approach. *European Journal of Operational Research*, *198*(1), 305-314.

Sabbaghtorkan, M., Batta, R., & He, Q. (2020). Prepositioning of assets and supplies in disaster operations management: Review and research gap identification. *European Journal of Operational Research*, *284*(1), 1-19.

Sabouhi, F., Bozorgi-Amiri, A., Moshref-Javadi, M., & Heydari, M. (2019). An integrated routing and scheduling model for evacuation and commodity distribution in large-scale disaster relief operations: a case study. *Annals of Operations Research*, *283*, 643-677.

Sadri, A. M., Ukkusuri, S. V., Murray-Tuite, P., & Gladwin, H. (2014). Analysis of hurricane evacuee mode choice behavior. *Transportation research part C: emerging technologies*, *48*, 37-46.

Salmerón, J., & Apte, A. (2010). Stochastic optimization for natural disaster asset prepositioning. *Production and Operations Management*, *19*(5), 561-574.

Samsonkin, V., Myronenko, V., Bulgakova, I., Shcherbyna, R., Yurchenko, O., & Pohorilyi, O. (2022). Multimodal logistics solutions in the conditions of incidental situations and threats to transport safety. *Chapters of Monographs*, 3-37.

Sarvari, P. A., Cevikcan, E., Ustundag, A., & Celik, M. (2018). Studies on emergency evacuation management for maritime transportation. *Maritime Policy & Management*, *45*(5), 622-648.

Seraji, H., Tavakkoli-Moghaddam, R., Asian, S., & Kaur, H. (2022). An integrative location-allocation model for humanitarian logistics with distributive injustice and dissatisfaction under uncertainty. *Annals of Operations Research*, *319*(1), 211-257.

Shahparvari, S., & Abbasi, B. (2017). Robust stochastic vehicle routing and scheduling for bushfire emergency evacuation: An Australian case study. *Transportation research part A: policy and practice*, *104*, 32-49.

Shahparvari, S., Abbasi, B., Chhetri, P., & Abareshi, A. (2019). Fleet routing and scheduling in bushfire emergency evacuation: A regional case study of the Black Saturday bushfires in Australia. *Transportation Research Part D: Transport and Environment*, *67*, 703-722.

Shamsi, N. G., Torabi, S. A., & Shakouri, G. H. (2018). An option contract for vaccine procurement using the SIR epidemic model. *European Journal of Operational Research*, *267*(3), 1122-1140.

Sherali, H. D., Carter, T. B., & Hobeika, A. G. (1991). A location-allocation model and algorithm for evacuation planning under hurricane/flood conditions. *Transportation Research Part B: Methodological*, *25*(6), 439-452.

Sheu, J.-B. (2024). Mass evacuation planning for disasters management: A household evacuation route choice behavior analysis. *Transportation Research Part E: Logistics and Transportation Review*, *186*, 103544.

Sheu, J.-B., & Pan, C. (2014). A method for designing centralized emergency supply network to respond to large-scale natural disasters. *Transportation Research Part B: Methodological*, *67*, 284-305.

Shi, D., Li, J., Wang, Q., Chen, J., Lovreglio, R., Lo, J. T., & Ma, J. (2025). Modeling and simulation of crowd dynamics at evacuation bottlenecks during flood disasters. *Transportation Research Part E: Logistics and Transportation Review*, *198*, 104064.

Shi, K., Peng, X., Lu, H., Zhu, Y., & Niu, Z. (2022). Application of social sensors in natural disasters emergency management: a review. *IEEE Transactions on Computational Social Systems*, *10*(6), 3143-3158.

Siam, M. R., Wang, H., Lindell, M. K., Chen, C., Vlahogianni, E. I., & Axhausen, K. (2022). An interdisciplinary agent-based multimodal wildfire evacuation model: Critical decisions and life safety. *Transportation Research Part D: Transport and Environment*, *103*, 103147.

Stepanov, A., & Smith, J. M. (2009). Multi-objective evacuation routing in transportation networks. *European Journal of Operational Research*, *198*(2), 435-446.

Taskin, S., & Lodree Jr, E. J. (2010). Inventory decisions for emergency supplies based on hurricane count predictions. *International Journal of Production Economics*, *126*(1), 66-75.

Thangavel, K., Spiller, D., Sabatini, R., Amici, S., Sasidharan, S. T., Fayek, H., & Marzocca, P. (2023). Autonomous satellite wildfire detection using hyperspectral imagery and neural networks: A case study on australian wildfire. *Remote Sensing*, *15*(3), 720.

Tofighi, S., Torabi, S. A., & Mansouri, S. A. (2016). Humanitarian logistics network design under mixed uncertainty. *European Journal of Operational Research*, *250*(1), 239-250.

Tuydes-Yaman, H., & Ziliaskopoulos, A. (2014). Modeling demand management strategies for evacuations. *Annals of Operations Research*, *217*, 491-512.

Uichanco, J. (2022). A model for prepositioning emergency relief items before a typhoon with an uncertain trajectory. *Manufacturing & Service Operations Management*, *24*(2), 766-790.

Üster, H., Wang, X., & Yates, J. T. (2018). Strategic Evacuation Network Design (SEND) under cost and time considerations. *Transportation Research Part B: Methodological*, *107*, 124-145.

Van Wassenhove, L. N. (2006). Humanitarian aid logistics: supply chain management in high gear. *Journal of the Operational Research Society*, *57*(5), 475-489.

Vanajakumari, M., Kumar, S., & Gupta, S. (2016). An integrated logistic model for predictable disasters. *Production and Operations Management*, *25*(5), 791-811.

Wang, H., Mostafizi, A., Cramer, L. A., Cox, D., & Park, H. (2016). An agent-based model of a multimodal near-field tsunami evacuation: Decision-making and life safety. *Transportation research part C: emerging technologies*, *64*, 86-100.

Wang, X., Li, F., Liang, L., Huang, Z., & Ashley, A. (2015). Pre-purchasing with option contract and coordination in a relief supply chain. *International Journal of Production Economics*, *167*, 170-176.

Waugh, W. L. (2015). *Living with hazards, dealing with disasters: An introduction to emergency management: An introduction to emergency management*. Routledge.

Wolshon, B., Urbina, E., Wilmot, C., & Levitan, M. (2005). Review of policies and practices for hurricane evacuation. I: Transportation planning, preparedness, and response. *Natural Hazards Review*, *6*(3), 129-142.

Wong, S. D., Pel, A. J., Shaheen, S. A., & Chorus, C. G. (2020). Fleeing from hurricane Irma: Empirical analysis of evacuation behavior using discrete choice theory. *Transportation Research Part D: Transport and Environment*, *79*, 102227.

Xie, C., Lin, D.-Y., & Waller, S. T. (2010). A dynamic evacuation network optimization problem with lane reversal and crossing elimination strategies. *Transportation Research Part E: Logistics and Transportation Review*, *46*(3), 295-316.

Yabe, T., & Ukkusuri, S. V. (2020). Effects of income inequality on evacuation, reentry and segregation after disasters. *Transportation Research Part D: Transport and Environment*, *82*, 102260.

Yahyaei, M., & Bozorgi-Amiri, A. (2019). Robust reliable humanitarian relief network design: an integration of shelter and supply facility location. *Annals of Operations Research*, *283*(1-2), 897-916.

Yang, X., Ban, X. J., & Mitchell, J. (2018). Modeling multimodal transportation network emergency evacuation considering evacuees' cooperative behavior. *Transportation research part A: policy and practice*, *114*, 380-397.

Ye, Y., Jiao, W., & Yan, H. (2020). Managing relief inventories responding to natural disasters: Gaps between practice and literature. *Production and Operations Management*, *29*(4), 807-832.

Yu, D., Yin, J., Wilby, R. L., Lane, S. N., Aerts, J. C., Lin, N., Liu, M., Yuan, H., Chen, J., & Prudhomme, C. (2020). Disruption of emergency response to vulnerable populations during floods. *Nature Sustainability*, *3*(9), 728-736.

Yuan, S., Chun, S. A., Spinelli, B., Liu, Y., Zhang, H., & Adam, N. R. (2017). Traffic evacuation simulation based on multi-level driving decision model. *Transportation research part C: emerging technologies*, *78*, 129-149.

Zbib, H., Balcik, B., Rancourt, M.-È., & Laporte, G. (2024). A mutual catastrophe insurance framework for horizontal collaboration in prepositioning strategic reserves. *Operations research*, *72*(5), 2014-2041.

Zhang, J., Liu, Y., Zhao, Y., & Deng, T. (2020). Emergency evacuation problem for a multi-source and multi-destination transportation network: Mathematical model and case study. *Annals of Operations Research*, *291*, 1153-1181.

Zhang, W., Shi, X., Huang, A., Hua, G., & Teunter, R. H. (2021). Optimal Stock and Capital Reserve Policies for Emergency Medical Supplies against Epidemic Outbreaks. *European Journal of Operational Research*.

Zhang, Y., Fung, J. F., Johnson, K. J., & Sattar, S. (2022). Review of seismic risk mitigation policies in earthquake-prone countries: lessons for earthquake resilience in the United States. *Journal of earthquake engineering*, *26*(12), 6208-6235.

Zhang, Z., Parr, S. A., Jiang, H., & Wolshon, B. (2015). Optimization model for regional evacuation transportation system using macroscopic productivity function. *Transportation Research Part B: Methodological*, *81*, 616-630.

Zhao, X., Ji, K., Xu, P., Qian, W.-w., Ren, G., & Shan, X.-n. (2020). A round-trip bus evacuation model with scheduling and routing planning. *Transportation research part A: policy and practice*, *137*, 285-300.

Zhao, X., Xu, Y., Lovreglio, R., Kuligowski, E., Nilsson, D., Cova, T. J., Wu, A., & Yan, X. (2022). Estimating wildfire evacuation decision and departure timing using large-scale GPS data. *Transportation Research Part D: Transport and Environment*, *107*, 103277.

Zhou, M., Dong, H., Ning, B., & Wang, F.-Y. (2018). Recent development in pedestrian and evacuation dynamics: Bibliographic analyses, collaboration patterns, and future directions. *IEEE Transactions on Computational Social Systems*, *5*(4), 1034-1048.

Zhu, Y.-J., Hu, Y., & Collins, J. M. (2020). Estimating road network accessibility during a hurricane evacuation: A case study of hurricane Irma in Florida. *Transportation Research Part D: Transport and Environment*, *83*, 102334.

Part II
Papers

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789181185492

Dissertations in Infra Informatics

Division of Communications and Transport Systems
Department of Science and Technology
Linköping University

1. Tobias Andersson (2005)
   Decision support tools for dynamic fleet management: Applications in airline planning and ambulance logistics.

2. Henrik Andersson (2006)
   Coordinated routing: Applications in location and inventory management.

3. Patrik Björklund (2006)
   Applications of resource optimization in wireless networks.

4. Ghazwan Al-Haji (2007)
   Road safety development index: Theory, philosophy and practice.

5. Iana Siomina (2007)
   Radio network planning and resource optimization: Mathematical models and algorithms for UMTS, WLANs, and Ad Hoc networks.

6. Anders Peterson (2007)
   The Origin-Destination matrix estimation problem: Analysis and computations.

7. Andreas Tapani (2008)
   Traffic simulation modelling of rural roads and driver assistance systems.

8. Johan Olstam (2009)
   Simulation of surrounding vehicles in driving simulators.

9. Erik Bergfeldt (2010)
   Available bandwidth estimation in packet-switched communication networks.

10. Carl-Henrik Häll (2011)
    Modeling and simulation of dial-a-ride and integrated public transport services.

11. Joakim Ekström (2012)
    Optimization approaches for design of congestion pricing schemes.

12. Lei Chen (2013)
    Performance engineering of mobile broadband: Capacity analysis, cellular network optimization, and design of in-building solutions.

13. Sara Modarres Razavi (2014)
    Planning and optimization of tracking areas for long-term evolution networks.

14. Lei Lei (2016)
    From orthogonal to non-orthogonal multiple access: Energy and spectrum-efficient resource allocation.

15. Fredrik Johansson (2016)
    Microscopic simulation of pedestrian traffic.

16. Qing He (2016)
A comprehensive analysis of optimal link scheduling for emptying a wireless network.

17. Micael Thunberg (2016)
Developing a framework for supply chain planning in construction.

18. Krisjanis Steins (2017)
Towards increased use of discrete-event simulation for hospital resource planning.

19. Henric Jonsson (2018)
Production strategy in project based production within a house-building context.

20. Ellen Grumert (2018)
Using connected vehicles in variable speed limit systems: System design and effects.

21. David Gundlegård (2018)
Transport analytics based on cellular network signalling data.

22. Tomas Lidén (2018)
Concurrent planning of railway maintenance windows and train services.

23. Joen Dahlberg (2018)
Cost allocation methods in cooperative transportation planning.

24. Ioannis Avgouleas (2019)
Cooperation and resource allocation in wireless networking towards the IoT.

25. Antzela Kosta (2020)
Age of information aware communication systems: Modeling and performance analysis.

26. Mats Janné (2020)
Construction logistics in a city development setting.

27. Abderrahman Ait Ali (2020)
Methods for capacity allocation in deregulated railway markets.

28. Cristian Tatino (2021)
Analysis and optimization for robust millimeter-wave communications.

29. Nils Breyer (2021)
Methods for travel pattern analysis using large-scale passive data.

30. Nikolaos Tsanakas (2021)
Data-driven approaches for traffic state and emission estimation.

31. Emmanouil Fountoulakis (2021)
Performance and optimization aspects of time critical networking.

32. Niki Matinrad (2022)
Models for dispatch of volunteers in daily emergency response.

33. Sara Gestrelius (2022)
Optimisation models for train timetabling and marshalling yard planning.

34. Alan Kinene (2022)
Models for the procurement of subsidized air services: Conventional aircraft and the adoption of electric aircraft.

35. Leonid Sedov (2023)
Development of critical enablers for unmanned traffic management.

36. Petter Haglund (2024)
Logistics organization design for building contractors.

37. Farah Naz (2024)
Improving transport efficiency in the construction supply chain.

38. Angelica Andersson (2024)
Modelling long-distance travel demand by combining mobile phone and survey data.

39. Emma Solinen (2025)
Improving railway timetable robustness: Development and application of robustness indicators.

40. Ivan Postigo (2025)
Microscopic traffic simulation of automated driving: Modeling and evaluation of traffic performance.

41. Anastasia Lemetti (2025)
Enhancing air traffic management: Weather and controller workload challenges.

42. Viktor Sköld Gustafsson (2025)
Decision support for emergency resource planning: Integrating interactions between natural hazards.

43. Abd Alla Ali Mubder Mubder (2025)
Port Community Systems and Just-in-Time arrival in port calls: Adoption and outcome.

44. Henrik Hardell (2026)
Environmental efficiency in terminal airspace: Performance modeling and arrival optimization.

45. Guillermo Pérez Castro (2026)
Microscopic simulation of bicycle traffic: Analysis and modeling of heterogeneity and free riding on bicycle paths.

FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology, Dissertation No. 2519, 2026
Department of Science and Technology (ITN)

Linköping University
SE-581 83 Linköping, Sweden

www.liu.se

LINKÖPING
UNIVERSITY