Disaster Response Operation Considering Road Network Disruptions: An Integrated Air-Land Transportation Model

道路網の寸断を考慮した災害応急対策：航空-陸上輸送統合モデル

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Individually, we are one drop. Together, we are an ocean." — Ryunosuke Satoro

"The only limit to our realization of tomorrow will be our doubts of today." — Franklin D. Roosevelt

DEDICATION

To my family, for their unparalleled love and support.

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A dream will remain a dream without the courage to take the first step. More than two years ago, it was the same for me until the opportunity knocked on my door and opened the path for me to walk towards my dream – to have a doctoral degree. As my PhD journey comes to an end, I look back and trace the steps I have taken that led me to Hiroshima University. For each step that I took, I knew I was never alone. The journey was not smooth, and I encountered a lot of challenges that tested me to my limits, but I am glad I made it through. This journey would have not been possible without the people who have been with me throughout my PhD life and for that I would like to show my appreciation.

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ABSTRACT

Disaster happens everywhere and may come in many types. Communities are often disrupted and can cause harm to people, property, economy, as well as to the environment specially during large scale natural disasters. Therefore, finding ways to minimize damage caused by disaster is very important. During disaster, transportation plays an important role in disaster relief operations and evacuation. It also serves as a means to minimize and repair the damage caused by disasters particularly, land transportation.

The low cost and abundance of land vehicles permits land transportation to carry out humanitarian activities immediately following a disaster. This means of transportation often performs most of the trips but in situations where roads are disrupted, land transportation may not be able to meet all the necessary demands specially when there are isolated places and low accessibility places. In this situation, humanitarian response cannot simply depend on land transportation only since road disruptions can happen anywhere but needs assistance from other transportation modes such as air transportation. Specially, in large scale disasters, assistance from other places, whether locally or internationally often use air transportation to deliver their aid since it is faster. In these situations, airports play an important role as emergency hubs to cater disaster response operations. During this time, receiving the relief goods is not only the role of the airports but it also plays role in distribution since aircraft such as emergency helicopters are often used to reach some areas during disasters. At times like this, the use of land transportation decreases and an increase in air transportation takes place. In most cases, the increase in demand to use aircraft such as emergency helicopters are hard to meet since air transportation in general are expensive and availability is low. In addition, an increase in the use of aircraft also increase noise and air pollution since these aircraft use fuel and produce high noise when operating.

Currently, this air and land transportation combination is common and often used. When taken as a separate systems, several problems can be identified such as: (1) roads can be disrupted during disaster and can cause increase in travel time due to detouring and low accessibility; (2) land transportation cannot be used to reach isolated places; (3) road disruption patterns are hard to identify before the disruption (4) conventional air transport is expensive; (5) there is low availably of air transport due to complexity in operation; (6) there is a significant increase in demand in air transport that cannot be met; (7) an increase in the use of air transportation will result to additional air, noise pollution and high cost.

To address these problems, this study proposed the use of a new air mobility called electric vertical take-off and landing (eVTOL) aircraft commonly known as air taxi or drone taxis. This new air mobility has a potential not only as a new form of transportation but also in logistics during disasters. Also, this new aircraft can address both the deficits of land and air transportation. These aircraft can help reach areas which are difficult to reach using land transportation because of disrupted roads especially isolated places. Also, since these are targeted to be a public mobility comparable to a regular land taxi, its availability will be higher compared to a emergency helicopters. Additionally, it also answers the problem in terms of cost and complex operation since studies shows it will be cheaper is less complex than its traditional air transportation counterpart. Moreover, since these are electric vehicles, it offers lesser noise and air pollution.

To effectively use this mobility, a suitable facility is needed to accommodate it. In this study, we propose the establishment of emergency ports that will serve as landing and takeoff as well as temporary holding area of goods for distribution but finding suitable location can be challenging since road disruption patterns are unknown before a disaster. To do so, a method of identifying these locations that considers road network disruption probability is necessary. Additionally, these locations must also consider the cost of transportation since one of the main considerations in disaster operation specifically in humanitarian logistics is budget. Also, since new technology contains a lot of uncertainties, a sensitivity analysis to address the variations in cost is also incorporated in the model.

Considering all the above factors, to highlight the importance of air and land transportation integration through the use of eVTOL aircraft in humanitarian logistics considering possibility of road disruptions caused by disasters, the following research objectives are presented: (1) to develop a method as to find the optimum locations of emergency ports that minimizes the transportation cost of relief goods to disaster shelters and the most suitable mode of transportation considering possible road network disruptions and place isolation; (2) to determine as to what degree will the new air mobility support the disaster response operations, and (3) to analyze the effect of the variations in transportation cost, operation cost, isolation cost, and demand change in the location of emergency ports and cost of operations. To realize these objectives, a mixed-integer linear programming (MILP) model was developed.

Lastly, to further illustrate how road disruptions affects disaster response, an enhanced model was introduced focusing on the degree of cooperation between the land and air transportation network. The model measures the usefulness of the emergency ports in reducing place isolation and using different means of transportation altogether. Since road network disruption patterns are unknown before the disaster, identification of suitable location is challenging. Therefore, the enhanced model was tested in a real network considering the probability of road disruption derived from a case study. It also determines the distribution of each mode of transportation used in the disaster response such as (1) land transportation; (2) air transportation; and (3) air and land transportation using eVTOL aircrafts through emergency ports. The goal of the enhanced model is not to replace one mode with another but to supplement the deficiencies of each mode and to test the potential of the new mobility not only as a public transport but as an additional mode of transportation during disaster.

Results showed that locations some candidate locations have high probability of being selected. With the given parameters, these locations are suitable for emergency ports considering both the transport cost as well as the condition of the road network. Additionally, the location of the emergency ports has very little variation for each scenario with an average of five emergency ports per scenario. Total cost varies depending on the number of emergency ports chosen as well as the mode of transportation used. The higher number of isolated disaster shelters serviced by conventional air transport such as helicopters results to a higher cost. There is an overall reduction of 8.64% in the number of isolated disaster shelters when the emergency port is introduced in the network. The distribution of transportation mode used to deliver goods and services to the disaster shelters comprised of 57% by land, 43% via emergency ports, and 1% via air (helicopter). While transport cost using eVTOL shows that lower cost promotes the use of eVTOL using emergency ports, in some situations, the need to establish emergency port can still lessen the overall cost of operation since place isolation serviced by conventional air transport still incurs higher cost when isolation cost is considered.

The sensitivity analysis showed that the number and location of emergency ports may vary due to changes in eVTOL aircraft transportation cost, operation cost, and demand change but some locations are common even with the variation of the said parameters. These locations exhibit characteristics that are tolerant to both the changes in different cost parameters and also to road disruptions since road disruption is also part of the model when the sensitivity analysis was done. Also, isolation cost directly affects the overall cost of transporting relief goods and also dependent on the number of isolated disaster shelters. Since isolation is inevitable, lower isolation cost would be preferable. The total travel time of the whole operation may vary depending on the number of trips performed by each mode as well the vehicle capacity. More trips performed by eVTOL aircraft and larger capacity vehicles are more advantageous to overall operation. From the results, several advantages can be derived by utilizing eVTOL aircraft in an integrated transportation network in humanitarian logistics, such as the reduction of isolated areas that resulted from road disruptions. By combining land and air networks, the disadvantages of each mode of transportation are complemented by the other.

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Chapter 1. Introduction

1.1. Background

Disaster happens everywhere and may come in many types. Regardless of what kind of disaster, damages are inevitable. Communities are often disrupted and can cause harm to people, property, economy, as well as to the environment specially during large scale natural disasters. Therefore, finding ways to minimize damage caused by disaster is very important. This is where the importance of an effective and efficient disaster management is needed. Disaster management is the organization, planning and application of measures preparing for, responding to and recovering from disaster (UNDRR, 2023). The role disaster management is composed of four phases: preparedness, response, recovery and mitigation. Preparedness refers to prior activities done to ensure readiness for disaster. Response refers to activities taken to protect people and property on the onset of the disaster. Recovery refers to activities taken to help in rebuilding and returning back to normal activities after the disaster while mitigation are activities are activities taken to minimize or prevent future effects of disasters (Kelly, 2020). The response phase that takes place immediately after the disaster and plays an important role in minimizing on-site damages. During this period, transportation is very important and understanding its contributions as a support entity will provide a more efficient preparedness and response (Anderson et al., 2022). The transportation system is comprised of several subsystems and can support each other to reduce vulnerability to some level (Mattsson & Jenelius, 2015).

During disasters, transportation plays an important in role specially in humanitarian logistics. To meet the needs of the affected population in disaster shelters, an effective, fast, and reliable means is necessary. More often, land transportation, specifically roads are the most widely is used during these activities (Ertem et al., 2017). In particular, road system is not only a means of people and goods mobility but also serves a life-line system during emergencies (Mattsson & Jenelius, 2015). The low cost and abundance of land vehicles permits land transportation to carry out humanitarian activities immediately following a disaster that is, on the onset of the disaster, first responders often take land transportation to reach affected areas. This means of transportation often performs most of the trips but in situations where roads are disrupted, land transportation may not be able to meet all the necessary demands specially when there are isolated places and low accessibility places. In this case, the reliability of road networks is very but no system is perfect and often times, disasters can cause road disruptions (Dalziell & Nicholson, 2001; Sansano & Chikaraishi, 2022; Santos, Safitri, et al., 2021) and can greatly affect relief operations and repairs of lifeline systems and increase vulnerability of communities (Nicholson & Du, 1997; World Bank, 2017).

During the 2005 Hurricane Katrina, all roads leading to New Orleans and Mississippi Gulf Coast were affected and transportation was stop resulting to large damage especially to economy (AARoads, 2023). In 2018 Heavy Rain Disaster in Hiroshima Japan, large mass movements and landslides caused heavy damage to roads and resulted to several isolated areas (MLIT, 2018). In the Philippines, the 2021 Typhoon Odette caused an estimated 448.9 million pesos, roughly 8 million US dollars, damage to roads, bridges, and flood-control structures that resulted to many unpassable areas (DPWH, 2021). In this situations, humanitarian response can not simply depend on land transportation only since road disruptions can happen anywhere but needs assistance from other transportation modes such as air transportation. Specially, in large scale disasters, assistance from other places, whether locally or internationally often use air transportation to deliver their aid since it is faster. In these situations, airports play an important role as emergency hubs to cater disaster response operations. During this time, receiving the relief goods and personnel is not only the role of the airports but it also plays role in distribution since aircraft such as helicopters are often used to reach some areas during disasters.

As an example, during the 2010 Haiti earthquake, cargo planes bringing food, water, medical supplies, and other necessities where utilized and helicopters was also used to transport critically inquired individuals (Katz, 2010). Also, during the 2011 Great East Japan Earthquake, aircraft such as civilian and government helicopters used Hanamaki Airport, Yamagata Airport, and Fukushima Airport as bases to gather information, and perform emergency rescue and goods transport (Hanaoka et al., 2013). In the Philippines, the 2013 Typhoon Yolanda caused massive damage and relief aids from different countries utilized Tacloban Airport and Ormoc Airport to received C130 aircraft carrier relief goods (NDRRMC, 2014).

In these situations where road disruptions happen, the use of land transportation decreases and an increase in air transportation takes place. Consequently, the demand for air transportation and the use of airport services increases just like during the 2010 Haiti earthquake where the local airport had to cater more than 100 flights a day compared to its normal 35 flight a day operation

(ATAG, 2023). In most cases, the increase in demand to use aircraft such as helicopters are hard to meet since air transportation in general are expensive and availability is low. In addition, an increase in the use of aircraft also increase noise and air pollution since these aircraft use fuel and produce high noise when operating.

Currently, this air and land transportation combination is common and often used. The question is how does these two systems performs together during disaster response and is there a better way to link these two systems together while considering its own shortcomings? In summary, while looking into these tow transportation systems several problems can be identified such as: (1) roads can be disrupted during disaster and can cause increase in travel time due to detouring and low accessibility; (2) land transportation cannot be used to reach isolated places; (3) road disruption patterns are hard to identify before the disruption (4) conventional air transport is expensive; (5) there is low availably of air transport due to complexity in operation; (6) there is a significant increase in demand in air transport that cannot be met; (7) an increase in the use of air transportation will result to additional air, noise pollution and high cost.

1.2. Research Objectives

To address these problems, this study proposed the use of a new air mobility called electric vertical take-off and landing (eVTOL) aircraft commonly known as air taxi or drone taxis. This new air mobility has a potential not only as a new form of transportation but also in logistics during disasters (METI, 2021). Also, this new aircraft can address both the deficits of land and air transportation. These aircraft can help reach areas which are difficult to reach using land transportation because of disrupted roads especially isolated places. Also, since these are targeted to be a public mobility comparable to a regular land taxi, its availability will be higher compared to a traditional helicopter. Additionally, it also answers the problem in terms of cost and complex operation since studies shows it will be cheaper is less complex than its traditional air transportation counterpart (Archer Aviation Inc., 2021; TransportUP, 2019). Moreover, since these are electric vehicles, it offers lesser noise and air pollution.

The use of drones in disaster management is not a new knowledge. Early applications of drones in disaster management involved mapping and damage assessment of areas struck by the disaster especially in inaccessible, mountainous areas, and areas surrounded by water. Earlier records where drones were used for this purpose in disaster includes the 2008 earthquake in

Sichuan, China where many infrastructure were damaged and where drones were used to help rescue team identify areas that needs to be prioritized as well as routes that are blocked due to damage in bridges and tunnels (Ip, 2022). Also, during the 2015 magnitude 7.8 earthquake in Nepal, drones were used to survey the region and produce detailed photos and videos to examine the condition of the area. The earthquake caused more than 7,180 injured people and large number of homeless populations as well as left many areas inaccessible that made the relief operations even more difficult. This led to the use of drones which enable them to identify which roads are blocked and to what extent are the infrastructure damaged to carefully plan their operation (Kwong, 2015; The Associated Press, 2015). Another example is during the 2022 severe flooding in KwaZulu-Natal and Eastern Cape provinces of South Africa where drones to capture images to gather information in order to analyze and assess the damages in the flooded region.

As more improvements to drone technology have been realized, its applications in disaster management also broadens. Since one of the concerns during disaster is the delivery of relief goods and medical supplies, this new function was added to drones. Real disaster events that demonstrated this application have also been documented. In Yufu City, Oita Prefecture, Japan, a large transport drone was also used to deliver relief supplies to the affected population of a large-scale landslide. The heavy rain caused road disruptions and also rendered damage to communication which made the relief operation slower. The transported goods were comprised of walkie-talkies, water, and retort-packed foods which took only 3 minutes to transport compared to a 2-hour travel by foot since the areas are difficult to access during that time (Jiji Press, 2023). In Florida, U.S.A., hurricane Ian caused the isolation of Sanibel Island when the only bridge in and out of the town was destroyed. Due to limited access to food and other resources, drones were used to deliver meals, portable chargers and other essentials to the residents of the said island (Daleo, 2022). In 2022, villages located in lower Assam India had been cut off from the rest of the state due to flooding caused by monsoon rain. During this time, drones were used to deliver food and medicine to victims trapped in floodwater (Kalita, 2022).

These real-life events that demonstrated the use of drone technology in disaster management is a proof that there is still a room for improvements that can further enhance disaster management especially in disaster response. While earlier drone models are effective it has limited capability in terms of capacity when use in relief operations. A single drone is only capable of transporting a few number of weights due to its small structure but with the introduction of eVTOL aircraft which is a new innovation of drone technology, this limitation can be addressed. Since the size of this new drone taxi is comparable to helicopters, more relief goods can be transportation. In addition, since this new mobility is originally used as a means of public transportation, it also has the capability to transfer emergency personnel which can lessen the travel time and help save more lives.

In order to effectively use this mobility, a suitable facility is needed to accommodate it. In this study, we propose the establishment of emergency ports that will serve as landing and takeoff as well as temporary holding area of goods and services for distribution but finding suitable location can be challenging since road disruption patterns are unknown before a disaster. To do so, a method of identifying these locations that considers road network disruption probability is necessary. Additionally, these locations must also consider the cost of transportation since one of the main considerations in disaster operation specifically in humanitarian logistics is budget constraint and humanitarian logistics is the most expensive part of disaster relief operation, accounting for about 80% of the total cost of operation (Van Wassenhove, 2017).

Considering all the above factors, to highlight the importance of air and land transportation integration through the use of eVTOL aircraft in humanitarian logistics considering possibility of road disruptions caused by disasters, the following research objectives are presented:

1. To develop a method as to find the optimum locations of emergency ports that minimizes the transportation cost of relief goods to disaster shelters and the most suitable mode of transportation considering possible road network disruptions and place isolation.
2. To determine as to what degree will the new air mobility support the disaster response operations.
3. To analyze the effect of uncertainties in transportation cost, operation cost, isolation cost, demand change, and vehicle capacity in the location of emergency ports and cost of operations.

1.3. Framework of the Study

The input-output diagram shown in Figure 1-1 describes the research flow of the study. The study first explores the factors affecting road disruptions by using the social and natural factors as an input. These factors output the road disruption patterns. These patterns are then use as an input to determine disaster shelters that may experience isolation or increase in travel time. As a result, transportation cost where calculated using this data. In cases of isolated disaster shelters, an isolation cost was used and for other locations, transportation cost was based on the travel time which was represented through travel distance using the shortest path algorithm. The resulting data becomes part of the input to determine the optimum location of emergency ports. Additional input represents other variables that contains uncertainties such as the transportation cost of using eVTOL aircraft, operation cost of emergency ports and change in the demand based on the number of evacuees.

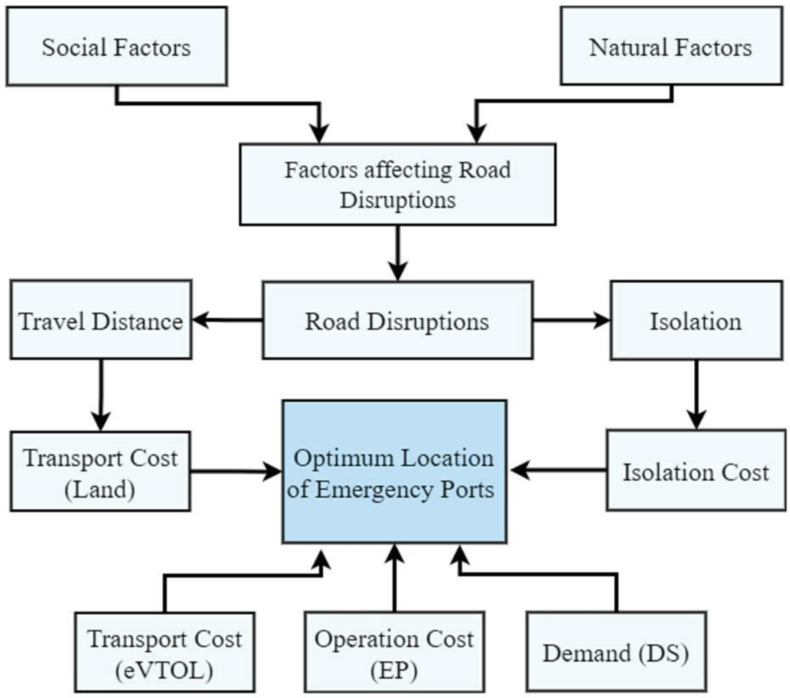


Figure 1-1: Research Flow Diagram

The use of a new mobility eVTOL aircraft was proposed to have an additional means for disaster response. This was implemented by introducing emergency ports that accommodates the operation of eVTOL aircraft in disaster-affected areas. Since the model considers cost and road disruptions, suitable locations of the emergency ports were identified based on these criteria.

Lastly, to further illustrate how road disruptions affects disaster response, an enhanced model was introduced focusing on the degree of cooperation between the land and air transportation network. The model measures the usefulness of the emergency ports in reducing place isolation and using different means of transportation altogether. Since road network disruption patterns are unknown before the disaster, identification of suitable location is challenging. Therefore, the enhanced model was tested in a real network considering the probability of road disruption derived from a case study. It also determines the distribution of each mode of transportation used in the disaster response such as (1) land transportation; (2) air transportation; and (3) air and land transportation using eVTOL aircrafts through emergency ports. The goal of the enhanced model is not to replace one mode with another but to supplement the deficiencies of each mode and to test the potential of the new mobility not only as a public transport but as an additional mode of transportation during disaster.

1.4. Dissertation Outline

This paper is divided into of seven chapters. Each chapter were written to properly explain the flow of the study and model development and enhancement to reach the research objectives. Chapters were constructed to explicitly show the relationship and interconnection of each issues introduced. Chapter 3 introduced the main source of the problem which are road disruptions caused by disasters and the factors affecting it. A model to address this problem was introduced in Chapter 4 and an enhancement model using real road network was introduced in Chapter 5. Chapter 6 provides a discussion on how variations in some parameters will affect the proposed model. Chapter 7 provides a summary of the whole study. The details of each chapter are as follows:

Chapter 1 composed of the introduction of the study that covers the background, research objectives, outlines and approach of the study and research contributions. Chapter 2 consists of relevant literature reviews focused on resilience of road networks, land and air transportation, drone technology and its innovations. This section also includes the literature that supports the models in Chapter 3, 4 and 5. Chapter 3 develops a model that empirically explores factors affecting road disruption patterns and duration of road recovery. The study was based on road network disruption and recovery records in Hiroshima, Japan over the last 19 years.

Chapter 4 developed a method to address road disruptions that can result to low accessibility or isolation of disaster sites introduced in Chapter 3. The method includes the utilization of eVTOL (electric vertical take-off and landing) aircrafts to expand air transportation network for better and efficient humanitarian activities. Road disruptions were represented using a toy network and different road network disruption scenarios were generated to illustrate the model.

Chapter 5 developed a model that extend the characteristics of the model introduced in Chapter 4. While Chapter 4 focused on introducing a model to solve the problem caused by road disruptions caused by disasters using eVTOL aircraft, Chapter 5 focused on the degree of cooperation and usefulness of eVTOL aircraft in supporting the disaster response. Using a real road network of Kure City Hiroshima Japan, the model shows the extent of how the new mobility and the proposed system can be used with varying factors in cost.

Chapter 6 provides a discussion on the different uncertainties on the use of new technology that may affect the selection of the location for emergency ports. A sensitivity analysis was used on several parameters to illustrate its impact that can assist policy makers in planning and integrating eVTOL aircraft to the existing disaster management plan.

Chapter 7 summarized the findings of the study by identifying suitable locations based on road disruptions generated through the Monte Carlo simulation. Recommendation for future works was also introduced to provide insights to future researchers that may want to further explore the potential of eVTOL aircraft in disaster management.

1.5. Contribution of the Study

The first model presented in the study focused on the factors affecting road disruption patterns and road recovery. This model provides empirical evidence that can help policy makers in decision-making process specially in road investments. Since road disruption patterns are unknown before the disaster, providing insights for better locations using the different factors can help in deciding locations of new road infrastructures that are more resilient to disasters.

Another contribution of the study is the introduction of a new concept where road disruptions are directly incorporated through different scenarios. By utilizing eVTOL aircrafts through the introduction of emergency ports, both relief goods and emergency personnel can be transferred through emergency ports to the disaster-affected regions. The introduction of these emergency ports allows the eVTOL aircraft to fill-in the deficiencies of both land transportation and conventional air transportation. This enhances the potential of these vehicles, highlights the importance of air-land cooperation during disasters, and increases the value of airports.

Also, while many articles have mentioned the potential of eVTOL aircraft in disaster response, to the best of our knowledge, this study is the first to empirically explore and show evidences of the application of this new air mobility in disaster response operation particularly in humanitarian logistics (Degel, 2023; Gipson, 2021; METI, 2021).

Lastly, this research provides an analysis on how some uncertainties involved in using new technology can affect the overall operation disaster response operations.

Chapter 2. Literature Review

2.1. Road Network Resilience

For the past few decades, the number of natural disasters has been surging dramatically. Climate- and weather-related disasters have increased five-fold over the past 50 years, with 74% of these disasters causing economic losses(United Nations News, 2021). This has led many researchers in different fields to focus on improving resilience towards disasters. Resilience is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management” (UNDRR, 2009). In transportation studies, Serulle et al., (2011) defined resilience as “the ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in specified timeframe”. This is very similar to the definition of resilience described by Balal et al., (2019), that is, “the ability for a transportation network’s operation to withstand and rapidly recover from a disruptive event that causes link closures, node closures, or reduced capacity”. Following these definitions, the resilience of a road network can be thought of as consisting of two phases: (1) the initial phase, which focuses on the initial impact on the network, and (2) the recovery speed from the damaged sustained from the disaster. The next subsection will review studies related to the first phase, which mostly focus on the concept of road network vulnerability, followed by a review of studies related to the second phase, which explore the road network recovery process.

2.1.1. Road Network Vulnerability

Road network vulnerability has been a focus of many studies in the past. Various evaluation approaches and techniques have been used in the literature to evaluate road network vulnerability. To perform the analysis, the evaluation approach is strongly linked to the availability and type of data used, and how the network was represented in the study, such as in abstract form or based on real-world network. (Pan et al., 2021) categorized quantitative methods used to analyze transportation vulnerability and resilience studies into topological analysis, model optimization, simulation, and those which are based on data. In their review of approximately 140 studies, 24%

used topological analysis, 48% employed model optimization, 18% performed simulations, and only 10% are data-based research.

Network topology is the abstract representation of transportation systems consisting of nodes and interconnecting links (Zhang et al., 2015). Studies that analyze topological structures of transportation networks often consider roads as links, with pieces of infrastructure or significant locations where these roads are connected being considered as nodes. This method may also incorporate the use of simulations to perform various analyses (Chen et al., 2021; Furno et al., 2018; Gao et al., 2019; Hu et al., 2022; Tang & Huang, 2019; Zhang & Yao, 2019).

On the other hand, data-based research requires a considerable amount of data to perform empirical analyses. Obtaining reliable and useful data for research can be challenging and difficult. Historical records, for example, are difficult to acquire, especially when proper data management on important events is not in place. Even when data are acquired, treating and cleaning the data to obtain reliable information may also be challenging. This is one of the reasons why there are fewer empirical studies compared to other methods. Examples of data-driven studies in transportation include that conducted by Kermanshah and Derrible (2016), who used U.S. Geological Survey ShakeMaps to determine the location of roads which are vulnerable to extreme earthquakes, and that conducted by Donovan and Work (2017), who used GPS data from taxis containing the beginning and end of trips, the metered distance, and the total travel time to analyze changes in traffic conditions caused by a hurricane.

In another study conducted by Santos et al., (2021), an empirical analysis was performed using rainfall data from the July 2018 heavy rain disaster in Hiroshima, Japan, to produce a risk map showing critical road segments and occurrence probabilities of sediment hazards. Results showed that areas within the hazard area and watershed boundary are more likely to be disrupted due to sediment hazard. This relationship also holds in the case of a high rainfall index value. However, the number of disrupted links used in the study is relatively low.

Another piece of research focusing on flood scenarios was conducted by Singh et al., (2018), who also used daily rainfall data for rainfall analysis to create flood maps at different stages based on water level. Two rainfall scenarios with different intensities, durations, and return periods (10 and 100 years) from the data were taken, and flood depth distribution over roads and its impact on road vulnerability in terms of reduced mobility were analyzed. Results of this study showed that even normal rainfall would cause delay in travel and congestion. In addition, an increase in rainfall intensity caused a nonlinear increase in traffic disruption.

The relationship between road vulnerability and tropical cyclone intensity was investigated by J. Zhu et al., (2022), using the records of road damage associated with three tropical cyclones in Hainan Province, China. The study specifically focused on two intensity hazard measures: maximum wind speed at 10 m above ground and cumulative precipitation during the tropical cyclone period. Results showed that vulnerability functions of the road are affected jointly by both cumulative precipitation and maximum wind speed. One limitation of this study is that it only contains 406 disrupted roads, including national roads, highways, provincial roads, and county roads, which is a relatively small proportion of the total number of roads.

A record of disruption between 1997 and 2010 caused by floods and landslides due to extreme rainfall or rapid snowmelt in the Czech Republic was used by Bíl et al., (2015). The authors analyzed the impact on the economy, people, infrastructure, connectivity, and serviceability. One limitation of this study is that only roads that were totally damaged and needed full restoration, and partially damaged roads that needed repair, were considered. Roads that were interrupted due to temporal flooding or sedimentation that had almost no repairs were not included, which implies that the analysis did not capture some portions of the damage.

While these studies made good use of data from past disasters, the focus is limited to one or two disasters and to certain events created by the disaster. This limits the applicability of the results of the studies to other disaster contexts.

2.1.2. Road Network Recovery

For studies on vulnerability, road recovery is the second phase of resilience. Social and economic recovery from major disasters is significantly influenced by the speed of reconstruction of transportation infrastructures (Rouhanizadeh & Kermanshachi, 2020). Road recovery plays an important role in the initial phase of the disaster, as well as in restoring communities back to their normal state (Lacuarin & Palmiano, 2020). In the past, a significant number of studies have been undertaken to investigate the challenges of improving road network recovery.

Following the framework of Çelik, (2016), studies in network restoration and recovery can be classified according to the set of decisions, objectives, and solution methods used in the study. Studies that deal with problems such as transportation infrastructure restoration or rehabilitation

(H. Pourmohammadi, 2008; Iloglu & Albert, 2020; Rouhanizadeh & Kermanshachi, 2020; Wang C.Y. & Hu S.R., 2005; Zhao & Zhang, 2020), debris clearance (Ajam et al., 2019; Berktaş et al., 2016; Sayarshad et al., 2020), sequencing and scheduling (Gokalp et al., 2021; Rey & Bar-Gera, 2020; Tadano et al., 2017), etc., may require different sets of decisions and solution methods, such as mathematical solutions and numerical experiments as well as simulations. Studies looking into different aspects of road recovery can be categorized as cost-related measures, travel time or distance, completion time, utility or benefit, accessibility, and delay or latency (Çelik, 2016).

Past studies mostly rely on creating scenarios to model possible outcomes and suggest solutions based on these results, which often contain many uncertainties. Lack of empirical data on road network recovery is often one of the reasons for this. Some studies attempt to close this gap by employing data-driven research using big data and other data sources. For instance, big data from individual ridership during two hurricanes that caused huge damage to transportation systems in New York City were used by Zhu et al., (2016) to study the post-hurricane recovery patterns of roads and the subway system in the city. Results showed that the recovery rate from the two hurricanes differed, and that the road networks have a higher resilience than the subway system. Joo et al., (2022) used a combination of mobile phone GPS data for human mobility, real road network information, and road reconstruction process information during the July 2018 heavy rain disaster in Hiroshima to build a model for multi-locational road recovery. One common aspect of the above-mentioned studies is the lack of historical data on road recovery time and damage. As in the case of the vulnerability studies, these studies only focus on a particular type of disaster, and the time span of the data is short. In addition, studies which use big data on passenger travel mostly focus on travel time and origin–destination information and lack information regarding road closures and their duration.

In summary, there are few studies which conduct empirical analyses on both road network disruptions and recovery using a long-term data record. We believe that this is the first study which explores factors affecting the probability of road disruptions and duration of road recovery using the road disruption and recovery record over a 19-year period. Such studies can provide policy makers with more reliable empirical evidence and aid them in decisions on policy interventions and resource allocation.

2.2. Transportation and Humanitarian Logistics

Transportation is considered as a critical infrastructure since it has a huge impact to economy and people when disrupted (Rodrigue, 2020). Transportation consists of several factors such as the vehicles itself, the infrastructures, and the operators that ensures the efficiency and operation of the system (Center for Disaster Philanthropy, 2023). While there are many forms of transportation that includes sea, air, and land, the operation of these transportation systems may or may not involve each other. Transportation systems may have some tolerance to disruptions but as some point may still experience disruption particularly during large scale disasters (Rodrigue, 2020). In cases where a single mode of transport is damaged, intermodal transportation which are more robust to network disruptions can be used specifically in relief operations (Ertem et al., 2022).

As there are several modes of transportation, land transportation, specifically roads are the most widely used particularly in disaster preparedness and response phrases (Ertem et al., 2017). Land transportations are basically cheaper and availability and accessibility is higher compared to other modes of transport. The downside is that, similar to other modes, land transportation is also vulnerable to disruptions particularly road disruptions (Sansano & Chikaraishi, 2022; Santos, Safitri, et al., 2021). In these situations, humanitarian logistics may be hindered.

Another mode of transportation used during disaster is air transportation. Past studies focused on the importance of this mode of transport during disasters and particularly aimed to improved its efficiency. Hanaoka et al., (2013) particularly focused on the operation of airports and the coordination within the different sections in the airport and analyze the positive and negative aspects that influenced the disaster response operations. Polater (2018) conducted a systematic review of airport disaster management in an effort to provide information to future studies in relation to non-aviation related disasters such as natural disasters. This study found out that past literatures focused on research topics such as stakeholder collaboration, scheduling problems, medical preparedness, infrastructure planning, and corporate social responsibility.

Polater (2020) focused on managing airport logistics surge capacity when airports function as logistic centers during humanitarian activities. The study found out that surge capacity management is closely connected to flight prioritization and activities related to operations. It also includes managing increase of people using the airport as well as the capacity of the infrastructure itself and the involvement of the people using the airport. The study conducted by Arreeras & Arimura (2021) focused on the vulnerability of airports to unexpected events such as natural disasters which may hinder its operations during this period. The model formulated was to ensure that flights can find new airports to land in case the disaster occurs, and the destination airport was affected and cannot receive the incoming flight. The model used the evacuation flight time and maximum airport capacity as a criterion to find the new airport to reroute the flights. Another study focusing on airport operation is Qin et al. (2021). In this study, the congestion on the loading and unloading of cargos during relief operations was investigated. The study particularly aimed to improve the process of management of air traffic and scheduling to ensure smooth operation and manage hangar space.

While these studies offer solutions to existing problems that the airport face during disaster response, these studies focus solely on airport entities and do not consider other transport systems such as road network. While airport function as emergency hubs, outside road condition is also important since the relief operations do not stop upon the arrival of aircrafts in the airport but must reach their intended destination such as the disaster sites. During disasters, the possibility of road network disruption is very high (Sansano and Chikaraishi, 2022) which can lead to an increase in travel time and travel cost. Additionally, the transportation of both relief goods and emergency personnel is also an important issue that needs to be addressed during disaster response.

While air transportation is important during disaster response, other modes of transportation is still needed. As mentioned, the use of one or more modes of transportation during disasters are not new in literatures. Ertem et al., (2022) particularly found out that intermodal transportation is more beneficial for humanitarian logistics during large-scale disasters specially when there is lack of transportation resources and transportation infrastructures are damaged. Maghfiroh & Hanaoka, (2020) focused on the multi-modal relief distribution during disaster response operations. The result of the student showed that multi-modal transportation comprised 45.67% of total use (31.98% for airplane–truck, 7.95% for sea vessels–truck, and 5.74% for airplane–helicopter). Zhang, MS et al., (2011) on the other hand focused on the factors that can increase the possibility of using intermodal transportation during humanitarian activities particularly on identifying the reasons why humanitarian organizations utilize different modes of transportation during operations. Compared to intermodal transport that involves several companies, multimodal transport also use two or more modes of transport but only involves one transportation company throughout the process (Khovrak, 2023).

In this study, two modes of transport will be utilized particularly, air and land transportation. Some studies that particularly focused on air and land transportation includes Salmerón & Apte, (2010) and Barbarosoğlu & Arda, (2017). Salmerón & Apte, (2010) particularly focused on resource allocation and transportation assets considering expected number of casualties. Similarly, Barbarosoğlu & Arda, (2017) focused on transportation of goods to disaster-affected areas using multi-modal network. Scenarios used in the study involves capacity, supply, and demand. While these studies are similar to the current study in terms of the use of both air and land transportation in disaster response, the current study explicitly represents the effect of road network disruptions and transport cost utilizing both modes of transportation.

2.3. Drone Applications and Innovations

The rapid development of technology had led the way to the invention of unmanned aerial vehicles (UAVs), more commonly known as drones. These remote-controlled electronic devices allow a wide variety of applications including intelligence gathering, monitoring, and delivery services (Lutkevich, 2021). One major advantage of utilizing drones in delivery services is the significant decrease in travel time since drones are not subjected to traffic jams (up to a certain number of vehicles) or other road disruptions. Studies including Shavarani et al. (2017), Farahani et al. (2014), Salama and Srinivas (2020), Chauhan et al. (2019), Dukkanci et al. (2021), Wen and Wu (2022), and Liu (2022) explores the capability of drones in delivery services including parcels and small to medium-sized packages with the aim of lessening delivery time to customers in different locations and establishing suitable depot locations to improve economic gains. This advantage in transporting goods faster is one of the main features that made drone technology a necessity in many fields including disaster management.

In disaster management, time is one of the most important factors that need to be considered and the use of drone technology give a way to enhance disaster response. Problems caused by road disruptions as a result of disasters have been one of the factors affecting the timely relief operations. In 2010 Haiti earthquake, 2008 Wenchuan earthquake, and 2011 Japan earthquake, land transportation systems including roads, bridges, and railways were damaged which severely limit the disaster operations (G. Zhang et al., 2022). From this perspective, finding a means to perform timely disaster operation is very important and the utilization of drones is one of the means that can fill in this gap.

In this context, some relevant studies have been conducted. Chowdhury et al. (2017) focus on minimizing the overall distribution cost for transporting emergency commodities by determining the optimal location of the distribution centers and their corresponding service regions as well as ordering quantities in disaster-affected areas. While considering road disruptions, this study focus on the possibility of using drone or trucks in distributing the relief goods. Chowdhury et al. (2021), on the other hand, use the potential of drones in surveillance by minimizing the inspection cost of areas affected by a disaster while taking into account trajectory-specific factors such as battery recharging cost, servicing cost, and many others. Estrada and Ndoma (2019) evaluates the role of drones in disaster response, particularly in aerial monitoring and damage evaluation, logistics and cargo delivery, and post-disaster aerial assessment under the assumption that natural disasters can damage major services such as transportation, communication, and other services. Ghelichi et al. (2022) also focus on the timely delivery of goods to disaster areas by minimizing the total disutility or cost by locating a set of drone take-off platforms when demand points are unknown based on discrete scenarios. Zhang et al. (2022) examine the use of drones to assess transportation network conditions to ensure feasible delivery of relief goods by considering the capability of drones to avoid road disruptions and to travel off-road and on-road to make an assessment. Rabta et al. (2018) also focus on the use of drone for last-mile distribution of relief goods such as light weight emergency supplies to certain remote locations in the disaster prone areas. While most of these studies consider the applicability of drones in relief operations while taking into consideration road disruptions and isolation of disaster areas, the models used did not explicitly showed how road disruptions affects the disaster response. The current study explicitly demonstrates the effect of road disruptions through numerical scenario analysis which shows how travel distance varies because of road disruptions and is reflected in the computation of total travel cost.

Golabi et al., (2017) also focused on a facility location problem minimizing the cost of relief distribution while taking into consideration collapse network edges. While this study also considered network disruption, the focus is the capacity of distribution centers and traveling distance of both people and drones. Chauhan et al., (2019) on the other hand proposed a facility location model that aims to maximize coverage with consideration of drone energy consumption and range constraints. Kim et al., (2019) focused on optimal locations and transport capacities of facilities with minimum cost with an assumption that regardless of the distance drones can transport supplies to meet the demand. While these studies utilized drones to disaster response, the current study differs in terms of focus, location of facilities with respect to both cost and road disruption and distribution of transport mode and type of transport mode used.

The use of drones in disaster management have gained a lot of attention recently due to its advantages particularly in travel time and accessibility. This also includes the field of public transportation. The advancement of drone technology stretches to transportation in the form of electric vertical take-off and landing (eVTOL) aircraft which are commonly known as air or flying taxis (Biba, 2023; JAL, 2023). This new innovation has been gaining a lot of attention in the business and transportation field, but little studies have been conducted.

Goyal & Cohen, (2022) examines the potential operational and market viability of air ambulance using variety of aircraft including eVTOL. Result of this study showed technological improvements on eVTOL aircrafts can make it more reliable and cost-effective mode of medical transport. Similarly, Mihara et al., (2021) focused on eVTOL as air ambulance and conducted a cost analysis. The proposed model allows analysis capital expense and operating cost of the said mobility. These studies particularly consider a special application of eVTOL in emergency in the medical field. While this is somehow similar to the current study as it also includes the transportation of emergency personnel to disaster shelters, the eVTOL considered in the study is not a dedicated vehicle for medical transport only but a regular airport air taxi which differs in availability and number of available vehicles.

Rajendran & Zack, (2019) focus on providing a method to estimate the demand of using air taxi and potential location of facilities to support its operation. Willingness to fly, demand fulfillment rate and time-cost tradeoffs are some of the factors considered in the study. Similar to this study, Rajendran et al., (2021) also focused on predicting demand of air taxi service but considers both ride-and weather related variables as predictors. While this study considers demand in terms of usage of air taxi, the current study assumes that this mobility is already available and meets the demand as a public transport. Similarly, Rajendran and Srinivas (2020) examine the potential impact of eVTOL on air traffic services in operation management perspective particularly in demand prediction, network design, vehicle configuration as well as its potential future challenges.

Bauranov & Rakas, (2021) on the other hand focused on airspace concepts that includes size, capacity, and geometry of urban airspace. The study also includes analyzing other concepts of eVTOL airspace from other studies and identify strengths and weaknesses of each proposed system.

Lewis et al., (2021) focused on creating an architectural approach that can be used to analyze air taxi shuttling system that considers both profit and safety. Shao et al. (2021) design an operation structure for terminal area of air taxi which includes control rules of air route as well as schedule. These studies focused more on the technical aspects of the eVTOL such as airspace and configurations while the current study focuses more on the application of eVTOL in other fields aside from public transportation. Ale-Ahmad and Mahmassani (2021) created a decision framework to address certain eVTOL activities such as request acceptance and rejection, allocation of request to flights, and aircraft routing and scheduling which also allows demand consolidation for increased utilization and service rate.

To sum up, the introduction of drone technology, particularly eVTOL aircrafts, in airports as new transportation, is a key factor to improve airport resilience. As pointed out by the studies discussed above, the capability of drones in disaster response is very high. By introducing new ways to utilize this technology through the establishment of emergency ports that can be used as landing and take-off facilities of eVTOL, extending the air transportation network becomes possible. Additionally, past literatures only focus on the transportation of relief goods, while in real situations, emergency personnel transport is also important. Lastly, to the best of our knowledge, this study explicitly fills the gap by taking into consideration airport-outside condition, particularly road network disruptions, which is one of the major cause of delay in relief operations.

2.3.1. Vertiport Locations

One concern in using eVTOL aircraft is the infrastructure such as vertiports that can be used to accommodate it. According to Northeast UAS Airspace Integration Research (NUAIR), *a vertiport is a collective term referring to areas designed specifically for AAM aircraft to take off and land.* This infrastructure is like heliport which is used by helicopters. Vertiports can also be built on other existing infrastructures such as buildings or be like a hub call vertihubs or function like bus stopss called as vertistops (McNabb, 2021). To successfully build this infrastructure, one important component is choosing its location. In literature, several considerations were investigated to come up with a guideline on choosing a proper location for vertiports.

Willey & Salmon (2021) ventured on the idea of air-metro and multi-leg travel by considering vehicle limitations, operational strategies, and possibility of vertiport-to-vertiport travel to identify location of vertiports. Amitanand Sinha & Rajendran (2023) used results from past studies on potential air taxi demand and tried to decrease the number of locations by considering additional parameters such as rental cost, daily number of trips, easy access to road facilities, and employee salary to find vertiport locations. Similarly, Sinha & Rajendran (2022) also considered rental cost, population density of an area, number of taxi trips per day per 1000 customers, average salary of the neighborhood, and road facility which are mostly socio-economic factors to find locations of vertiports concentrating its operation in urban areas. Lim & Hwang (2019) prioritized population distributions in selecting vertiports locations and analyzed the impact of different number of vertiports and their locations.

Rath & Chow (2022) proposed a model to determine location of vertiports for the use of air taxis connecting to airports which they refer to as skyports. The model incorporates the trade-offs between trip length and trip cost based on mode choice behavior of travelers with consideration on travel cost, transfer times, and user demand. Rajendran & Zack (2019) focused on estimated air taxi demand by considering regular taxi customers who are likely to use the new service to identify potential locations for vertiports. It also looked into the impact of willingness to fly rate, demand fulfillment rate and time-cost trade-offs in determining the potential locations. Kim et al. (2023) considers the importance and influence of factors related to passenger environment such as locations with good transfer, accessibility in urban areas, and safe take-off and landing in identifying potential location of vertiports.

In the literatures presented above, vertiports are presented as a solution to lessen the traffic congestion by introducing air taxis as new mode of public transportation under normal condition which mostly focus on demand ridership as one of the important factors for identifying vertiport locations. In contrast, this study considers the application of eVTOL aircraft during disasters while considering road disruptions and therefore suitable location of vertiports which are introduced as emergency ports in the study are determine by considering factors that affect road disruptions together with the least transportation cost. Since this new mobility is still not implemented, finding suitable location can be challenging as many factors can affect decision making even during normal condition and therefore when considering a more variable condition such as disasters, this problem is more difficult to address.

2.3.2. Uncertainties in New Technology

The introduction of new technology can be challenging. As new technologies often have many uncertainties, handling and using it may need a more thorough understanding and plan. Uncertainties may include the technology itself, its potential market applications and users, its ecosystems, and right business model (Klueter, 2021). To fully realize the potential of new technologies, many researchers focused on addressing these uncertainties and tried to come up with a model that would best handle the effect of uncertainties in using the new technology.

One particular new technology in the field of transportation is autonomous vehicles (AV). This new land mobility offered a variety of advantages compared to conventional cars such as high accuracy, reduced probability of accidents, higher traffic efficiency and less carbon emission (Tenorio, 2021). Despite the said advantages, the use of these vehicles in public transportation is still not clear. One reason is because of the public acceptance to willingly use this kind of vehicles. As a new technology, many uncertainties specially in safety have been a hindrance to its integration to public transportation. These issues have been a topic of many researchers in hope to find solutions or lessen these uncertainties. An et al. (2020) focused on improving the driving control of AVs by developing a model that concerns uncertainties in human behavior and physical environment where both pedestrians and conventional cars and AVs interact. The model focused on classifying human drivers as models. Compared with other models that focused on the driver of the vehicle, the model used focused on classifying the driving style of surrounding human-driven vehicles.

Other researchers tried to focus on the users of AVs to understand what factors affects their decision in using AVs. O'Hern & St. Louis, (2023) found out in their research regarding readiness and intentions of using conditionally automated vehicle (CAV) that people with optimistic views in technologies and have prior experience of using other technologies such as Advance Driving Assistance Systems (ADAS) have stronger intentions to use AVs. Also, one factor that influence their decision is the sense of security regarding the new technology.

Aside from the technical capabilities of AVs, another concern is the cost since this new technology aims to be implemented as a public transportation. One concept introduced is shared autonomous vehicles (SAVs) which can lessen the overall cost of transportation using AVs. Kaddoura et al., (2020), as an example, researched on the impact of SAVs and different pricing setup on the transport system. It involves pricing using base fare with no congestion charge and predict the overall usage of SAV in the selected area. Results indicates a 17.7% share on the rides. Also, with the application of congestion charge users tend to shift to other modes of transport. Similarly, Shatanawi et al., (2022) also focused on pricing of both AVs and SAVs using dynamic traffic assignment model to investigate the impact of road pricing to network performance and social welfare. Using three scenarios which involves conventional cars, Avs, and SAVs in varying ratios, the research tried to find in which scenario will dynamic and static pricing will be more beneficial.

Aside from technological and pricing uncertainties, another issue is the integration of AVs to the physical environment. According to Elvarsson et al., (2021), the use of AVs will result to high uncertainty in parking demand with one scenario where the need for parking lot disappears. Based on this, the focus of the research is to minimize the risk of over or underspending to construct new infrastructure to accommodate AVs. The real option methods introduced in the study involves operation cost, refurbishment cost for each design alternatives proposed, and estimate net benefits. The idea is to allow the parking garages to be easily transformed to other beneficial infrastructure in case the needs for these spaces diminish.

Similar to AVs, the utilization of eVTOL aircraft also face many uncertainties. As a new technology, many factors are still under testing and optimal performance is still unclear. While it also offers more advantages over conventional air transportation, these uncertainties also affect its integration to the current system. In this study, we tried to address the uncertainties concerning the transportation cost and operation cost of this new mobility by observing the effect of varying prices to the performance of eVTOL aircraft as a means of transportation during disasters.

Chapter 3. Exploring Natural and Social Factors Affecting Road Disruption Patterns and the Duration of Recovery: A Case from Hiroshima, Japan

3.1. Introduction

As climate change has progressed over the past few decades, its widespread impacts on both society and the environment have become more noticeable (IPCC, 2014). The increase in the occurrence and severity of disasters can cause huge upheavals in people's daily activities. One major problem is the disruption of roads, which results in the loss of accessibility and longer travel times, especially during evacuation and relief operations. It may also cause recovery to take longer and lead to bigger problems, including economic loss, reduced level of public services such as police and fire services, and so forth. As pointed out by Nicholson & Du (1997), damage to the transport system inhibits repairs to other lifeline systems, including water supply, energy supply, sewage disposal, and IT infrastructure. In this sense, road recovery is a vital part of all phases of disaster management, including mitigation, preparedness, response, and recovery (Poser & Dransch, 2010).

Drawing on the road network disruption and recovery record in Hiroshima, Japan, over the last 19 years, this study aims to empirically explore factors affecting road disruption patterns and their recovery durations using (1) a binary logit model to identify factors affecting the disruption probability of each road link, and (2) a survival model to identify the factors affecting the duration of road recovery. In particular, we focus on the impacts of both social and natural factors on the duration of road recovery and disruption patterns. We believe that separating social factors from natural factors is critical because social factors can be controlled more easily than natural factors. This will also provide a means to properly allocate resources as well as to devise a plan to facilitate more efficient operations at the onset of disasters. For example, during the 2018 Heavy Rain disaster in Japan, which caused mass movements and landslides in various parts of the Chugoku region, including Hiroshima, roads were heavily damaged (as shown in Figure 3-1). This disaster negatively affected both commercial distribution and regional economy (MLIT, 2018).

Figure 3-1. Road Damage in Hiroshima caused by the Julys 2018 Heavy Rain Disaster (MLIT, 2018)

It was observed that road recovery was quickly achieved for expressways and national roads, while it took a longer time for roads managed by prefectures and cities (Safitri & Chikaraishi, 2022; Santos, Safitri, et al., 2021). Since this difference might come from the differences in the authorities' ability and the resources available for the recovery (rather than from optimal strategies of road recovery), there is a high possibility that the road network recovery process can be improved by sharing knowledge and resources across different road administrators. To encourage such a sharing scheme, it is important to show empirical evidence on the extent to which social factors play a role in disaster management and how policy makers can influence the flow of the management process. However, little quantitative evidence on the differences in road recovery duration has been given in existing studies. This study attempts to fill in this gap by providing empirical evidence focusing on the case of Hiroshima, Japan. Although the results cannot be straightforwardly generalized to other regions, the findings could be useful in other regions, as it may provide lessons for other countries to learn from.

3.2. Research Framework

3.2.1. Study Area and Data

The study area is Hiroshima Prefecture, Japan. The total land area of Hiroshima Prefecture is 8479 square kilometers. It is ranked the 11th biggest prefecture based on size, with a total population of 2.84 million as of 2016 (Visit Hiroshima, 2019).

We have used data from the Hiroshima Road Disaster Prevention Information System. It is a record of roads that were disrupted by different types of natural disasters from 25 February 2002 to 22 February 2021, and is managed by the prefectural government. The dataset contains the date and time of occurrence of disruption, cause of disruption, road type, location of the disrupted road, and date and time that the roads were repaired. For road network data, we have used the Digital Road Map of Japan, which is the standard national digital road map database. These datasets were then merged with other information from the website of the National Land Information Division; National Spatial Planning and Regional Policy Bureau; Ministry of Land, Infrastructure, Transport, and Tourism, which includes elevation data, sediment hazard area data, population data, and land classification data. Roads in Japan are classified into National Highways, National Expressways, Prefectural Roads, and Municipal Roads. Activities such as (i) development and improvement and (ii) repair and maintenance of the roads differ across road administrators. Further details of burden sharing can be found in the Ministry of Land, Infrastructure, Transport, and Tourism Road Bureau quick road guide, including the budget distribution (MLIT, 2021). Based on this, the cost of maintenance and repair of national roads are all covered by the national government, while the national government supports up to 50% of the maintenance and repair of the main prefectural roads. On the other hand, local prefectural roads have no direct subsidy from the national government for maintenance and repair costs.

Due to limited access to the data source, only the roads managed by Hiroshima Prefecture have been considered in this study. Note that the prefecture also manages some national roads upon the request of the national government. The total number of road links considered is 25,102, of which 1512 (or 6.02%) were disrupted at least once during the 19-year period. Table 1 shows a summary of the two datasets, including the composition of the factors considered in the study. Note that betweenness centrality is a centrality indices which is widely used in network analysis (Freeman, 1977). In this study, the index measures the degree of centrality of each link, which is defined as the total number of shortest paths between all link pairs that passes through the target link in the road network.

Table 3-1. Summary of Study Datasets

	Probability of Disruption Dataset		Road Recovery Dataset	
Variables	Frequency	%	Frequency	%
Road Class				
National	6295	25.08	285	18.85
Main (Prefectural)	7862	31.32	408	26.98
Local (Prefectural)	10,945	43.60	819	54.17
Sediment Hazard Area				
In hazard area	6672	26.58	808	53.44
Not in hazard area	18,430	73.43	704	46.56
Terrain type				
Hilly area	18,621	74.18	1427	94.38
Others	6481	25.82	85	5.62
Cause of Disruption				
Landslide related	-	-	683	45.17
Flood related	-	-	123	8.13
Others	-	-	706	46.70
	Mean	Standard Deviation	Mean	Standard Deviation
Betweenness Centrality	4.69	5.39	4.22	4.52
Population Density (people per km^2)	975.69	1854.22	326.04	380.34
Elevation (m)	188.23	177.46	269.84	199.36
Sample Size	25,102		1512	

Figure 3-2 shows a map of the Hiroshima Road network. The blue lines represent road links that have not been disrupted over the past 19 years, while the red lines represent road links which have experienced some disruption over the past 19 years. It can be observed that the major business areas of Hiroshima Prefecture, such as Hiroshima City, Higashi-Hiroshima City, Fukuyama City, and Miyoshi City have not been disrupted over the last 19 years.

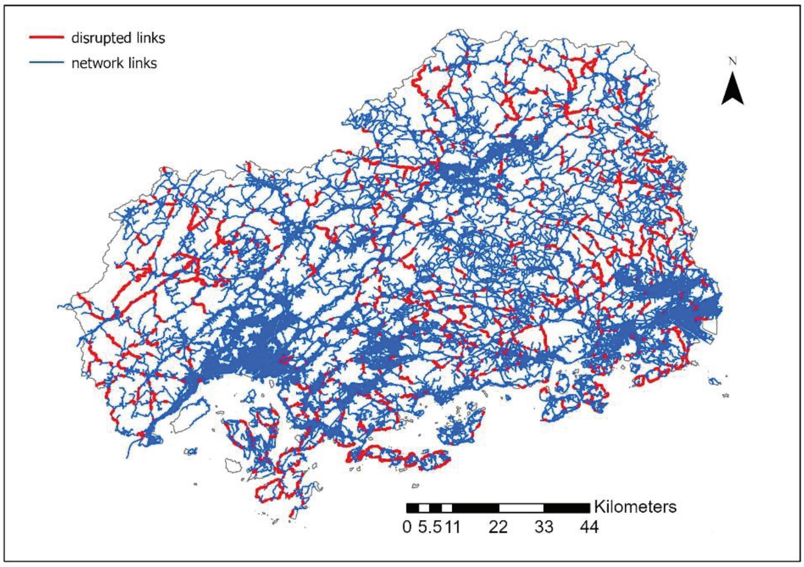


Figure 3-2. Map of the Hiroshima Road Network

Figure 3-3 shows the duration of the disruption in days, both in normal and in logarithmic transformed histogram. From the figure, it is noticeable that after the disaster, 54% of the road links recovered within a week after the disruption, while roughly 20% took more than 100 days to recover, which is a relatively long period.

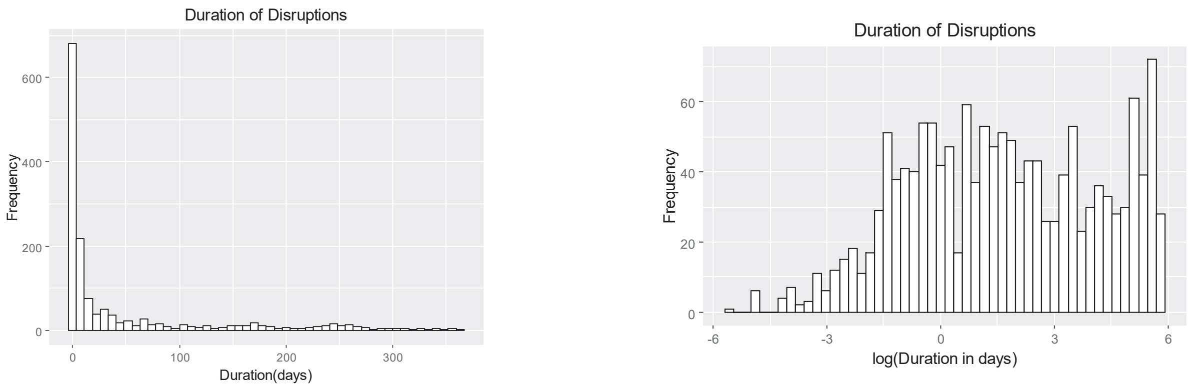


Figure 3-3. Histogram of duration of disruptions

3.2.2. Probability of Road Link Disruption

In this study, factors that affect the probability of road link disruption were explored using a binary probit model, where the dependent variable was defined as 1 when the road was disrupted at least once over the last 19 years, and 0 otherwise. The explanatory variables include social factors, namely road type (national, main prefectural road, or others), betweenness centrality, population density, and natural factors—namely elevation, whether the road is in the sediment hazard area or not, and type of terrain (hilly or not). These natural factors would directly affect the disruption probability: elevation is considered to be a proxy variable of slope, where steeper-slope areas are expected to have higher disruption probability, and roads in the sediment hazard and hilly areas would tend to be disrupted. Apparently, social factors do not seem to affect the disruption probability, but this may be because social factors may influence (1) the quality of the road infrastructure, e.g., the quality of road embankment, and (2) road network configuration, e.g., national roads have been developed to connect major cities, while other roads are meant to fill in the missing links that accommodate intra-city travel demand. Given that, road type dummy variables and population density have been introduced as proxy variables of the quality of the road infrastructure, and the betweenness centrality index has been introduced as a variable of road network configuration.

The correlation of variables was tested to ensure that all chosen variables in the study are not highly correlated to each other, as this may affect the result of the analysis. Figure 3-4 shows the result of the correlation test, confirming that no variables are highly correlated with each other.

Table 3-2 shows the variable specification used in the study, with the corresponding mean and standard error.

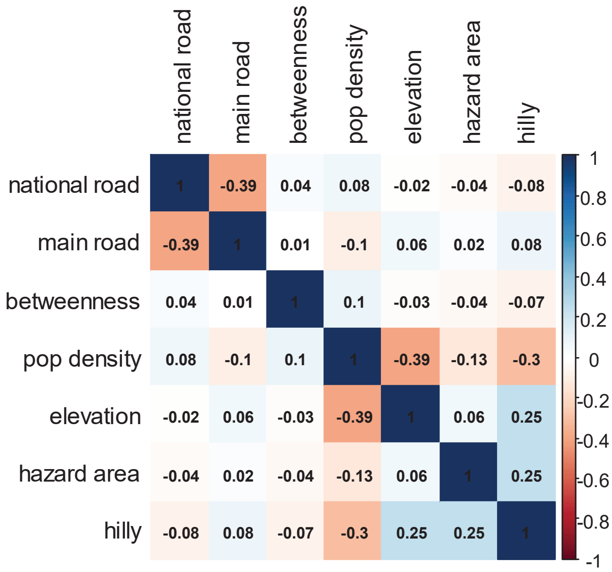


Figure 3-4. Correlation Matrix for Road Disruption Model

Table 3-2. Variable Specification for Road Disruption Model

Covariate	Definition	Specification	Mean	Standard Error
Social factors				
r_nat	road classification dummy1	1 if road class is national road, 0 otherwise	0.25	0.003
r_main	road classification dummy2	1 if road class is main local road, 0 otherwise	0.31	0.003
bet_cent	centrality index	betweenness centrality measure of each link	4.69	0.034
pop_den	population density	population density where the link is located	975.68	11.703
Natural factors				
elev	elevation	average elevation of the area where the link is located, measured in meters	188.20	1.120
h_area	hazard area dummy	1 if the link is located within the sediment hazard area, 0 otherwise	0.27	0.003
hilly	geologic location dummy	1 if the link is located in a hilly area, 0 otherwise	0.74	0.003

3.2.3. Road recovery Duration

Survival analysis was conducted to investigate the factors affecting road recovery duration (Kleinbaum & Klein, 2005). Specifically, this study utilized the four common distributions of Accelerated Failure Time (AFT) models: exponential, Weibull, Log-Logistic, and Log-Normal, where the best-fit model was chosen based on Akaike's Information Criterion. AFT models are parametric survival models that do not assume constant hazards, which is closer to real world data (Faruk, 2018). In addition, roads that did not fully recover or remained disrupted until the end of the study period can be utilized as right-censored data.

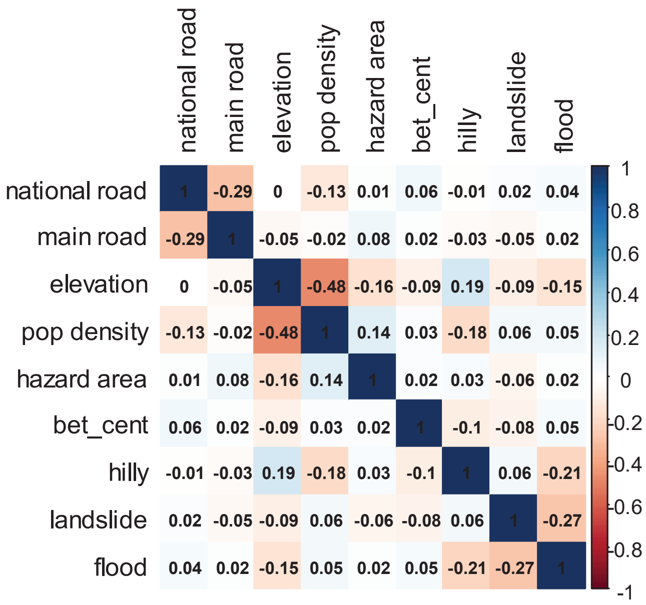


Figure 3-5. Correlation Matrix for Road Recovery Duration

Figure 3-5 shows the correlation results of the explanatory variables for the road recovery duration model. As shown, no variables are highly correlated, which means that this will not affect the result of the analysis.

Table 3-3 shows the explanatory variables used for the road recovery duration model. Natural factors include (1) natural disasters that cause road disruption (flood related, landslide related, and others), (2) geologic condition (terrain type), (3) elevation, and (4) sediment hazard location (whether the road is located in the sediment hazard area or not). On the other hand, social factors are defined in the study as factors where human intervention has a large influence, such as the type of road (national, main, or local), the centrality index (betweenness centrality), and the population density. Similar to the model for road link disruption, we assume that introducing natural factors would directly affect the recovery duration: a road disrupted by flood would quickly recover since in most cases, the road damage would be smaller, while it would not recover quickly for landslide since sediment would cover the road, and thus certain recovery actions would be needed; elevated and hilly areas are hard-to-reach areas in general, and thus, the recovery actions tend to get delayed, although this would depend on where equipment for recovery actions is located.

Table 3-3. Summary of Explanatory Variables for Road Recovery Duration

Covariate	Definition	Specification	Mean	Standard Error
Social factors				
r_nat	road classification dummy1	1 if road class is national road, 0 otherwise	0.19	0.010
r_main	road classification dummy2	1 if road class is main road, 0 otherwise	0.27	0.011
bet_cent	centrality index	betweenness centrality measure of each link	4.22	0.116
pop_den	population density	population density where the link is located	326.04	9.735
Natural factors				
elev	elevation	average elevation of the area where the link is located, measured in meters	269.84	5.127
h_area	hazard area dummy	1 if the link is located within the sediment hazard area, 0 otherwise	0.53	0.013
landslide	cause of disruption dummy1	1 if the cause of link disruption is landslide related, 0 otherwise	0.45	0.013
flood	cause of disruption dummy2	1 if the cause of link disruption is flood related, 0 otherwise	0.08	0.007
hilly	geologic location dummy	1 if the link is located in a hilly area, 0 otherwise	0.94	0.006

For social factors, road type dummy variables have been introduced as proxy variables of ability to take quick recovery actions: in general, the national government has a higher capacity for recovery compared to prefectural and city governments. The centrality index and population density have been introduced since it is expected that the roads with higher demand tend to be prioritized by road administrators.

Using all the covariates, the four AFT models were analyzed as a full model and were compared to the intercept-only model (no covariates). Taking into consideration the AIC values of the models, the Log-Normal distribution was chosen as the basis of the final model. The model was further optimized by removing the covariates without statistical significance based on the z value. Since the optimized model yielded a lower AIC value, it was adopted for interpretation in the results.

3.3. Results

3.3.1. Probability of Road Link Disruption

Table 34 shows the estimation results of the Probit model for road disruption. The results show that all variables significantly affect the likelihood of the road to be disrupted, except for the betweenness centrality index.

To confirm the stability of the model estimation results, we further estimated two models: one omitting the sediment hazard area dummy and geologic location dummy (Adjusted Model 1), and the other omitting the centrality index (Adjusted Model 2). The results show that the location of the road (whether it is located in a sediment hazard area or not, and whether it is a hilly terrain or not) affects the result of the model when considering betweenness centrality. When these two variables are removed, the betweenness centrality index is also a significant factor for road disruptions, indicating that betweenness centrality is negatively correlated with hazard area dummy and geologic location dummy. This can be explained by the fact that areas with high betweenness centrality are those areas located in the Central Business Districts (CBD). In the selection of location of CBDs, it is only natural to choose areas that are not located in hazard areas, to ensure lesser probability of damage from a disaster. Additionally, flat lands are preferable for building CBDs, since they provide easier access and a better location for businesses. Across all models, the type of road, population density, and elevation revealed a consistent result.

Table 3-4. Model Estimation Results of Road Disruption

Explanatory Variable	Full Model		Adjusted Model 1		Adjusted Model 2	
	Estimate	z Value	Estimate	z Value	Estimate	z Value
intercept	-2.057×10^{0}	−39.28 **	-1.417×10^{0}	−46.68 **	-2.071×10^{0}	−40.83 **
r_nat	-2.208×10^{-1}	−6.29 **	-2.361×10^{-1}	−6.99 **	-2.223×10^{-1}	−6.34 **
r_main	-2.496×10^{-1}	−7.99 **	-2.376×10^{-1}	−7.86 **	-2.504×10^{-1}	−8.02 **
bet_cent	-2.822×10^{-3}	−0.99	-5.395×10^{-3}	−1.97 *	-	-
pop_den	-1.487×10^{-4}	−8.39 **	-2.020×10^{-4}	−11.12 **	-1.489×10^{-4}	−8.41 **
elev	5.121×10^{-4}	6.62 **	6.047×10^{-4}	8.01 **	5.125×10^{-4}	6.62 **
h_area	5.472×10^{-1}	20.04 **	-	-	5.476×10^{-1}	20.06 **
hilly	4.839×10^{-1}	10.21 **	-	-	4.857×10^{-1}	10.25 **
AIC	10,304		10,930		10,303	
Initial log-likelihood	−5738.20		−5738.20		−5738.20	
Final log-likelihood	−5144.04		−5458.82		−5144.55	
Sample Size	25,102		25,102		25,102	

Significance codes: 0 shown by ‘**’; 0.01 shown by ‘*’; 0.05 shown by ‘.’; 0.1 shown by ‘ ’.

3.3.2. Road Recovery Duration

Table 3-5 shows the performance of the four AFT models tested in the study. As shown in the table, the model with log normal distribution produced the best goodness of fit.

Table 3-5. Performance of AFT Models

Survival Model	Initial Log-Likelihood	Final Log-Likelihood	AIC
Log Normal	−6222.3	−6144.7	12,311.32
Log Logistic	−6275.2	−6190.7	12,403.31
Exponential	−7663.7	−7326.7	14,673.32
Weibull	−6270.6	−6173	12,368.05

Table 3-6 shows the estimation results of the full and adjusted models. The full model containing all the variables showed that only three variables are significant: betweenness centrality; whether or not the road is a main road or not; and whether the cause of road disruption is a flood or not. The adjusted model containing only these three significant variables showed a lower AIC compared to the full model.

Table 3-6. Model Estimation Results of Road Recovery

Explanatory Variable:	Full Model		Adjusted Model	
	Estimate	z Value	Estimate	z Value
constant	2.13×10^{0}	6.04	2.25	23.33
r_nat	-2.32×10^{-1}	−1.33	-	-
r_main	-4.56×10^{-1}	−3.00	−0.39	−2.72
bet_cent	-2.88×10^{-2}	−2.02	−0.03	−2.16
pop_den	-5.97×10^{-5}	−0.31	-	-
elev	-6.02×10^{-5}	−0.16	-	-
h_area	2.64×10^{-2}	0.20	-	-
landslide	-7.57×10^{-2}	−0.56	-	-
flood	-2.79×10^{0}	−11.14	−2.80	−12.01
hilly	2.37×10^{-1}	0.82	-	-
Log (scale)	9.06×10^{-1}	49.61	0.91	49.67
μ	2.13		2.25	
AIC	12,311.32		12,302.3	
Initial log-likelihood	−6222.3		−6222.3	
Final log-likelihood	−6144.7		−6146.2	
Sample Size	1512		1512	

Based on the results, we can confirm that two social factors (road type—whether or not the road is main road or not, and betweenness centrality), and one natural factor (whether the cause of road disruption is flood or not) affects the duration of the road recovery. Furthermore, these results show that the main roads recover faster than other types of roads; roads with a higher betweenness centrality index recover faster; and roads disrupted by floods recover faster compared to roads disrupted by other types of disaster. The existence of these social factors indicates that policy makers can have a certain influence on the speed of recovery of roads. By taking into consideration the social factors found in this study, better policies focused on these factors can be developed. For example, by knowing which road type recovers faster than others, policies towards further improvement of other road types that connect important pieces of infrastructure such as medical institutions, evacuation centers, and the like will increase connectivity during disasters. Furthermore, even though roads recover faster after floods (because roads can be used immediately after the water subsides), flooding still affects road connectivity because it is more common than other disasters. For this reason, developing policies to alleviate flooding is also important.

3.4. Discussion

3.4.1. Probability of Road Link Disruption

The empirical results confirm that national roads and main roads are less likely to be disrupted compared with local roads. Since these roads provide the main connections between major establishments and are often a gateway to other cities, this is a very positive result, as relief operations can be sustained during disasters. This can help policy makers to focus on how to design the delivery system for relief goods in areas where connectivity may be lower, such as areas where most local roads serve as access roads.

Furthermore, the results show that the geologic location of the road network has an impact on the probability of road disruptions. Specifically, roads located on sediment hazard areas, higher elevation, and hilly terrain are most likely to be disrupted. Since Hiroshima mostly consists of mountains and islands, it is not surprising that roughly 74% of the road links are located on hilly terrain (Place and See, 2022). This is a challenge for road maintenance offices since uneven terrain and higher elevation require more effort to maintain. Since the results show that a higher probability of road disruptions is associated with hilly terrain and higher elevation, policy makers in Hiroshima should develop more measures to lessen this probability. Additionally, hilly terrain and higher elevation locations experience more problems because natural disasters such as heavy rain can result in additional types of road disruption such as mudslides and landslides. Since Japan receives twice as much precipitation compared to the rest of the world [45], these additional problems associated with hilly terrain and high elevation should also be given attention by policy makers (Wei et al., 2022).

3.4.2. Road Recovery Duration

One major finding of this study is that main roads recover faster that other types of roads. In addition, the results show that roads with a higher centrality index recover faster. Since business districts are usually connected by major roads with a high centrality index, this implies that business districts will restore connectivity faster. This is a positive thing, as it will minimize losses and provide access to people. Policies to further improve roads located in these areas, such as repair and maintenance, will be beneficial as they will further enhance connectivity in the business districts, thereby supporting business continuity even during disasters.

Interestingly, the results show that most factors do not affect the duration of road recovery. In terms of natural factors, only flooding, which is a source of road disruption, shows a significant result. Roads disrupted by flooding recover faster than other disasters because most of the time, roads can be restored easily to full operation as soon as the water level goes down. This can be further improved by policies to improve drainage systems and flood control infrastructure. Furthermore, the results show that other disasters may cause greater damage and longer road recovery, so to improve road recovery, policy makers should strengthen policies targeted at other disasters, such as landslides.

In addition, these results show that policy makers are key players in improving the duration of road recovery since social factors have a greater effect on the duration of road recovery than natural factors. This implies that human intervention in terms of policies developed by policy makers can greatly shorten the duration of road recovery. Lastly, the results show that the type of road affects the duration of road recovery. Therefore, policy makers must allocate resources effectively to ensure that all road types will be managed properly so as to maintain connectivity.

Factors affecting road recovery play a vital role in the resilience of transportation networks. To address road disruptions, roadworks are often needed, whether for a short time or a long time. These repair works often cause an increase in traffic flow and travel time delays. In the studies conducted by Safitri & Chikaraishi (2022) and Wei et al., (2022) , economic losses were calculated from road disruptions. The duration of road recovery directly affects the magnitude of these economic losses, so policies targeting a faster recovery from disruptions on the road network would also lessen economic losses. Furthermore, the results of the present study suggest that the repair and maintenance of road networks can lead to faster recovery. Knowing which factors may help speed up the road recovery can help policy makers to maximize the allocation of their scarce resources.

A better understanding of the social and natural factors affecting road network disruption and its recovery process will also aid policymakers in improving their disaster management plans. As road recovery requires a considerable amount of resources, proper planning is needed to efficiently restore roads (Rey & Bar-Gera, 2020; Gokalp et al., 2021). For example, by knowing which natural factors can affect the duration of road recovery and road disruption patterns, policy makers will be able to properly prepare countermeasures to lessen the impact of such natural factors. While natural factors cannot be controlled, measures to alleviate their impact can be taken. For instance, flooding is a natural factor, but measures such as improving drainage system and flood control infrastructures can help lessen its impact.

3.5. Chapter Conclusions

The aim of this study was to investigate which factors affect the probability of road disruptions and the duration of road recovery. Factors considered in the study were categorized as either social factors or natural factors. In this study, natural factors are defined as factors that are naturally occurring and are therefore beyond the control of policy makers, while social factors are defined as factors which can be influenced by human interventions.

The Probit model estimation results show that national roads and main roads, as well as roads located in places with a higher population density, are less likely to be disrupted. On the other hand, roads located in sediment hazard areas, hilly areas, and areas with higher elevation are more likely to be disrupted. Here, both social factors and natural factors affect the probability of road disruptions, except for the betweenness centrality.

Based on the results of the analysis of the factors affecting the duration of road recovery, two social factors (road type—whether or not the road is main road or not, and betweenness centrality) and one natural factor (where the cause of road disruption is flood or not) affect the duration of road recovery. Furthermore, these results show that main roads recover faster than other types of roads, roads with higher betweenness centrality index recover faster, and roads that were disrupted by flooding recover faster compared to roads disrupted by other types of disaster.

In conclusion, while both social and natural factors affect the probability of road disruptions and duration of road recovery, natural factors are more dominant with respect to road disruptions, while social factors are the major contributing factor in the duration of road recovery. By identifying these factors, policy makers will have more options on how to further improve the social factors highlighted in this study, as these can be influenced by human interventions. On the other hand, while natural factors are beyond the control of policy makers, identifying which of these factors are significant could help policy makers to produce better mitigation and improvement plans, and thereby lessen the impact of these factors. In addition, this study could be helpful for guiding the decision-making process for road investments. By providing an insight to better locations, new road infrastructure can be made more resilient to disasters. Further improvements to this study may be to see how other social and natural factors not considered in this study affect the probability of road disruption and duration of road recovery. Due to data availability, this study only covered roads managed by the road administrators of Hiroshima prefecture. Road disruption records from other road administrators, including expressway companies and city government, are needed to conduct a analysis with the complete road network. Another important remaining task is that, although this study only considered the direct effects of natural and social factors, they could have a more complex relationship. For example, the road quality could vary depending on the geological conditions and geographic locations.

Chapter 4. An Illustrative Numerical Analysis on the Optimum Location of Emergency Ports for eVTOL Aircraft for Disaster Response and Relief Operations

4.1. Introduction

As the number of disasters increases, more and more people are affected by disasters. After a disaster occurs, an immediate response is of great importance. However, humanitarian aid needed to support the affected population may be hindered by a lot of factors, of which keeping transport routes open is of great importance since damage to the transportation system inhibits relief operations and repairs to lifeline systems (Nicholson and Du, 1997). To alleviate this, a more effective and efficient humanitarian response, especially focusing on road network conditions, should be in place.

Air transport plays an important role in relief operations. Since the airport typically has less damage when a disaster occurs, it can be used to provide support to first responders and relief operations (Schlumberger, 2015). As such, airports have been a vital part of disaster relief operations in the past years. Some events in the past include the 2011 Great East Japan earthquake where three airports in Japan, Iwate Hanamaki Airport, Yamagata Airport, and Fukushima Airport, were used as bases for the disaster response for the areas damaged by the disaster (Choi and Hanaoka, 2017; Hanaoka *et al.* 2013). Also in the Philippines, Tacloban and Ormoc Airports was used to receive aid during the 2013 Typhoon Yolanda, which was recorded as one of the strongest typhoon in the history (NDRRMC, 2010).

Mostly functioning as emergency hubs, airports provide a means for relief operations to take place to aid disaster areas. As a support entity, this role is undeniably important in disaster response but very limited. In fact, the role of airports tends to stop upon receiving the aircrafts carrying relief services. In situations where the road network is damaged by the disaster or when outside traffic is not considered, relief services that the airports cater will either not be delivered immediately or at worst will not reach its intended destination. To facilitate better disaster response, it is important to extend the capabilities current network of airports to respond to disasters while also considering road network conditions.

In the coming years, the use of eVTOL aircrafts, commonly known as drone or air taxis, will be integrated as means of public transportation (Ramos, 2022). By utilizing these eVTOL aircraft not only during normal conditions but also during disasters, the potential of these vehicles will increase and in turn, will also increase the value of airports as emergency hubs during disasters. Since eVTOLs have a wide range of advantages over land transportation such as a decrease in travel time and the ability to reach inaccessible and remote areas, relief operations will be more efficient in transporting goods and emergency personnel during a disaster, particularly in an area road network is vulnerable, like the areas prone to landslide disaster (Safitri and Chikaraishi, 2022). Additionally, in comparison with conventional air transportation such as emergency helicopters used during disaster response such as emergency helicopters, the eVTOL aircrafts offers more advantages in terms of lower noise pollution and carbon emission, lower manufacturing and operation cost, and less complex architecture (Archer Aviation Inc., 2021; TransportUP, 2019). Also, this study assumes that eVTOL aircraft are already integrated in the public transportation system, contributing to reducing the cost of using eVTOL, which is one of its major advantages compared to emergency helicopters.

Given the above background, this study proposes to utilize electric vertical take-off and landing (eVTOL) aircraft as a means of transporting both relief goods and emergency personnel from the airports to the affected areas. More specifically, we investigate the optimal location of the emergency ports that can be used as a landing and take-off area considering road network disruptions during disasters. The proposed model would assist in finding a suitable location where the risk of getting isolated is lower and more robust in terms of road disruptions in order to allow delivery of goods and services. However, as reviewed in the next section, to the authors' knowledge, there is no study considering road network disruption scenarios in determining the eVTOL emergency port locations.

In order to find the suitable location of emergency ports, several challenges have to be addressed in the study such as road disruption patterns and cost. To address these challenges, different scenarios are introduced in the study that represents changes in road disruption patterns and transportation cost. This new concept of utilizing eVTOL aircraft by establishing emergency ports in disaster response while taking into consideration its advantages compared to emergency helicopters specially in terms of availability and public usage can help policymakers in improving the efficiency of disaster response operations.

By finding the suitable location of the emergency ports, especially in areas prone to isolation and road disruption, the use of both air and land transportation can increase the resilience of the whole network. In the disaster affected areas, especially in isolated areas, emergency ports can serve as a connection to increase the continuity of the road network. Also, emergency ports can act as additional nodes for air transportation network and thereby increase its coverage area. The major contribution of this study is to illustrate to what extent adding urban air transport would improve the performance of relief operations through numerical simulations.

4.2. Research Framework

4.2.1. Problem Description

This paper considers a disaster response operation that includes airports, emergency ports (EP), and disaster sites as shown in Figure 4-1. The relief operation starts upon receiving the relief goods (RG) and emergency personnel from the established airport/s. Based on the predetermined demand on the disaster sites, the required demand will be transported using eVTOL aircraft to the chosen emergency ports (from the candidate ports), and then transported to different disaster sites. The proposed emergency port is a type of vertiport that can be used as a landing and takeoff area of the eVTOL aircraft that can also receive and hold goods and emergency personnel before sending it to the disaster sites. In essence, it is a depot with the capability to receive the eVTOL aircraft. In this study, the establishment of emergency ports is determined by the location which provides the lowest transportation cost from the airport to the disaster site. Demands on the disaster sites are delivered via land transportation while considering the effect of road network disruption, in this case, an increase in transportation cost following the shortest path distance from the emergency port to the disaster sites. In the event where accessibility is lost or the area is totally isolated due to road disruption, land transportation will be replaced by the conventional air transport such as helicopters. Since helicopter are a lot more expensive due to its complexity, fuel consumption (Vandenputte, 2022) and limited availability, an increase in transport cost will result in using this mode of transport. As mentioned earlier, these disadvantages of the conventional air transport are offset by the use of eVTOL. Considering the cost of transporting the goods and services to fulfill the demands of the disaster sites, the total number and location of the emergency ports from the candidate emergency ports will be determined. The airports a serve as the origin of the supplies that will pass through the emergency ports j to fulfill the demands on the disaster sites i. Depending on the scenario, the location of the emergency ports will be chosen. The following assumptions are made to formulate the model: A1) the delivery vehicles is not considered; A2) in case there is no shortest path found between the emergency port and disaster site due to road disruption, conventional air transport such as emergency helicopters will be used which is reflected by the increase in transportation cost; (A3) one (1) RG units (RG_{tw}) weighs ten (10) kilograms which is comprise of immediate needs such as water, food, and non-food items like hygiene and bedding materials; (A4) delivery of RG based on one day operation; (A5) the demand of each person in disaster site is one (1) RG unit per person.

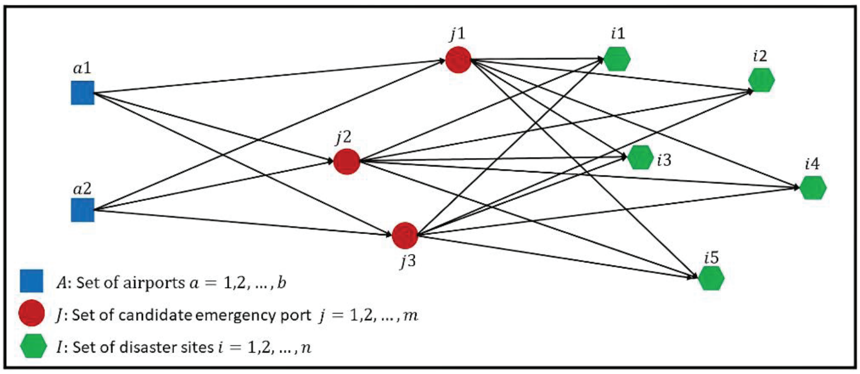


Figure 4-1. Problem Illustration

4.2.2. Model Formulation

In disaster management, finding the strategic location of important facilities such as depots, warehouses, emergency facilities, transfer facilities, transportation hubs, etc., plays an important part in humanitarian activities. In doing so, existing studies have employed methods optimizing facility location, allocation, assignment, and routing with the aim of minimizing travel time and cost or maximize demand, coverage, efficiency, etc. (Chen and Yu, 2016; Ghezavati *et al.*, 2015; Khanchehzarrin *et al.*, 2022; Mete and Zabinsky, 2010; Sharma *et al.*, 2019; Shavarani, 2019; Sun *et al.*, 2021; Zhong *et al.*, 2020).

In this study, utilizing a facility location-allocation model, an extended facility location-allocation optimization model is proposed which determines the optimal location of emergency ports from predetermined candidate locations, considering different road network disruption scenarios. The proposed model involves the following indices, parameters, and decision variables. (see Figure 1 for an illustrative example).

Set of indices

A Set of origin airports $a = 1,2 \ldots, b$

J Set of candidate emergency port locations $j = 1,2 \ldots, m$

I Set of disaster sites (demand points) $i = 1,2, \ldots, \mathrm{n}$

S Set of scenarios $s = 1,2, \ldots, r$

Parameters

F_j Fixed cost of emergency port at candidate location j in dollars ($)

C_{ij}^s Cost of transporting 1 RG unit from emergency port j to disaster site i under scenario s in dollars ($)

C_{ja} Cost of transporting 1 RG unit from airport a to emergency port j in dollars ($)

D_i Demand at disaster site i in RG units

M_j Amount of RG units that emergency port j can hold per day

M_a Amount of RG units that of airport a can hold per day

SP_{ij}^s Shortest path distance from emergency port j to disaster site i under scenario s in km

T_l Transportation cost using land vehicle per km

Decision variables

Y_j 1 if emergency port j at candidate location j is selected, 0 otherwise

X_{ij} Amount of RG units transferred from emergency port j to disaster site i

X_{ja} Amount of RG units transferred from airport a to emergency port j using eVTOL aircraft

$$\min_{\mathrm{Y_j, X_{ja}, X_{ij}}} \sum_{j=1}^{m} F_j Y_j + \sum_{a=1}^{b} \sum_{j=1}^{m} C_{ja} X_{ja} + \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij}^s X_{ij} \tag{4.1}$$

Subject to:

$$\sum_{j=1}^{m} X_{ij} = D_i \qquad for\ all\ i = 1, \ldots, n \tag{4.2}$$

$$\sum_{i=1}^{n} X_{ij} \le M_j Y_j \qquad for\ all\ j = 1, \ldots, m \tag{4.3}$$

$$X_{ij} \leq D_i Y_j \qquad for\ all\ i = 1, \dots, n;\ j = 1, \dots, m \tag{4.4}$$

$$\sum_{j=1}^{m} X_{ja} \leq M_a \qquad for\ all\ a = 1, \dots, b \tag{4.5}$$

$$\sum_{a=1}^{b} X_{ja} \leq M_j \qquad for\ all\ j = 1, \dots, m \tag{4.6}$$

$$\sum_{a=1}^{b} M_a \geq \sum_{j=1}^{m} M_j \qquad for\ all\ a = 1, \dots, b;\ j = 1, \dots, m \tag{4.7}$$

$$\sum_{a=1}^{b} X_{ja} = \sum_{i=1}^{n} X_{ij} \qquad for\ all\ j = 1, \dots, m \tag{4.8}$$

$$X_{ij}, X_{ja} \geq 0 \qquad for\ all\ \ a = 1, \dots, b;\ i = 1, \dots, n;\ j = 1, \dots, m \tag{4.9}$$

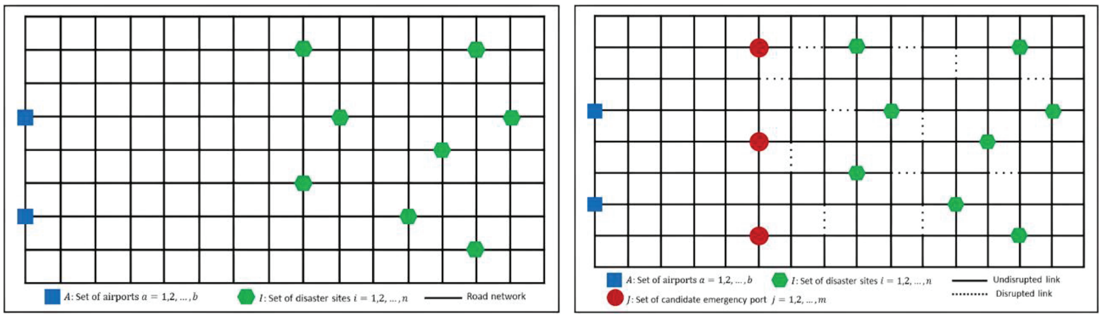
$$Y_j \in \{0,1\} \qquad for\ all\ j = 1, \dots, m \tag{4.10}$$

Objective function (4.1) minimizes cost which includes both fixed cost of eVTOL ports and transportation cost. Fixed cost is the average cost to maintain the emergency port per year. We simply assume a certain fixed value for the cost at this moment, while in reality the cost would vary depending on the future technology development, maintenance scheme employed, etc. The setting of fixed cost needs to be further elaborated in the future. It should also be noted that we can another specification consider of the objective function, such as the *expected* cost over multiple disaster scenarios. The current model introduced in the study solves each scenario separately and calculates the total cost of transporting relief goods for each scenario. While considering multiple scenarios can be considered an effective way to determine the most efficient locations of emergency ports, this may ignore some scenarios may have very low probability but very high cost. To deal with this, minimizing the maximum cost would be another candidate of objective function, but the choice of objective function would involve the value judgement of policymakers. In order to avoid the implicit involvement of value judgement through the optimization, we decided to solve the optimization problem for each scenario separately, and then have a look on the impacts over different scenarios. Another technical reasons is that solving optimization issues over multiple scenarios will also increase the computation burden on the simulation. Of course, if the clear objective function can be established, we could solve a single optimization problem over multiple disaster scenarios. In this case, the generation of road network disruption scenarios would be crucial, since it would affect the results significantly (Santos et al., 2021).

Constraint (4.2) ensures all demands at disaster site i will be satisfied. Constraint (4.3) ensures that each established emergency port j has capacity M_j . Constraint (4.4) ensures all demands at disaster site i are met. Constraint (4.5) ensures that amount supplied by airport a to emergency ports j ($\in J$) does not exceed its capacity M_a. Constraint (4.6) ensures that the amount supplied by airport a to emergency ports j does not exceed the capacity of the emergency ports j, M_j. Constraint (4.7) ensures that airports a will be able to fulfill the capacity of the emergency ports j. Constraint (4.8) is the flow conservation constraint for the quantity of goods and services that is transferred from the airport to the disaster sites. Constraint (4.9) ensures that quantity transferred is non-negative and constrain (4.10) is the binary constraint to dictate whether the emergency port will be established or not in candidate location j.

While we assume that eVTOL aircraft are already integrated into the public transportation system and widely use and therefore the diffusion rate is higher compared to emergency helicopters, several additional constraints and parameters can be considered to explicitly reflect the characteristics of eVTOL, such as maximum distance that the aircraft can travel, charging time of battery, payload capacity and others. Also, adding a constraint to limit the maximum number of emergency ports selected during the simulation can represent budget constraints since the initial cost of setting up an emergency port is high. This will help policymakers to choose better locations when a limited budget is a major concern. Also, the current model can be used to confirm if the existing vertiports used in normal situation are suitable as an emergency port in disaster situation. If existing vertiports can be utilized during disaster, the cost for setting up emergency ports will also lessen.

Additionally, to emphasize the effect of road network disruption to the transportation cost (C_{ij}^{s}) in the optimization model, let us consider Network G as shown in Figure 4-2. Network G illustrates the conventional process where goods and services are transferred directly from the airport to the disaster sites.



(a) normal network. (b) disrupted network

Figure 4-2. Normal and disrupted network

Now let us consider a scenario where a disaster caused road disruptions. Let us call this network as Network G^{s}. To simply account an increase in transport cost associated with the road network disruption caused by scenario s, we introduce the term β^{s} (≥ 1), which represents the increase in transport cost per kilometer due to road disruption. More specifically, we define C_{ij}^{s} as $\beta^{s} D_{ij}$ where D_{ij} is the unit transport cost from j to i under the normal condition or when there are no road disruptions. In this specification, β^{s} indicates how vulnerable the road network is: $\beta^{s} = 1$ represents that the road network performance would not be degraded by scenario s. As the value of β^{s} increases, the unit transport cost will also increase. Note that, although this simple treatment would be good enough to confirm how the proposed model works, in future applications, we should calculate transport cost through the shortest path search with an explicit consideration of transport network, or by solving a traffic assignment problem. In the latter case, the optimization problem would be a bi-level problem where the lower problem is to solve a traffic assignment problem. Since β^{s} increase in transport cost per kilometer due to road disruption but cannot explicitly show the breakdown of its component, when dealing with real road network, increase in travel cost should be calculated for example by searching the shortest path under the disrupted road network, as employed in Santos *et al.* (2021). This enables us to consider road network disruption patterns in a straightforward manner.

4.2.3. Scenario Generation for the Toy Network

To test the model, a toy network was used to exemplify how the optimization works. A Mixed Integer Program was coded using Python 3.10. A total of six scenarios were tested where five scenarios includes the establishment of emergency ports and one scenario where no emergency port was established.

Scenario 0

To illustrate the scenario where no emergency port is established, the goods and services received from the airport will be transported directly to the disaster sites using land transportation whenever possible or via conventional air transport (e.g. emergency helicopter) in case of isolation, as shown in Figure 4-3. In this case, the transport cost associated will be minimized as shown in the objective function (11), where C_{ia} is the unit transport cost from airport a to the disaster site i and X_{ia} is the quantity of demand load transferred from airport a to disaster site i.

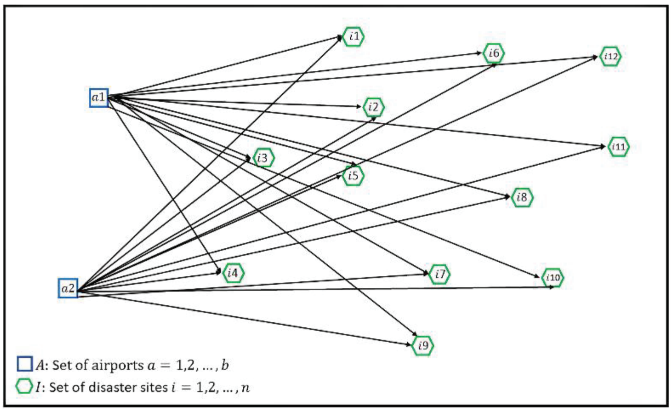


Figure 4-3. Direct Transportation from Airport a to Disaster site i

$$\min_{X_{ia}} \sum_{a=1}^{b} \sum_{i=1}^{n} C_{ia} X_{ia} \tag{4.11}$$

Subject to:

$$\sum_{a=1}^{n} X_{ia} = D_i \qquad for\ all\ i = 1, \dots, n \tag{4.12}$$

$$\sum_{i=1}^{n} X_{ia} \le M_a \qquad for\ all\ a = 1, \dots, b \qquad (4.13)$$

$$\sum_{i=1}^{n} D_i \le \sum_{a=1}^{b} M_a \qquad for\ all\ \ a = 1, \dots, b;\ i\ = 1, \dots, n \qquad (4.14)$$

$$\sum_{a=1}^{b} X_{ia} = \sum_{i=1}^{n} D_i \qquad for\ all\ \ a = 1, \dots, b;\ i\ = 1, \dots, n \qquad (4.15)$$

$$X_{ia} \ge 0 \qquad for\ all\ \ a = 1, \dots, b;\ i = 1, \dots, n;\ j = 1, \dots, m \qquad (4.16)$$

Constraint (4.12) ensures that all demands in disaster site i will be satisfied. Constraint (4.13) and (4.14) are airport a capacity constraints. Constraint (4.15) is quantity equilibrium constraint while constraint (4.16) is the non-zero constraint for quantity. Table 4-1 shows the parameter values used in scenario 0 to run the optimization.

Table 4-1. Parameter values for Scenario 0

	C_{ia}												M_a
	$i1$	$i2$	$i3$	$i4$	$i5$	$i6$	$i7$	$i8$	$i9$	$i10$	$i11$	$i12$	
$a1$	204	212	124	170	206	306	292	326	312	374	400	396	2500
$a2$	292	272	180	128	236	374	286	356	276	374	436	452	2500
D_i	100	120	150	100	130	140	110	100	150	160	150	140	-

Scenario 1

To set the base line for comparison, a normal road network condition (no road disruption) was first tested. The scenario consists of two airports, five candidate emergency ports, and twelve (12) disaster sites as shown in Figure 4-4. Using the parameter values in Table 4-2, the aim is to find which candidate locations are the most suitable to establish emergency ports that will yield the lowest possible cost to transport the goods and services from the airport to the disaster sites.

Table 4-2. Parameter values for Scenario 1

C_{ij}^{s}													F_j	M_j
	$i1$	$i2$	$i3$	$i4$	$i5$	$i6$	$i7$	$i8$	$i9$	$i10$	$i11$	$i12$		
$j1$	20	13	24	42	29	49	54	58	72	78	72	72	2000	600
$j2$	50	33	19	18	37	72	54	68	68	83	87	95	2000	600
$j3$	52	38	26	19	25	57	22	43	33	52	63	77	2000	600
$j4$	37	32	33	40	17	32	13	18	29	35	38	50	2000	600
$j5$	25	31	42	54	25	13	32	22	47	42	30	35	2000	600
D_i	100	120	150	100	130	140	110	100	150	160	150	140		

C_{ja}						M_a
	$j1$	$j2$	$j3$	$j4$	$j5$	
$a1$	126	100	236	270	280	2500
$a2$	230	100	200	286	336	2500

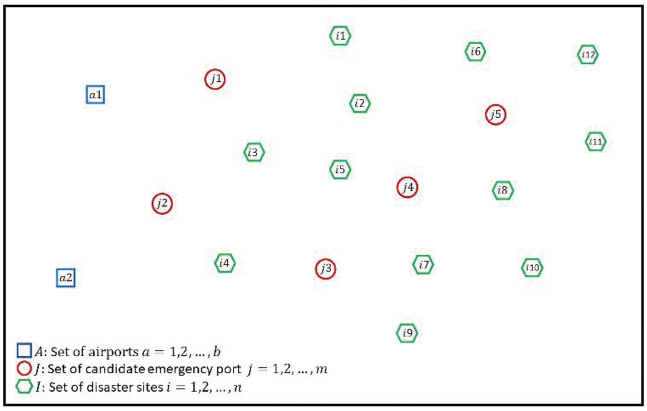


Figure 4-4. Scenario 1 Problem Illustration

Scenario 2

For the second scenario, let us assume that the area around the emergency port *j3* is disrupted which forced the delivery to take detours and increased the transportation cost to nearby disaster sites (*i3, i4, i5, i7,* and *i9*) to triple and other disaster sites to increase by 50%.

Scenario 3

In Figure 4-5, the area where the disaster sites *i1* to *i5* experienced road disruptions which caused the transportation cost from emergency ports *j1* to *j4* to triple while access to *j1* and *j2* to the rest of the sites cost 50% more.

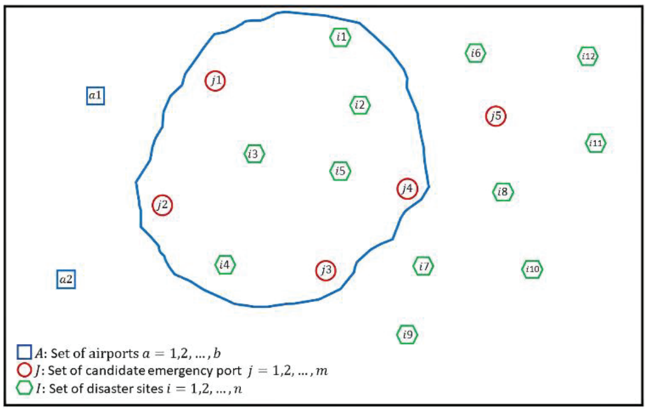


Figure 4-5. Scenario 3 Problem Illustration

Scenario 4

For scenario 4, a disaster took placed and there was a severe road disruption. As a result, roads leading to disaster sites *i11* and *i12* were unpassable and these sites become totally isolated. Due to the isolations, transporting goods and services to these sites via land transport is impossible and only air transport is available but at a high cost.

Scenario 5

In this last scenario, let us consider a situation where the problem occurred in the emergency port in addition to the damage on the disaster site. For this scenario, emergency port *j1* became inaccessible due to road disruption. To reach this facility only air transport can be used. The disadvantage is it would incur a high cost to use this facility.

4.3. Results

Table 4-3 shows the result of scenario 0. The total cost calculated to transport all the loads from the airport using eVTOL from the airport to the disaster sites is 427,600 and both two airports were used. Majority of the demands was fulfilled by airport *a1*. Only disaster sites i4, i7, and i9 was serviced by *a2*. To visualize the result, Figure 4-6 shows the distribution of goods and services from each airport to the different disaster sites.

Table 4-3. Result of Scenario 0

Total Cost	Airport Used	Allocation (X_{ia})	
427600	*a1, a2*	i01,a1 = 100	i07,a2 = 110
		i02,a1 = 120	i08,a1 = 100
		i03,a1 = 150	i09,a2 = 150
		i04,a2 = 100	i10,a1 = 160
		i05,a1 = 130	'i11,a1 = 150
		i06,a1 = 140	i12,a1 = 140

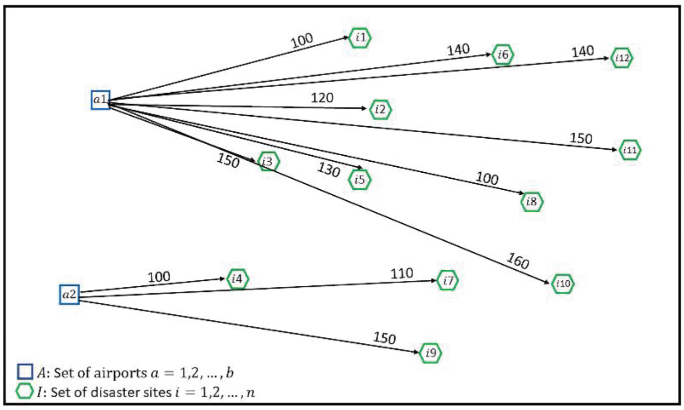


Figure 4-6. Scenario 0 Optimization Result Illustration

Table 4-4 shows the solutions for scenarios 1 to 5 (scenarios with candidate emergency ports). The base-line scenario (Scenario 1) is used to compare the other scenarios. As shown by the results, any road disruption causes an increase in the optimization value (total cost) for all the scenarios. Both airports are chosen in all scenarios to accommodate the demand on the disaster sites. In scenario 1, only three emergency ports were chosen and the chosen locations are the locations nearest to the airport. Since air transport is assumed to be higher in cost, locations farther from the airport has lower chance of being chosen unless there is a need or if the cost will be lower compared to the other locations. Figure 4-7 illustrates scenario 1 optimization result. The figure shows where each emergency port j received its supply and on which emergency port *j* satisfied the demand in each disaster site *i*.

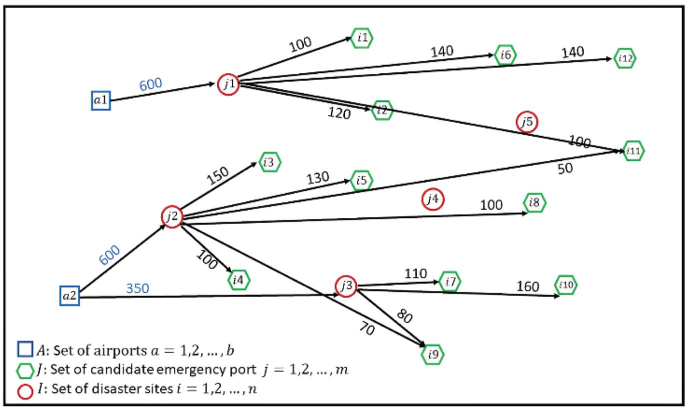


Figure 4-7. Scenario 1 Optimization Result Illustration

In scenario 2, it can be observed that because of the increase in cost from emergency ports *j3* to disaster site *i9*, the demand was fully fulfilled by emergency port *j2* as compared to normal scenario where the demand was fulfilled by both emergency ports *j2* and *j3*. Since the capacity of emergency port *j2* is limited emergency port *j3* must fulfill the demand for disaster site *i8*. Also, the demand for disaster site *i7* must be fulfilled by both emergency ports *j2* and *j3* instead of emergency port *j3* alone.

The model clearly prioritized the assignment of the disaster sites to the emergency ports that will yield lower cost. While it is true that the same three emergency ports from the base line scenario were also chosen, the assignment and amount distributed to the disaster sites changes.

In Scenario 3, results showed a change in quantity for disaster site *i5*, when there is no road disruption, the demand in disaster site *i5* was fulfilled only by emergency port *j2* but in scenario 3, it was fulfilled by both emergency ports *j1* and *j2*. Same situation happened with the demand in disaster site *i7* which was fulfilled by both emergency ports *j2* and *j3* instead of emergency port *j3* alone. For the demand in disaster site *i9*, scenario 3 assigned the whole demand to emergency port j2 alone compared to normal scenario where it was fulfilled by both emergency ports *j2* and *j3*.

Lastly, there is a change in assignment of the disaster site *i11* since it was first assigned to emergency ports *j1* and *j2*, but was assigned to emergency port *j3* in scenario 3. Although there are no changes in other disaster sites, road disruption indeed caused some changes in the distribution of the goods and services to the disaster sites.

Table 4-4. Optimization Results

Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total Cost	278850	289110	323140	382890	337770
Airport Used	*a1, a2*	*a1, a2*	*a1, a2*	*a1, a2*	*a1, a2*
Allocation (X_{ja})	j1,a1 = 600 j2,a2 = 600 j3,a2 = 350	j1,a1 = 600 j2,a2 = 600 j3,a2 = 350	j1,a1 = 600 j2,a2 = 600 j3,a2 = 350	j1,a1 = 600 j2,a1 = 600 j3,a2 = 60 j5,a1 = 290	j2,a1 = 600 j3,a2 = 600 j5,a1 = 350
Emergency Port Used	*j1,j2, j3*	*j1,j2, j3*	*j1,j2, j3*	*j1,j2, j3,j5*	*j2, j3,j5*
Allocation (X_{ij})	i01,j1 = 100 i02,j1 = 120 i03,j2 = 150 i04,j2 = 100 i05,j2 = 130 i06,j1 = 140 i07,j3 = 110 i08,j2 = 100 i09,j2 = 70 i09,j3 = 80 i10,j3 = 160 i11,j1 = 100 i11,j2 = 50 i12,j1 = 140	i01,j1 = 100 i02,j1 = 120 i03,j2 = 150 i04,j2 = 100 i05,j2 = 130 i06,j1 = 140 *i07,j2 = 70* *i07,j3 = 40* *i08,j3 = 100* *i09,j2 = 150* i10,j3 = 160 i11,j1 = 100 *i11,j3 = 50* i12,j1 = 140	i01,j1 = 100 i02,j1 = 120 i03,j2 = 150 i04,j2 = 100 *i05,j1 = 100* *i05,j2 = 30* i06,j1 = 140 *i07,'j2 = 70* *i07,'j3 = 40* i08,'j2 = 100 *i09,'j2 = 150* i10,'j3 = 160 *i11,j3 = 150* i12,j1 = 140	i01,j1 = 100 i02,j1 = 120 i03,j2 = 150 i04,j2 = 100 *i05,j1 = 130* i06,j1 = 140 *i07,j2 = 50* *i07,j3 = 60* *i08,j1 = 100* *i09,j2 = 150* *i10,j1 = 10* *i10,j2 = 150* *i11,j5= 150* *i12,j5 = 140*	i01,j2 = 100 i02,j2 = 120 i03,j2 = 150 i04,j2 = 100 i05,j2 = 130 *i06,j5 = 140* i07,j3 = 110 i08,j3 = 100 *i09,j3 = 150* i10,j3 = 160 *i11,j3 = 80* *i11,j5 = 70* *i12,j5 = 140*

For scenario 4, where some of the disaster sites where isolated, a huge change in the objective function value can be observed. This is due to the fact that air transport was used to reach these areas to fulfill the demands and therefore result in higher transportation cost. As seen, an increase in the number of emergency ports were observed (from 3 to 4 emergency ports) and the nearest emergency port *j5* to disaster sites *i11* and *i12* which was chosen despite not being chosen from the previous three scenarios. Emergency port *j5* was only used for the two isolated disaster sites and the rest of the disaster sites were assigned to emergency ports *j1*, *j2* and *j3*.

For the last scenario, where an emergency port itself is not accessible by land transport due to road disruption, huge increase in the object function value can also be observed since air transport was also used in this scenario. The result also showed that the isolated emergency port was not chosen, and land transport was prioritized since it yielded lower transportation cost. Lastly, as showed in the results, it can also be observed that demands for disaster sites i1 to i4 is always fulfilled by emergency ports j1 and j2 for scenarios 1 to 4.

4.4. Discussions

When road disruptions are severe, high transport cost is reflected in Scenario 0 where transport cost from airport to disaster site is higher due to either high cost of transport using conventional air transport such as helicopter or longer distance due to rerouting as default path is not available due to road disruptions. In this situation, building emergency ports is more efficient and economical in humanitarian response since transporting directly from the airport after receiving the relief goods and services yield comparably higher cost. We also confirm that the location of the emergency ports is clearly affected by road disruptions. In situations where the road disruption is severe, it is expected that higher transportation cost is needed to transport the goods and services from the airport to the disaster sites.

The strategic location of the emergency ports as shown in above scenarios plays an important role in satisfying the demands in the disaster sites with the lowest possible cost. Results show that lower number of emergency ports is more advantageous even if the distance to some disaster sites is greater. This is shown in results where the emergency port *j4* was not chosen to supply the needs in the disaster sites nearby. Instead, these disaster sites are often assigned to the next nearer emergency port which has a lower cost. This is the same with the emergency port *j5*, where it was only chosen when the nearby disaster sites became inaccessible by land transport and therefore air transport was used to fulfill the demands. For policymakers, this can be helpful to maximize the budget since, lower number of emergency ports will yield a lower budget as long as it is strategically located. Also, this helps in disaster management since it expands the humanitarian activity more efficiently by introducing an additional means of transportation to reach the disaster sites.

It is also evident from the result that certain locations of emergency ports are always chosen. This means that these locations are the best candidate since it is strategically located and even under different road network disruption scenarios are still always chosen. These locations show strength and better serviceability since it connects to more disaster sites. Therefore, for emergency ports in these types of locations, policymakers could consider increasing the capacity to maximize the usage rather than building additional facilities.

4.5. Chapter Conclusions

Humanitarian activities are often linked with transportation. The efficient disaster response is often hindered by road network disruptions which are undesirable. During disasters, airports that serve as emergency hubs receive relief goods and services but transporting these can prove to be problematic due to road network disruptions. The expansion of the road network through the establishment of emergency ports for the use of eVTOL aircraft is a promising solution to this problem.

In this study, we have explored the effect of road network disruption on the location of the emergency ports. The results showed how some locations are ideal for building emergency ports since it is not highly affected by road disruptions and how some locations are useful when road disruptions are severe and accessibility is totally lost. Also, transporting goods and services from airports to disaster areas through emergency ports yields lower transport cost and maximizes the use of both air and land transport. This allows the distribution of the goods and services to reach its destination faster and more efficiently. Additionally, by providing an additional means of transport, the expanded air transport network can offer a mores diverse way of humanitarian response that can be utilized even in severe road network disruptions caused by disasters.

Since the model was only tested with fewer emergency sites and disaster sites, a case study involving a real network will be desirable as it can further illustrate more scenarios that can show how road network disruption affects the location of emergency ports. In this case, in terms of scenario generation, the use of estimated link disruption probabilities using Monte Carlo Simulation analysis can be used (e.g., Santos *et al*., 2021).

The capacity constraint can also be taken into consideration to examine how emergency ports with higher capacity be compared to the total number of emergency ports affects budget. Even though the above-mentioned extensions of the proposed methods are needed, this study successfully illustrates how the introduction of emergency ports would help humanitarian activities.

As mentioned earlier, fixed cost may depend on some variables such as frequency and extent of damage of disaster and location of emergency ports. Different values of this cost may be needed depending on the area where the emergency ports are located since different areas may have different characteristics. Also, the frequency and extent of damage of the disaster may also affect this cost since more frequent disaster requires more usage of the emergency ports and more severe damage may require longer disaster operation time and therefore also increases the usage of this facility. Therefore, it is recommended to examine changes association with this variable to set a more realistic value.

Chapter 5. Efficient Deployment of eVTOL Aircraft for a Joint Air and Land Disaster Response Operation: A Mixed-Integer Linear Programming Model

5.1. Introduction

Transportation is an important part of disaster management. A better understanding of the transportation network's contribution as a support entity during disasters will allow communities to prepare and respond to it more effectively (Anderson et al., 2022). In this regard, a considerable amount of efforts had been made by researchers in the past including Borghetti & Marchionni (2023), Chirisa et al. (2023), Crespo et al. (2022), and Kapucu et al. (2023), that focused on investigating and improving infrastructures including transportation infrastructures in order to reduce or mitigate the effects of disasters. However, further improvement is still needed to improve disaster management, given that still a considerable number of people have suffered from the insufficient transport supply in practice. The immediate delivery of goods and services to the affected areas can significantly reduce the damage cause by disasters.

Although improved transportation infrastructure can facilitate relief operations, a more effective humanitarian logistics operation can significantly enhance these efforts (Nikbakhsh & Zanjirani Farahani, 2011). However, maintaining a smooth humanitarian logistics operation can be challenging especially in keeping transport routes open. Since natural disasters can cause disruption to road networks (Dalziell & Nicholson, 2001; Santos, Varghese, et al., 2021), this can inhibits relief operations and repairs to lifeline systems (Nicholson & Du, 1997). Also, while some roads recover easily, some others take longer time to recover (Sansano & Chikaraishi, 2022) and detouring may cause increase in travel time and travel cost. At worst, some disaster affected areas may be totally isolated (Chikaraishi, 2022; Santos et al., 2021). Therefore, while the land transport is the most commonly used mode of transportation due to its availability and lower cost compared to other mode of transportation to deliver goods and services to the affected areas, it is vulnerable to the disruptions caused by disasters.

Disruptions on the road networks can greatly decrease the efficiency of the humanitarian activities and increase the cost of operations. An increase in operational cost may also affect the disaster response since humanitarian logistics is the most expensive part of disaster relief operation, accounting for about 80% of the total cost of operation (Van Wassenhove, 2017). Therefore, the longer the operation runs, the greater will be the cost, which in the long run can be a heavy burden to the managing authorities since budget constraints may exist.

However, humanitarian logistics does not only concern land transportation network. Humanitarian air services such as planes and helicopters also provide assistance, ensuring fast delivery to disaster-affected areas that have no reliable roads, ports or areas that are inaccessible due to disaster (ECHO, 2021). Additionally, airports also plays an important role as critical infrastructure in disaster response (Hanaoka et al., 2013; Schlumberger, 2015). Aviation industry acts as emergency hubs by catering the efficient arrival of relief goods and services which are of utmost importance specially during the first hours after the disaster occurs (ICAO, 2023). This is possible since airports often sustain less damage and becomes operational within hours after the disaster. Additionally, since runways are open space, debris clearing are faster and runways are more sturdy and received less damage even in strong earthquakes (Schlumberger, 2015).

While using air transportion for delivering goods to disaster shelters offers a lot of advantages such as reduced time and reaching isolated areas, it also has its own limitations including high cost of operation, limited availability (in terms of number of units and immediate availability), and operation complexity. Since disasters often affect wide area, air transport may not be able to fully serve the number of victims requiring immediate attention. To meet the demands of the disaster-affected areas, it is necessary to also make use of land transportation to deliver the relief goods that comes from the airport to other areas that cannot be covered by the air transport.

Although the use of both air and land transport may enable to manage the needs of the disaster-affected areas, this makes humanitarian logistics more complex particularly when severe road disruptions occur, hindering the operation of land transport and increasing the demand for air transport. With the used of electric vertical take-off and landing (eVTOL) aircraft as means to transport both relief goods and emergency personnel from the airport to the disaster-affected areas through the emergency ports, several limitations of the conventional air transport can be solve since in comparison with other aircrafts such as helicopters, the eVTOL aircraft offers more advantages in terms of lesser noise and carbon emission, lower manufacturing and operation cost, and less complex architecture (Archer Aviation Inc., 2021; TransportUP, 2019). This also increase the potential of eVTOL aircraft not only as a public transport but also as an emergency transport, and in turn, will also increase the value of airports and highlight the importance of air-land cooperation during disasters. This new air mobility has been undergoing various test from different countries around the world and is set to join the aviation industry as a new public transport in the coming years (Ehman, 2023; Fingas, 2022; JAL, 2023; Nolan, 2022; Reuters, 2022). Recently in Japan, ANA Holdings and Joby Aviation were selected to operate the so called “electric air taxi” for the upcoming 2025 World Exposition in Osaka, Japan. This move will help in the introduction of this new mobility to the general public. A flight test for the air taxi was also conducted last March 14, 2023 at the Osaka Castle Park.

To enable the use of eVTOL aircraft, a suitable location to accommodate these aircraft is necessary. Since these aircraft has a potential to bridge the gap between air and land transportation, these locations must complement the weakness of both mode of transportation, that is, cost, availability, and connectivity. Since road disruption pattern is unknown before a disaster, finding locations which enables connectivity and lessens place isolation is a challenge.

To address this problem, this study proposed the use of (eVTOL) aircraft to deliver relief goods to the disaster shelters through the establishment of emergency ports to selected suitable locations that have higher accessibility and lesser risk of getting isolated while considering different road disruption scenarios. This study also aims to provide evidence as to what degree can the new air mobility economically supports land transport specifically when road disruptions hinder disaster response to highlight the importance of air-land cooperation by identifying the most suitable mode of transportation with the minimum transport cost.

Lastly, during disasters, uncertainties put additional burden to disaster response such as the extent of the damage to lives, properties, and economy as well to the different systems including the transportation system. This can also include the change in demand since the damage of the disaster dictates the number of affected population and thus affects the demand itself. Aside from the uncertainties caused by the disaster itself, other uncertainties arising from the use of new technology can also affect the performance of the model. This may include uncertainties in risk perception such as the perceived and the actual risk of using the new technology, and uncertainties in terms of cost such as transportation cost and operation cost. Quantifying uncertainties is another challenge since it covers a wide area of possibilities and methods involving uncertainties are not very common. In this study, uncertainties in cost brought by new technology were examined through a sensitivity analysis to understand its effect in the model.

5.2. Research Framework

5.2.1. Problem Description

This paper takes into account the use of air transport to aid the disaster response operation by focusing on how air and land transport coordination can improve humanitarian logistics especially during road disruptions where some disaster shelters may encounter lower accessibility or isolation. We consider the situation of delivering relief goods (RG) received at the airport to the disaster shelters, which are the demand shelters, through the air and land transportation network as shown in Figure 5-1. The mode of transport includes (1) direct transport from airport *a* to the disaster shelters *i* via land transport; (2) direct transport from airport a to the disaster shelters *i* via conventional air transport (e.g. helicopters); and (3) transporting RG from airport *a* to the disaster shelters *i* via emergency ports j using eVTOL aircraft, i.e., a combination of air and land transport. The problem at hand is to transport the RG units to the disaster shelters *i*, based on the predetermined demand, with the lowest possible cost using the most suitable mode of transport.

The demand was based on the percentage of population in the area that evacuated to the disaster shelters. The proposed emergency port is a type of vertiport that can be used as a landing and takeoff area of the eVTOL aircraft that can also receive and hold RG before sending it to the disaster shelters. In essence it is a depot with the capability to receive the eVTOL aircraft. The introduction of the emergency ports (EP) helps to expand the current air transportation network as well as serves as a bridge to connect air and land transportation network and aid the isolated places.

The process involves both the conventional way of transporting RG which is either via land transportation or via air transportation in case the area is isolated and cannot be reach by land transportation. Additionally, the third mode of transportation which is using eVTOL aircraft by introducing the EP is added. Therefore, the aim is to compensate the weakness of the two conventional modes and not to replace them.

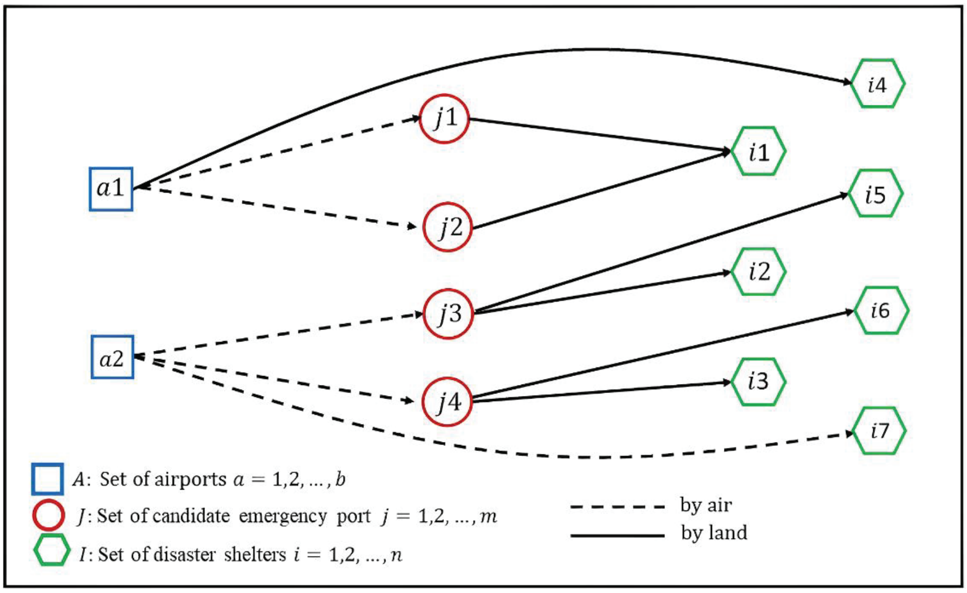


Figure 5-1: Illustration of Disaster Relief Operation

In the case that the area is totally isolated due to road disruption, land transportation will be replaced by conventional air transportation such as emergency helicopters which will be reflected by the isolation cost. Isolation cost includes uncertainties such the need to fulfill the demand of the disaster shelter even at a high cost, the importance of saving a human life in an isolated area, and so on. Considering the cost of transporting the goods and services to fulfill the demands of the disaster shelters, the total number and location of the emergency ports from the candidate emergency ports will be determined as well as the most suitable mode of transport.

To ease the burden of calculation, some simplification in the form of assumptions was also made. In this study vehicle routing was not considered, therefore, it is assumed that each vehicle will only service one emergency port or disaster shelter. Also, vehicle capacity was not considered and assumed to be the same regardless of the vehicle type. Since vehicle routing is not considered, larger capacity vehicle is the same as smaller vehicle since it can only visit one location. The calculated cost is also based on one way trip only. The time frame of relief operation considered in the study is the first twenty-four (24) hours following the disaster where the demand and immediate response is at peak. Also, since one of the concerns in using eVTOL aircraft also includes weather and terrain, it is assumed in the study that the weather condition during the operation is within the eVTOL aircraft capabilities and no flight cancellation will happen and that the selected emergency ports is capable of receiving the said aircraft (Randall, 2021).

As mentioned, demand is only based on the percentage of population that evacuated to the disaster shelters. Since the demand is based on the population, the amount of relief goods per person were determine. According to Sphere, (2018), the minimum amount of drinking water needed for each person per day is 2.5 kg while the World health organization suggests that each person needs at least 2,100 kilocalories of food per day which is roughly equivalent to 560 grams of food (WHO, 2004; MRRC, 2023). For calculation purposes, the amount of food was set to one (1) kilogram and an additional of 1.5 kg of non-food items was added. In total, in this study, each person requires 5 kg of relief goods that contains drinking water, food, and non-food items. Non-food items or core relief items are items other than food used in humanitarian contexts such as bedding materials, plastic containers, plastic sheets, cooking utensils, hygiene kits, clothing and other immediate personal needs (MRRC, 2023; UNHCR Syria, 2016) therefore, it is assumed that each RG unit weighs five (5) kilograms. Also, it is assumed that conventional air transportation such as the helicopter is used to reach the isolated disaster shelters and that these vehicles can reach these areas without additional requirements.

5.2.2. Model Formulation

In normal condition, land transportation is used to reach the disaster shelters but due to some uncertainties caused by disasters such as the difficulty to identify road disruption patterns before the disaster, this mode of transportation may not be able to meet all the demands. To illustrate the effect of road disruption in this research, road disruptions are incorporated into the road network which cause the increase in travel time due to rerouting or detouring and other unforeseen problems caused by road disruptions. In this study, it is assumed that travel time is proportional to transportation cost, that is, an increase in travel time results in higher transportation cost of each relief goods units. Travel time savings was calculated based on travel distance and introduced latter in the study. The cost of transporting relief goods from the airport to the disaster shelters are then considered using the three modes of transportation mentioned above. To enable the use of eVTOL aircraft introduced in the study, the suitable facility called the emergency port (EP) has to be built to the candidate locations. This facility aids the integration of air and land transportation to facilitate the RG operations.

This study introduced a model that will determine how this new type of mobility can enhance disaster response and will also show as to what degree air and land transport can support each other while considering the cost of operation. The model also includes the uncertainties involving road disruption patterns and the use of new technology in terms of cost as well as demand and vehicle capacity. A mixed integer linear programming model utilizing facility location-allocation optimization is formulated to answer the problems at hand. The proposed model involves the following indices, parameters, and decision variables that will determine (1) the suitable location for emergency ports, and (2) the most suitable mode of transfer and determine the degree as to which the new mobility can support the disaster response operation. Eq. (1) to Eq. (12) shows the optimization function and the constraints of the model.

Set of indices

- A Set of origin airports $a = 1,2 \ldots, b$
- J Set of candidate emergency port locations $j = 1,2 \ldots, m$
- I Set of disaster shelter (demand points) $i = 1,2, \ldots, n$
- S Set of scenarios $s = 1,2, \ldots, r$

Parameters

- F_j Operation cost of emergency port at candidate location j in dollars ($)
- C_{ij}^s Cost of transporting 1 RG unit from emergency port j to disaster shelter i under scenario s in dollars ($)
- C_{ja} Cost of transporting 1 RG unit from airport a to emergency port j in dollars ($)
- C_{ia}^s Cost of transporting 1 RG unit from airport a to disaster shelter i under scenario s in dollars ($)
- D_i Demand at disaster shelter i in RG units
- M_j Amount of RG units that emergency port j can hold per day
- M_a Amount of RG units that of airport a can hold per day
- EM Maximum number of emergency ports to be build
- VP Maximum payload of eVTOL aircraft in kg
- VM Maximum distance that eVTOL can travel in km
- RN Amount of RG units that each eVTOL aircraft can carry per trip
- RW Weight of each RG unit in kg
- EN Number of eVTOL aircraft that the emergency port can accommodate per hour

EH Number of hours of operation of emergency port per day

AN Number of eVTOL aircraft that the airport can accommodate per hour

AH Number of hours of operation of airports per day

SP_{ij}^{s} Shortest path distance from emergency port j to disaster shelter i under scenario s in km

SP_{ia}^{s} Shortest path distance from airport a to disaster shelter i under scenario s in km

ED_{ja} Euclidean distance from airport a to emergency port j in km

TL Transportation cost using land vehicle per km

TE Transportation cost using eVTOL aircraft per km

Decision variables

Y_j 1 if emergency port j at candidate location j is selected, 0 otherwise

X_{ij} Amount of RG units transferred from emergency port j to disaster shelter i

X_{ja} Amount of RG units transferred from airport a to emergency port j using eVTOL aircraft

X_{ia} Amount of RG units transferred from airport a to disaster shelter i

$$\min_{Y_j, X_{ja}, X_{ij}, X_{ia}} \sum_{j=1}^{m} F_j Y_j + \sum_{a=1}^{b} \sum_{j=1}^{m} C_{ja} X_{ja} + \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij}^{s} X_{ij} + \sum_{a=1}^{b} \sum_{i=1}^{n} C_{ia}^{s} X_{ia} \tag{5.1}$$

Subject to:

$$\sum_{j=1}^{m} X_{ij} + \sum_{a=1}^{b} X_{ia} = D_i \qquad for\ all\ i = 1, \dots, n \tag{5.2}$$

$$\sum_{i=1}^{n} X_{ij} \le M_j Y_j \qquad for\ all\ j = 1, \dots, m \tag{5.3}$$

$$X_{ij} \le D_i Y_j \qquad for\ all\ i = 1, \dots, n;\ j = 1, \dots, m \tag{5.4}$$

$$\sum_{j=1}^{m} X_{ja} \leq M_a \qquad for\ all\ a = 1, \dots, b \tag{5.5}$$

$$\sum_{a=1}^{b} X_{ja} \leq M_j \qquad for\ all\ j = 1, \dots, m \tag{5.6}$$

$$\sum_{a=1}^{b} M_a \geq \sum_{j=1}^{m} M_j \qquad for\ all\ a = 1, \dots, b;\ j = 1, \dots, m \tag{5.7}$$

$$\sum_{a=1}^{b} X_{ja} = \sum_{i=1}^{n} X_{ij} \qquad for\ all\ j = 1, \dots, m \tag{5.8}$$

$$\sum_{j=1}^{m} Y_j \leq EM \qquad for\ all\ \ j = 1, \dots, m \tag{5.9}$$

$$ED_{ja} \leq VM \qquad for\ all\ a = 1, \dots, b;\ j = 1, \dots, m \tag{5.10}$$

$$X_{ij}, X_{ja} \geq 0 \qquad for\ all\ \ a = 1, \dots, b;\ i = 1, \dots, n;\ j = 1, \dots, m \tag{5.11}$$

$$Y_j \in \{0,1\} \qquad for\ all\ j = 1, \dots, m \tag{5.12}$$

Objective function (5.1) minimizes overall cost of transporting relief goods from the airport to the disaster sites. Constraint (5.2) ensures all demands at disaster shelter i will be satisfied. Constraint (5.3) ensures that each established emergency port j has capacity M_j . Constraint (5.4) ensures all demands at emergency port j will be satisfied based on the demands at disaster shelter i. Constraint (5.5) ensures that amount supplied by airport a to emergency ports j does not exceed its capacity M_a. Constraint (5.6) ensures that the amount supplied by airport a to emergency ports j does not exceed the capacity of the emergency ports j. Constraint (5.7) ensures that airports a will be able to fulfill the capacity of the emergency ports j. Constraint (5.8) is the flow conservation constraint for the quantity of goods and services that is transferred from the airport to the disaster shelters. Constraint (5.9) limits the number of emergency ports that can be build. This can assist in finding the suitable location where budget is a major concern since this will help maximize the locations with the given budget. Constraint (5.10) is a technical specification constraint. This constraint represents that travel distance capacity of eVTOL aircraft which is also proportional to its battery capacity since it is dependent on battery for its operation. Constraint (5.11) ensures that quantity transferred is non-negative and constrain (5.12) is the binary constraint to dictate whether the emergency port will be established or not in the candidate locations. Equations 5.13 to 5.15 is used to calculate the transportation of each unit of RG from the airport to the disaster shelters based on the shortest path (SP) distance and in case of eVTOL aircraft Euclidean distance. In cases where shortest path does not exist, isolation cost is used.

$$C_{ja} = ED_{ja}TE \tag{5.13}$$

$$C_{ij}^{s} = SP_{ij}^{s}TL \tag{5.14}$$

$$C_{ia}^{s} = \begin{cases} SP_{ia}^{s}TL & \text{if SP exist} \\ IC & \text{if DS is isolated} \end{cases} \tag{5.15}$$

As shown in Eq. 5.16, the amount of RG units (RN) that each eVTOL aircraft was calculated given the assumed weight of each RG unit (RW) which is 5 kilograms. The study assumed that the maximum payload of eVTOL aircraft (VP) is 450 kg but considering bulkiness of the load, only 400 kg was used which allows each eVTOL aircraft to carry 80 RG units per trip.

$$RN = \frac{VP}{RW} \tag{5.16}$$

$$M_a = AN * AH * RN \tag{5.17}$$

$$M_j = EN * EH * RN \tag{5.18}$$

Additionally, calculate the capacity of each airport, we assume that each airport have ten (10) parking space for eVTOL aircraft that can accommodate 30 aircraft per hour (AN) and the airport operates for 16 hours (AH). Using Eq. (5.17) with the assumed parameters, each airport has the capacity of 38, 400 RG units. Similarly for the emergency ports, we assumed that each emergency port has two (2) parking space for eVTOL aircraft and can accommodate four (4) aircraft per hour and that each emergency port can operate for nine (9) hours. Using Eq. (5.18), the calculated capacity of each emergency port is 2,880 RG units.

5.2.3. Study Area

In July 2018, the heavy rain disaster in Chugoku region, including Hiroshima brought about sediment-related mass movement disaster and cause a road disruption everywhere (MLIT, 2018). In Hiroshima, one of the heavily damaged cities was Kure City. Kure City, shown in Figure 5-2, is in southern part of Hiroshima Prefecture, Japan, surrounded by mountains on one side and sea on the other side (Britannica, 2018). To test the proposed method two nearby airports to Kure City namely, Hiroshima Airport, and Iwakuni Airport were chosen as origin airports, as shown in Figure 5-3. Since eVTOL aircraft are short distance aircraft, only nearby airports were chosen for this case study.

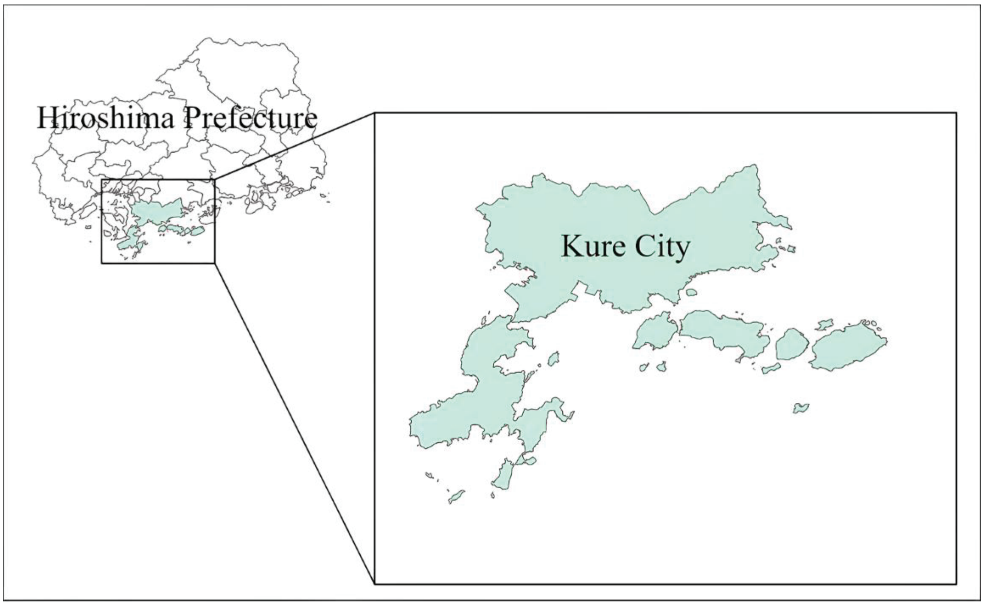


Figure 5-2: Map of Kure City, Hiroshima

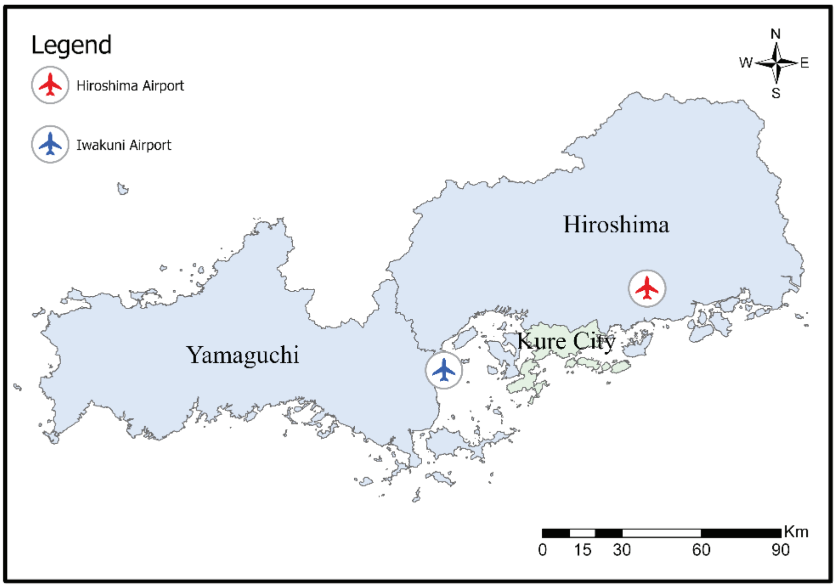


Figure 5-3: Nearby Airports to Kure City

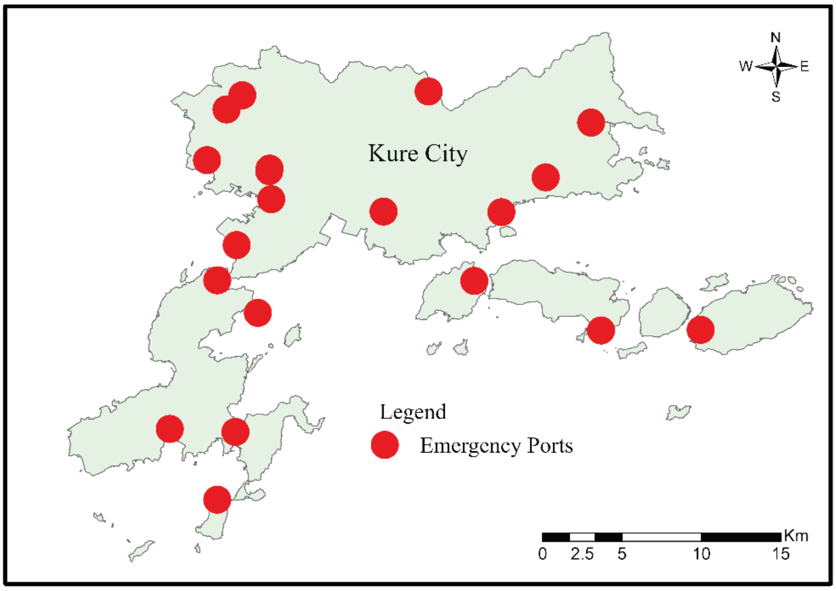


Figure 5-4: Candidate Locations Emergency Ports

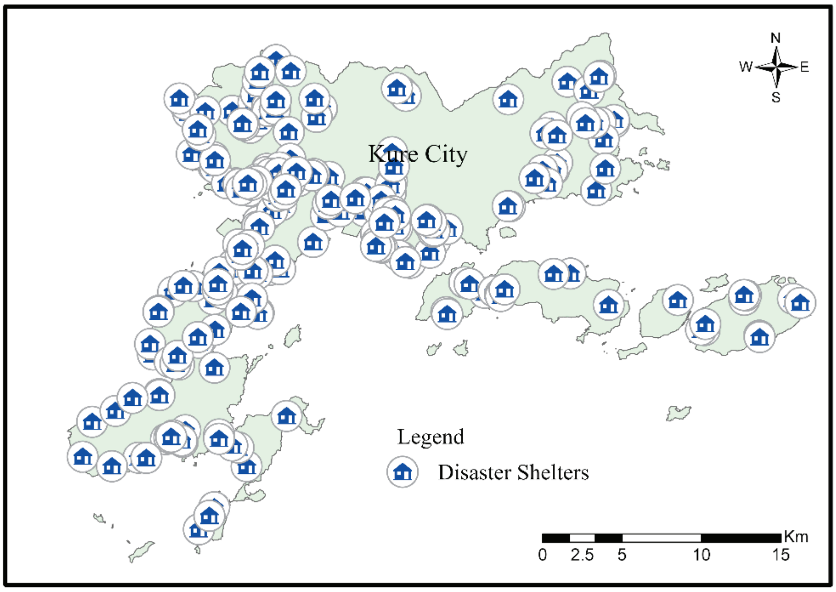
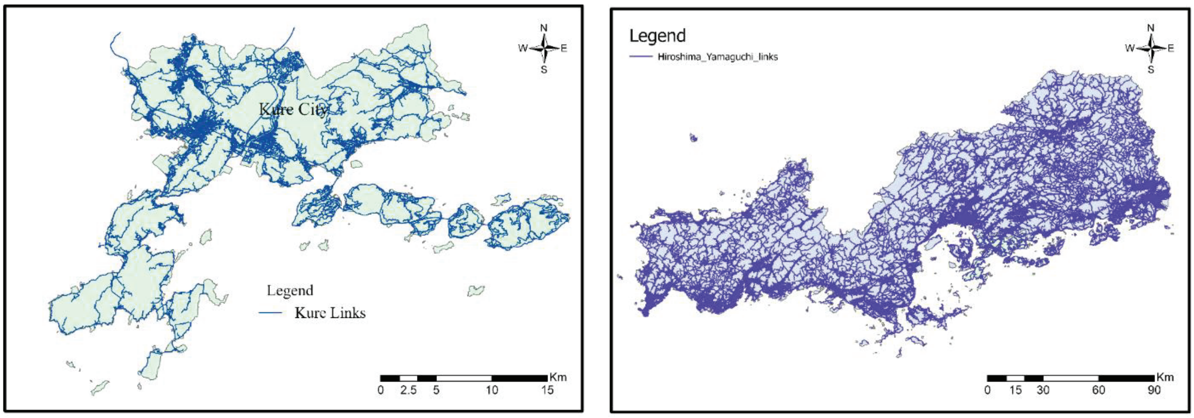


Figure 5-5: Disaster Shelters around Kure City

Twenty-four (24) candidate emergency port locations, shown in Figure 5-4, were chosen around Kure City. These locations are identified from the list of evacuation facilities, which are mostly categorized as wide area evacuation center or located in an island as indicated in regional disaster plans prepared by different prefectures and municipalities in Japan based on the Disaster Countermeasures Basic Act from the National Land Numerical Information Download Service website. We assume that goods and services need to be delivered to 265 disaster shelters shown in Figure 5-5, which were chosen from the same list of evacuation facilities around the city.

To explicitly show the road network disruption in the scenarios, approximately 18,122 road links in Kure City, as shown in Figure 5-6 (a), and around 432,573 road links in Yamaguchi and Hiroshima Prefectures, as shown in Figure 5-6 (b), were used to generate the network and calculate the shortest path (SP) distance from the airport to the disaster shelters and from the emergency ports to the disaster shelters.



(a) (b)

Figure 5-6: Hiroshima and Yamaguchi Prefecture Road Network

5.2.4. Scenario Generation

To generate the different road network scenarios, the method proposed by Santos, et al. (2021) in determining probabilities of road disruptions and occurrence probability were adapted. The binary logit model proposed by Santos, et al. (2021) shown in Eq. (5.19) includes the preparatory factors (potential debris flow locations, debris flow damage hazard area, and watershed boundaries), and triggering factor (rainfall intensity) as the explanatory variables.

$$v_l = \beta_0 + \beta_1 X_{l1} + \beta_2 X_{l2} + \beta_3 X_{l3} \tag{5.19}$$

$$OP_l = \frac{\exp(v_l)}{1 + \exp(v_l)} \tag{5.20}$$

As shown in the equation, v_l is the degree of disruption of road link l, X_{l1} and $X_{l2}$are variables that describes the location of road link l, whether it is within the exposure hazard area or not and if the road link is within the watershed boundary or not respectively. While X_{l3} is the maximum value of rainfall index. The rainfall data was based on the July 6, 18:00-21:00, to July 7, 3:00-6:00 record during the heavy rain disaster. Lastly the occurrence probability of sediment hazard was calculated using Eq. (5.20). Using the result of the occurrence probability for each link, a map showing the location of the links with the given probability was generated as shown in Figure 5-7 where the links with the highest probability is represented by the red links.

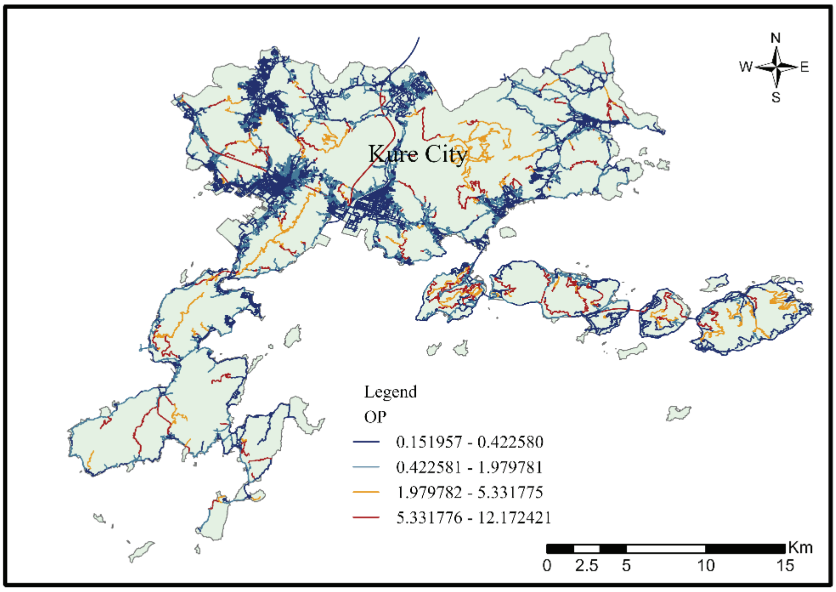


Figure 5-7: Occurrence Probability of Kure City Road Network

Following the flowchart shown in Figure 5-8, a Monte Carlo simulation was used to generate 500 random road disruption pattern scenarios. The generated uniform random probability was compared to the occurrence probability of each link based on Santos, et al. (2021) model was used to decide where to remove the link or not in each scenario. After comparing the random probability and occurrence probably for all the Kure road network links, the disrupted network was created. Following the shortest path (SP) algorithm, the distance from the airport to the disaster sites where then calculated. In situations where the shortest path does not exist (land transportation is not available), the isolation cost is added which represents the needs to meet the demand regardless of high cost using conventional air transportation such as emergency helicopters. After obtaining the shortest path distance, the transport cost is calculated and the optimization to find the suitable location of emergency ports followed.

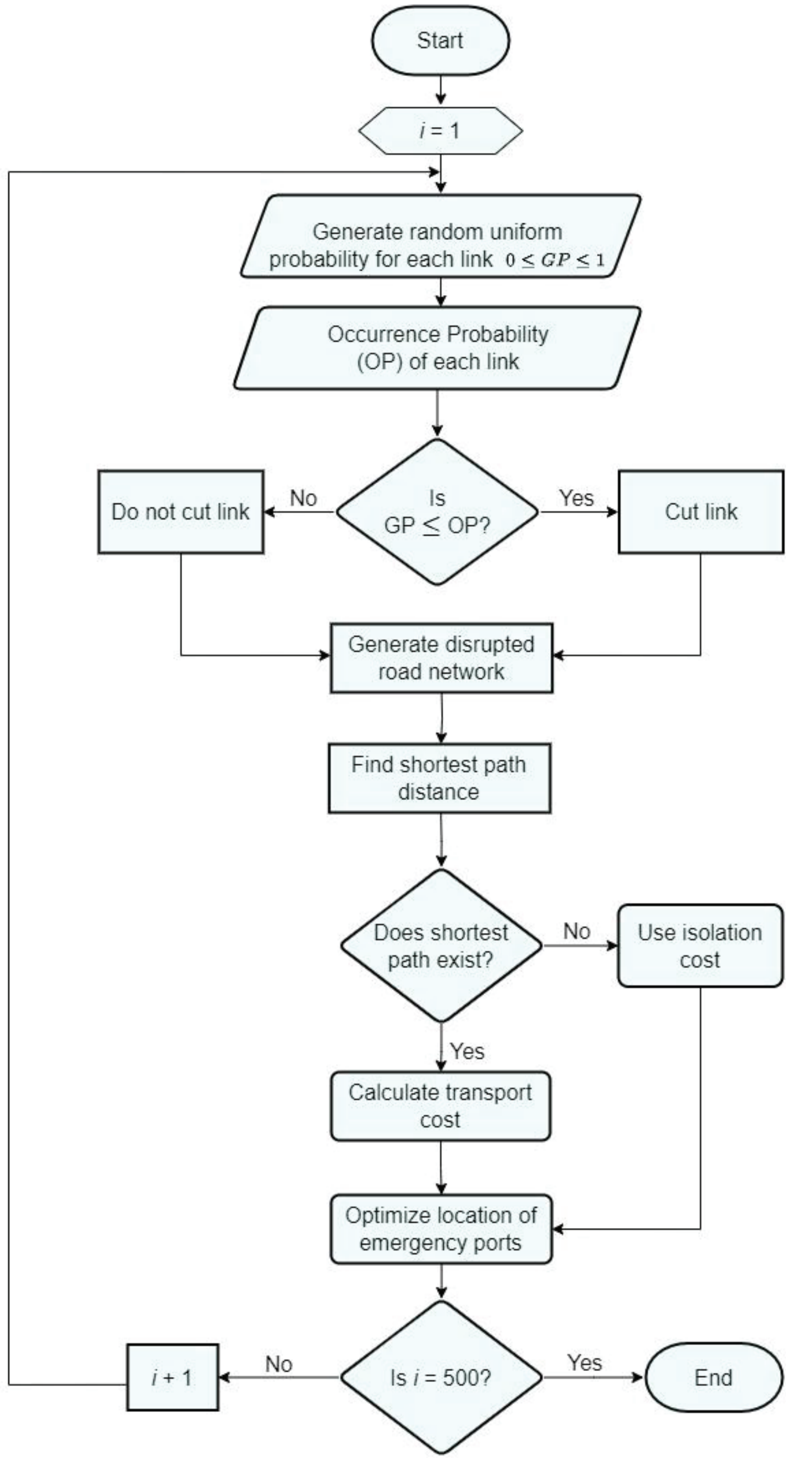


Figure 5-8: Monte Carlo Simulation for Optimizing EP Locations

To optimize the locations, several parameters were set. The operation cost of each emergency port was set to \$10,000 while the isolation cost was set to \$5,000. The land transportation cost per kilometer were set to $2 in reference to Taxiautofare, (2023). Since eVTOL aircraft is still not publicly used, the transport cost contains many uncertainties. In this study, it is assumed that the transport cost of eVTOL is $2.5 slightly higher than the land transportation cost. To check the effect of parameters that contains uncertainties such as operation cost, eVTOL aircraft transport cost, isolation cost, and demand change, a more detailed sensitivity analysis was performed and introduced in the latter part of this paper.

It is also important to note that this road disruption scenario pattern generation is based on a single event, in this case the 2018 Heavy Rain Disaster in Hiroshima, and therefore the generated disruption pattern may differ when dealing with other type of disasters. Consequently, this choice was made due to the geography and history of Hiroshima Prefecture where a large area is composed of mountains and the most common natural disaster that the prefecture experience throughout the history is heavy rain and the like which causes road disruptions.

5.3. Results and Discussions

This section presents the result of the optimization model using the assumptions and the parameters presented on the earlier section of this paper followed by the discussions associated with each result.

Figure 5-9 shows the location of the selected emergency ports marked with red circle with respect to the other emergency ports that are not selected for the first four scenarios. As shown, some of the locations are always selected and the location of the emergency ports have very little variation for each scenario and distributed throughout the Kure City area. These locations are good candidate locations since despite the changes in road disruption patterns, it is still selected.

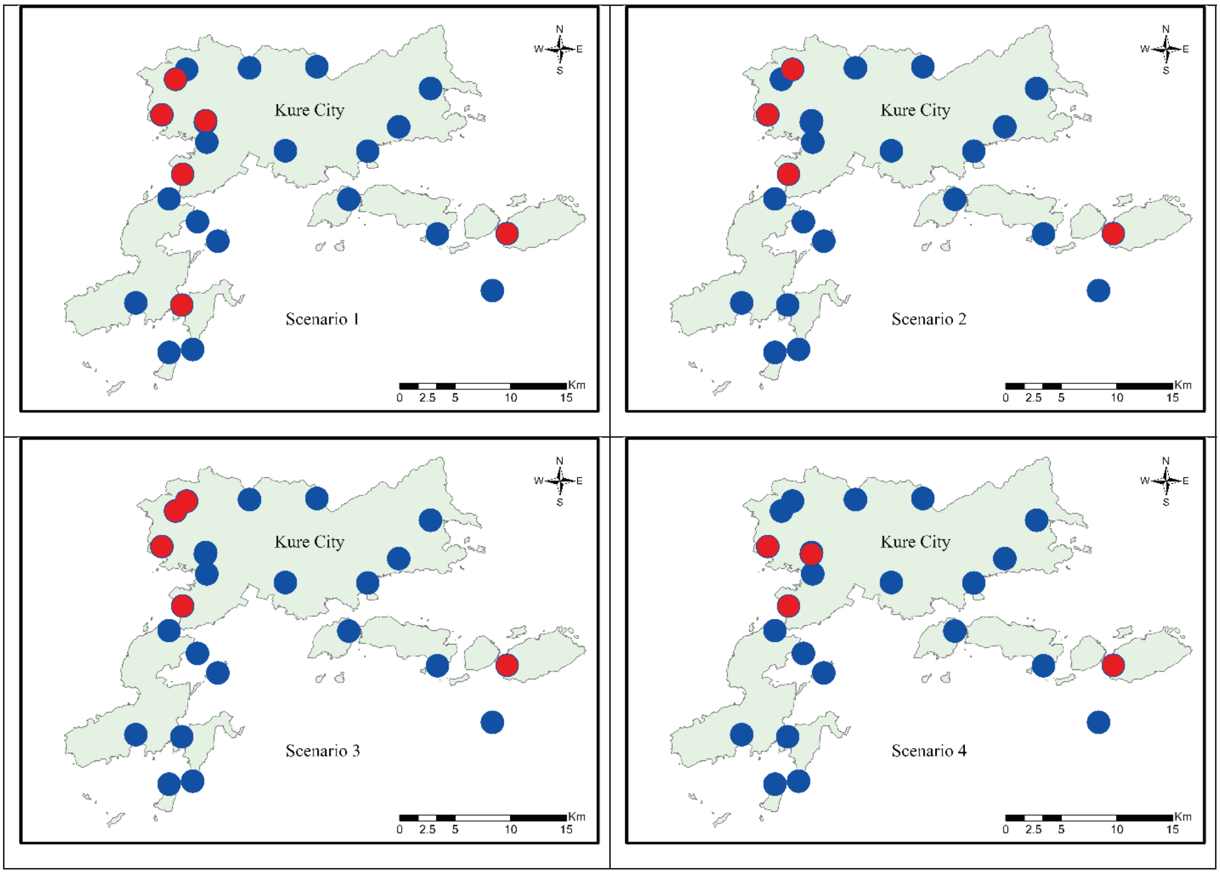


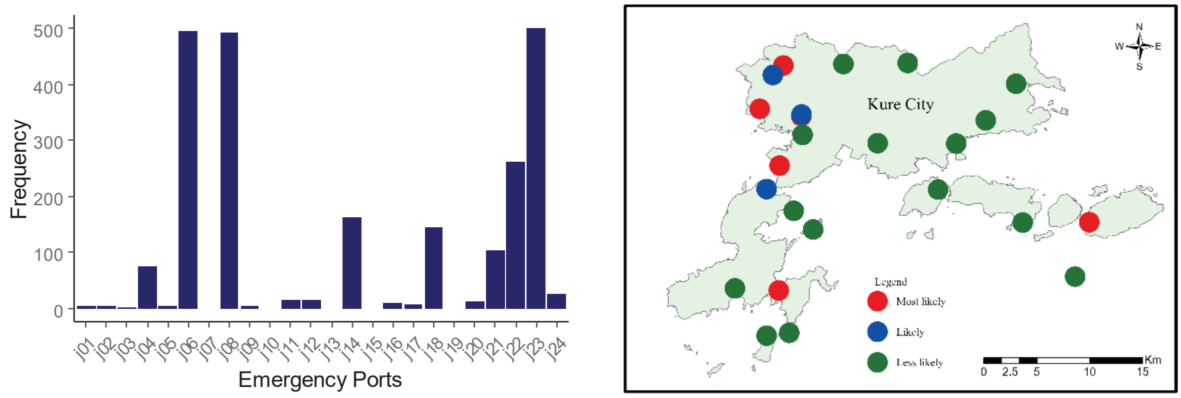
Figure 5-9: Location of Selected Emergency Ports for the First Four Scenarios

Table 5-1 shows the optimization result of the first 20 scenarios as well as the average of each variable for the 500 scenarios. Data gathered from the result includes the total cost, the number of disaster shelters served by each transportation mode as well as the number of isolated disaster shelters per scenario. The total cost is from \$2,029,273 to \$5,397,215 with an average cost of \$2532767 as compared to the baseline scenario which has a total cost of 2,115,146. Baseline scenario is set as a condition where there is no road disruption. The minimum number of EP selected was 4 and the maximum is 10 with an average of 5 EP per scenario. As for the disrupted links, the range is from 112 link to 166 links with an average of 130 links per scenario. The number of isolated disaster shelters which were served by air transportation slightly varies per scenario. It can be observed that in general, higher cost is associated when there are more isolated disaster shelters since isolation cost is high. Also, the number of isolated disaster shelters were reduced when the emergency ports are introduced compared to when there is no EP.

Table 5-1: Optimization Result of 20 out of 500 Scenarios

Scenarios	Total Cost	No. of EP	Disrupted Links	via EP	by land	by air	No. of Isolated DS	Reduction in isolated DS
Scenario 1	2054073	7	124	125	140	0	10	10
Scenario 2	5142826	6	147	115	145	5	5	0
Scenario 3	2185010	6	125	108	155	2	3	1
Scenario 4	2443662	5	138	113	150	2	2	0
Scenario 5	2604883	6	130	119	145	1	1	0
Scenario 6	2047569	6	129	129	136	0	0	0
Scenario 7	2508017	7	127	121	143	1	10	9
Scenario 8	2680492	6	114	129	134	2	2	0
Scenario 9	2636985	7	133	126	137	2	11	9
Scenario 10	2031150	5	127	114	151	0	0	0
Scenario 11	3059388	6	135	114	148	3	22	19
Scenario 12	2037261	5	125	112	153	0	0	0
Scenario 13	2035077	5	134	112	153	0	0	0
Scenario 14	2441389	8	129	139	125	1	17	16
Scenario 15	2045006	6	121	118	147	0	9	9
Scenario16	4383750	7	131	121	137	7	17	10
Scenario 17	2409008	7	140	114	149	2	4	2
Scenario 18	2517528	6	135	115	147	3	4	1
Scenario 19	2226050	7	126	126	138	1	1	0
Scenario 20	2233076	6	145	119	145	1	8	7

Average (500 scenarios)	2532767	5	130	113	150	2	6	2
Base scenario	2115146	-	-	-	265	-	-	-



(a) (b)

Figure 5-10: Summary of Emergency Port Selection

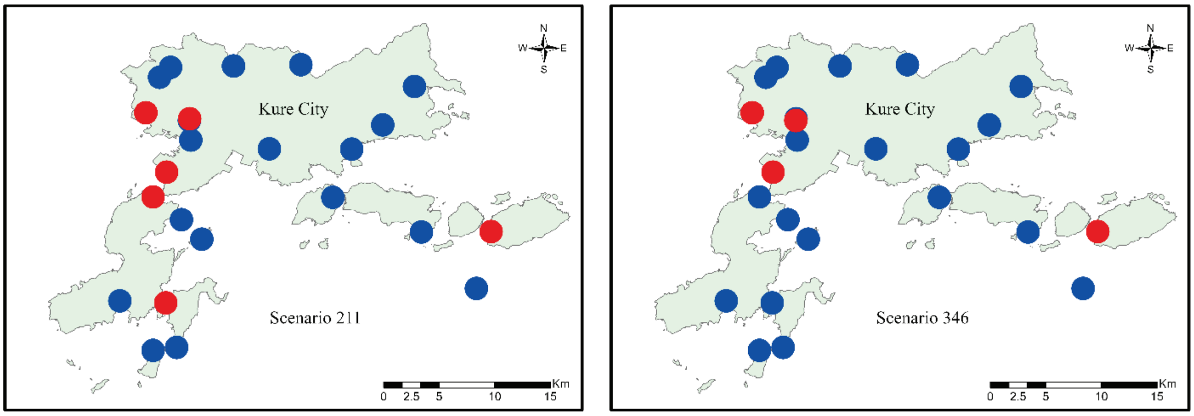
As shown in Figure 5-10 (a), some emergency ports are always selected during each scenario, particularly, emergency ports *j06, j08*, and *j23*. When groups according to probability of being selected for each scenario, each location can be identified as shown in Figure 5-10 (b). In the figure, emergency ports which have 5% and below probability were labeled as less likely to be selected while those EP which have greater than 5% to 25% probability are likely to be selected and the rest with probability of higher than 25% are labeled as most likely to be selected location for emergency port which includes locations *j06, j08*, *j14, j18, j22,* and *j23*. The figure also showed the location of each EP on the map based on the said categories. Locations with high probability of being selected are locations which are suitable for emergency ports when transportation cost and road disruptions are considered.

Table 5-2: Top Four Scenarios with the Highest Total Cost

Scenarios	Total Cost	No. of EP	Disrupted Links	via EP	by land	by air
Scenario 211	5397215	6	131	117	142	6

Scenario 346	5219950	4	137	112	150	3
Scenario 146	5213467	5	135	125	138	2
Scenario 2	5142826	4	147	99	161	5
Average (500 scenarios)	2532767	5	130	113	150	2
Base scenario	2115146	-	-	-	265	-

When examining the total cost, several factors have been observed to affect the increase in total cost. As Shown in Table 5-2, the top four scenarios with the highest total cost reached around 5 million dollars compared to the average of all scenarios which is around 2.5 million dollars and the base line scenario which is around 2.1 million dollars. When looking at the distribution of the modes of transport, when trips performed by air is high, total cost is also high since this trips are performed by emergency helicopters and the transportation cost is equal to the isolation cost. In cases where there is lower number of trips performed by emergency helicopters, the number of trips performed by eVTOL aircraft is generally slightly higher than the average which contributes to the higher total cost. It can also be noticed that the number of disrupted links is higher compared to the average which results to more areas being less accessible and isolated.



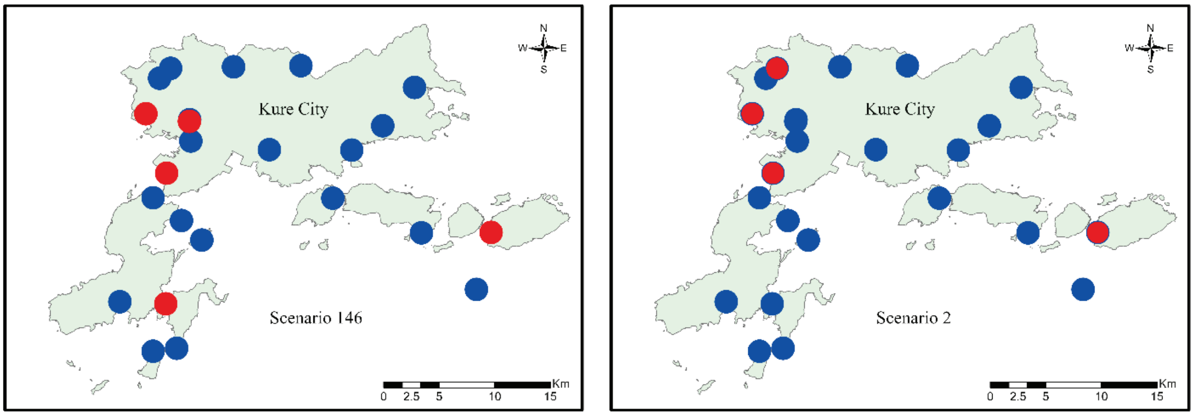


Figure 5-11: Location of EP for the Top 4 Scenarios with the Highest Total Cost

Figure 5-11 shows the location of the emergency ports that were selected for the top four scenarios with the highest total cost. As shown, there are particular locations that are the same across all four scenarios. Since several factors can affected the increase in total transportation cost, such as location of the disaster shelters, number of disrupted links, and number and location of isolated disaster shelters, this common location can be a good candidate when considering the worst case scenario in terms of total transportation cost.

When each scenario was simulated, some road where disrupted that caused isolation in some place. Isolation is defined as loss of land access from the airport to the disaster shelter which hindered the transportation of goods and services to these areas. Figure 5-12 showed the summary of all the disaster shelters that experienced isolation at least once throughout the simulation process. Disaster shelters marked in red are areas that experienced isolation at least once. As shown, most of the areas experienced isolation.

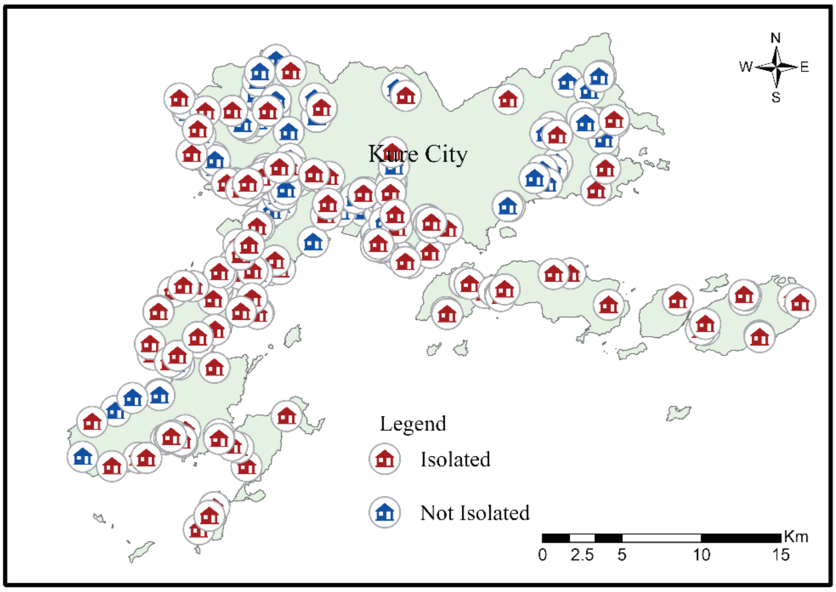


Figure 5-12: Disaster Shelters Isolation Summary

As mentioned, one of the considerations in introducing the establishment of emergency ports is to aid the disaster response operation, thus, as shown in Figure 5-13, when emergency ports were incorporated in the network, some disaster shelters that experienced isolation before where removed, marked by red, which indicates the reduction in number of isolated areas. Normally, when some roads where disrupted, the access from the airport to the disaster shelters were lost and that disaster shelter will be considered isolated, but when emergency ports are introduced in some locations, it served as a link from the airport to the isolated disaster shelters and therefore lessen the number of isolated shelters in some cases. This is possible when the road disruption occurs between the area of the airport to the emergency port and allows the transfer of goods and services from the emergency port to the disaster shelters. By delivering the RG units to the emergency ports, land transportation can reach more disaster shelters that were previously isolated.

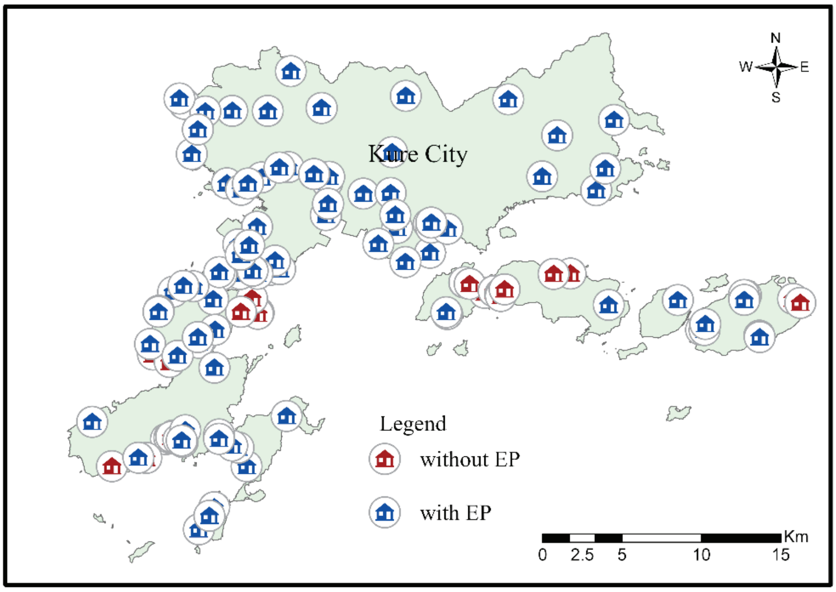
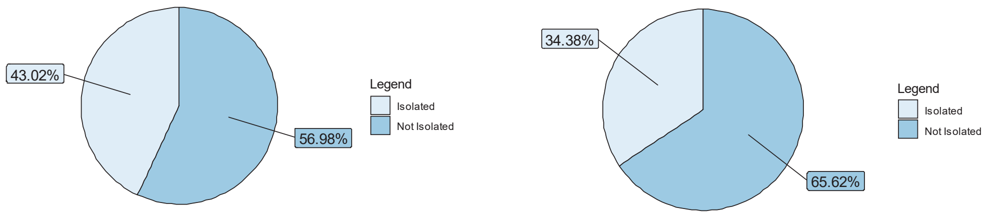


Figure 5-13: Comparison of Isolated Disaster Shelters with and without EP

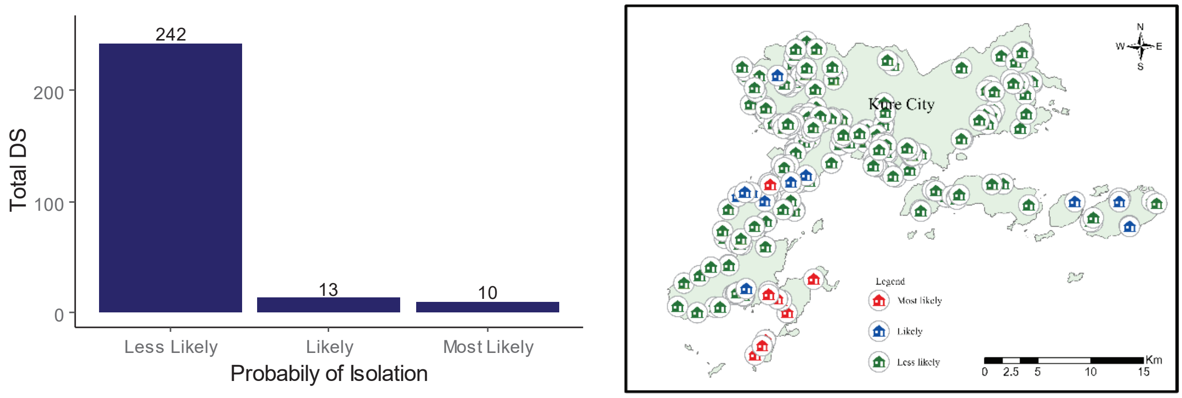
Using the consolidated result of 500 scenarios, Figure 5-14 (a) and (b) showed the distribution of the disaster shelters that were isolated.



(a) without emergency port (b) with emergency port

Figure 5-14: Reduction of Isolated Disaster Shelters

As shown, the total number of isolated disaster shelters reduced by 8.64%, from 43.02% to 34.38%, with the given scenario parameters. This supports the importance of establishing emergency ports to lessen isolation of disaster shelters. 114 out of 265 disaster shelters was isolated at least once while only 88 shelters where isolated when emergency port was introduced in the network which is 26 less than the original isolated disaster shelters.



(a) (b)

Figure 5-15: Distribution of Disaster Shelters Based of Probability of Isolation

Figure 5-15 (a) and (b) shows the distribution of disaster shelters based on the probability of being isolated. Disaster shelters marked in red are most likely to be isolated and have a probability of more than 20%. Disaster shelters with probability of more than 5% up to 20% are likely to be isolated and marked in blue while the rest of the disaster shelters have probability of being isolated of 5% and below are less likely to be isolated and marked in green. While majority of the disaster shelters are less likely to be isolated, there are still some disaster shelters that have a high probability to be isolated.

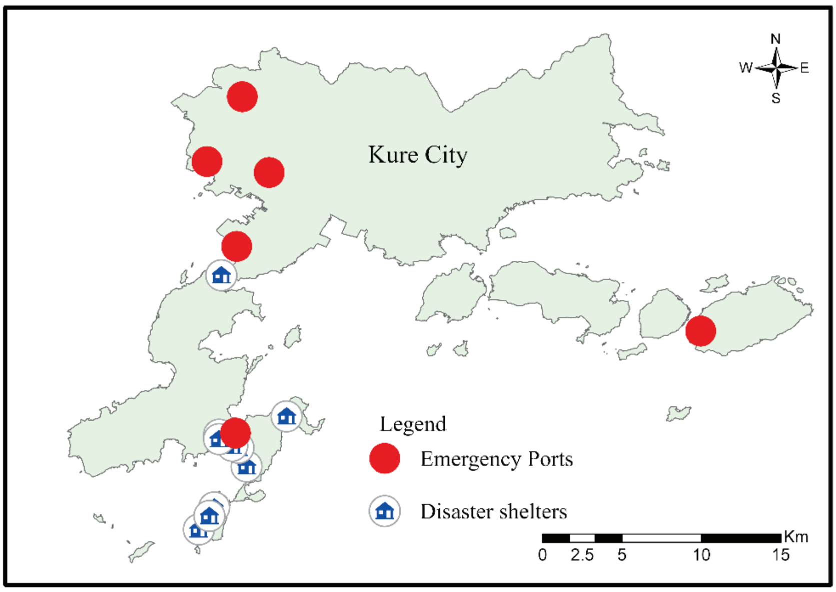


Figure 5-16: Emergency Port Location compared to Disaster Shelters

When emergency that are most likely to be selected and disaster shelters that are most likely to be isolated are interlap in the map the following figure in Figure 5-16 can be generated. As shown, the model was able to identify locations that are most likely to be isolated and most locations of the emergency ports coincide with the location of the disaster shelters that are most likely to be isolated. This also supports the objective of the study of not only minimizing the cost but also illustrate the direct effect of road disruption such as place isolation.

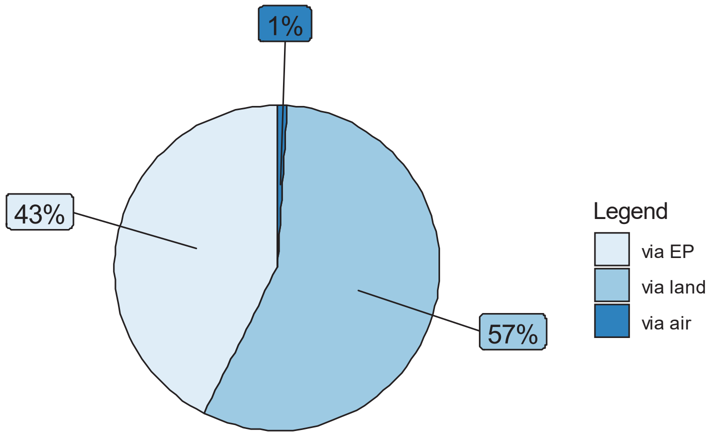


Figure 5-17: Distribution of Transport Mode

To further understand as to what degree the establishment of emergency port and the use of eVTOL aircraft can support the disaster response operation, the distribution of disaster shelters served by each mode of transportation is also analyzed. Figure 5-17 shows how each mode contributes to the overall process given the parameters mentioned in the scenario generation. As shown, 43% of the disaster shelters were served using the combination of air and land transport that is, transporting the goods and services from the airport to the emergency port using eVTOL aircraft then transporting it using land transportation from emergency port to the disaster shelter. The conventional way of transportation which is the land transport gives a share of 57% while the goods and services transferred using conventional air transport such as helicopters is 1%. While this share is relatively small compared to the two modes of transport, this part represents the isolated disaster shelters that utilized the isolation cost. These areas are areas that needs to be served even with a high cost and can only be reached using air transport. This also shows that there is a need to use both air and land transport to meet the demands in all the disaster shelters.

5.4. Chapter Conclusion

Transportation is an important part of disaster response operation specially in humanitarian logistics. The timely and efficient transport of goods and services to the disaster shelters does not only save lives but can also lessen the economic loss and aid in recovery. The most common mode of transportation used during disaster is the land transportation, but due to the damage caused by disasters, response operations is hindered. Road disruptions can increase travel time which can in turn increase the cost of transportation and in worst cases, these disruptions can cause isolation of affected areas. To aid the operation, air transportation is often used, but due to high cost and availability, this mode of transport is often used in worst case scenarios and are often limited in operation. While air transport is fast and can reach isolated areas, it is expensive and has limited capacity. Given that, this study proposed the use of both air and land transport where eVTOL aircraft and emergency ports are.

Results showed some locations showed a consistent result such as locations *j06, j08,* and *j23* which are almost chosen in every scenario which indicates that these locations have high probability of being selected. With the given parameters, these locations are suitable for emergency ports considering both the transport cost as well as the condition of the road network. Additionally, the location of the emergency ports has very little variation for each scenario with an average of five emergency ports per scenario. Total cost varies depending on the number of emergency ports chosen as well as the mode of transportation used. The higher number of isolated disaster shelters serviced by conventional air transport such as helicopters results to a higher cost. There is an overall reduction of 8.64% in the number of isolated disaster shelters when the emergency port is introduced in the network. The distribution of transportation mode used to deliver goods and services to the disaster shelters comprised of 57% by land, 43% via emergency ports, and 1% via air (helicopter). While transport cost using eVTOL shows that lower cost promotes the use of eVTOL using emergency ports, in some situations, the need to establish emergency port can still lessen the overall cost of operation since place isolation serviced by conventional air transport still incurs higher cost when isolation cost is considered.

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disasters, response operations is hindered. Road disruptions can increase travel time which can in turn increase the cost of transportation and in worst cases, these disruptions can cause isolation of affected areas. To aid the operation, air transportation is often used, but due to high cost and availability, this mode of transport is often used in worst case scenarios and are often limited in operation. While air transport is fast and can reach isolated areas, it is expensive and has limited capacity. Given that, this study proposed the use of both air and land transport where eVTOL aircraft and emergency ports are.

Results showed that locations *j06, j08, j14, j18, j22,* and *j23* have high probability of being selected. With the given parameters, these locations are suitable for emergency ports considering both the transport cost as well as the condition of the road network. Additionally, the location of the emergency ports has very little variation for each scenario with an average of five emergency ports per scenario. Total cost varies depending on the number of emergency ports chosen as well as the mode of transportation used. The higher number of isolated disaster shelters serviced by conventional air transport such as helicopters results to a higher cost. There is an overall reduction of 8.64% in the number of isolated disaster shelters when the emergency port is introduced in the network. The distribution of transportation mode used to deliver goods and services to the disaster shelters comprised of 57% by land, 43% via emergency ports, and 1% via air (helicopter). While transport cost using eVTOL shows that lower cost promotes the use of eVTOL using emergency ports, in some situations, the need to establish emergency port can still lessen the overall cost of operation since place isolation serviced by conventional air transport still incurs higher cost when isolation cost is considered.

Chapter 6. Addressing Uncertainties of Using New Technology: eVTOL Aircraft as a New Air Mobility for Disaster Relief Operations

6.1. Introduction

As human needs increase, the thirst for research and development also increases. Finding new methods to improve the current system have become a natural part of human development. The advancement in technology, particularly, have led human lives to a brighter future. On the other hand, not everything is perfect and new technology itself have challenges in integrating itself to the current stable system. Knowing that some aspects are uncertain, doubt may hinder the potential of new technologies and delay its introduction.

Uncertainties of new technology may come into many forms, arising from the technology itself, to its potential market and users, to the environment, as well as to the organization that creates and manages it (Klueter, 2021).

To explore the potential of new technologies, researchers develop models to come up with methods that can best help introduce the new technology to users and to alleviate their doubts. However, uncertainties are always present in any model. The behavior of each parameter can significantly affect the overall result of the research and may reduce its credibility. Finding the right value can be challenging especially when dealing with new technology where established parameters are still under study. While it is hard to deal with uncertainties, completely ignoring these variables can make the model less reliable and unstable. To do so, methods addressing uncertainties in the model such as sensitivity analysis must be done. Addressing uncertainties in an organized manner can help policy makers open more opportunities to use the system and provide them with a basis in decision making.

In this study, the aim is to address the uncertainties involving the introduction of eVTOL aircraft as a new means of emergency transportation. Variables such as transportation cost, operating cost, isolation cost, demand, travel time, and capacity were addressed using sensitivity analysis to show how each variable can affect the model and help policy makers come up with a better management plan when integrating this new mobility to the current disaster management system.

6.2. Method

To understand the impact of different parameters to the model, a sensitivity analysis was performed. The sensitivity analysis was done by varying the value of one particular parameter in at a time in the model and observing the changes that the parameter caused in the model. Using Eq. (6.1) which was introduced in the previous chapter, parameters including transportation cost, operation cost, isolation cost, and demand was tested. Additional analysis was also performed for the time savings and vehicle capacity to observe how these two variables affect the proposed model.

$$\min_{Y_j, X_{ja}, X_{ij}, X_{ia}} \sum_{j=1}^{m} F_j Y_j + \sum_{a=1}^{b} \sum_{j=1}^{m} C_{ja} X_{ja} + \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij}^{s} X_{ij} + \sum_{a=1}^{b} \sum_{i=1}^{n} C_{ia}^{s} X_{ia} \quad (6.1)$$

Assumed values of the other parameters given on Chapter 5, as well as the other assumptions were also used in this chapter and only the specified parameter to be tested was varied one at a time. A graphical representation and tabulated tables were created in order to visualize and understand the result of the analysis.

6.3. Results and Discussions

This section presents the results of the sensitivity analysis on the different parameters that were selected to be examined in this study.

6.3.1. eVTOL Aircraft Transportation Cost

To address uncertainties of using a new technology in the study, a sensitivity analysis was conducted. The relationship between the number of emergency ports selected and the transportation cost, operation cost, isolation cost and demand change were examined to determine the effect of each variable in the model.

As shown in Figure 6-1, the number of emergency ports reduces as the transportation cost of eVTOL aircraft per kilometer increases. With the initial value of \$0.5 that is half the set transportation cost of land transportation, the number of emergency ports selected decreases as the transportation cost of eVTOL aircraft increases. At a value of \$3.5, the number of emergency ports selected remained constant even with the great increase in the transport cost up to \$40 which is twenty times compared to the set land transportation cost. This means that when the transportation cost of eVTOL aircraft is similar to land transportation, the usage of eVTOL aircraft is more desirable.

In general, lower transportation cost of eVTOL aircraft will encourage the use of these aircraft and would also help in establishment of more emergency ports which in term can help lessen isolation of many areas that can be damaged by disasters.

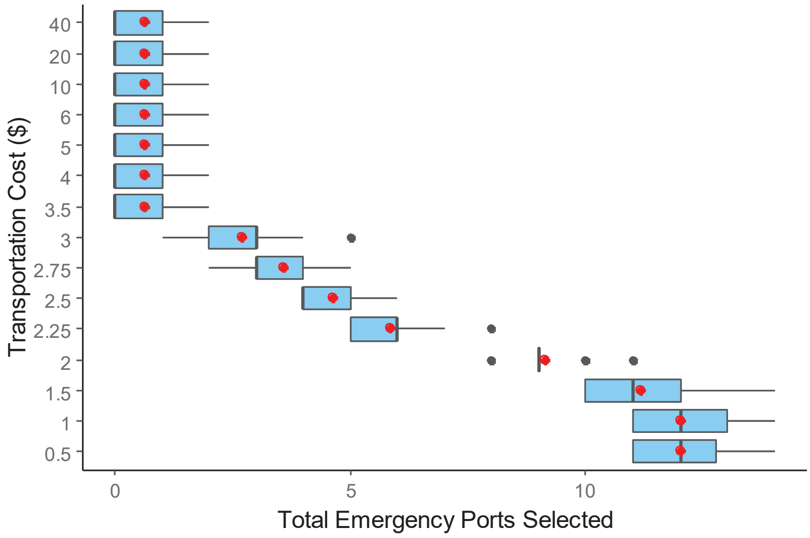


Figure 6-1: Relationship of eVTOL Transportation Cost and Total Number of EP

As shown in Figure 6-2 (a) a noticeable shift from air to land transportation is evident as the transportation cost of eVTOL aircraft increases. While higher transport cost signifies lower usage of these aircraft, it can also be seen that even the transport cost is high, there is still some areas that required an emergency port. When examined, as shown in Figure 6-2 (b), some emergency ports are always selected regardless of the transportation cost.

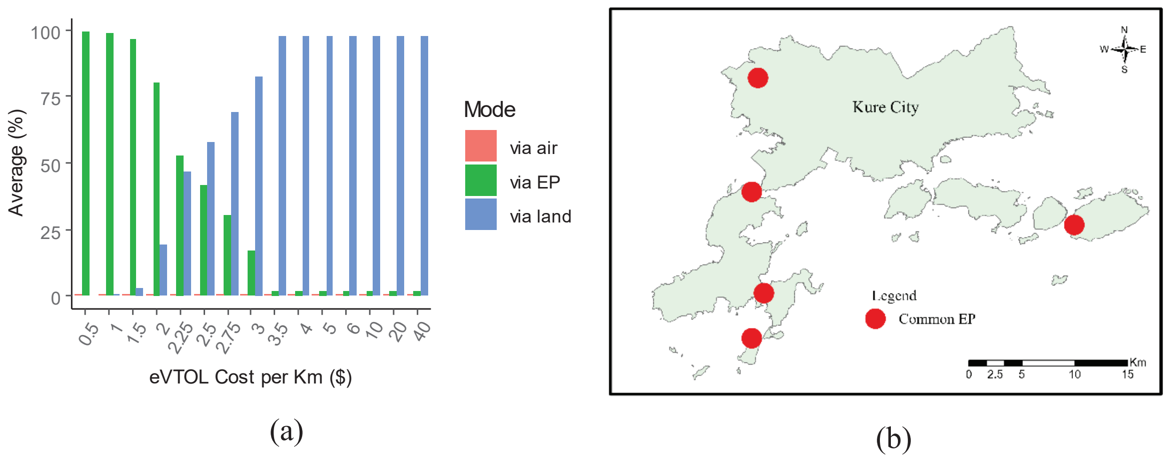


Figure 6-2: Relationship of EP Operation Cost and Total Number of EP

6.3.2. Operation Cost of EP

Another parameter that influences the total cost of operation is the operation cost of emergency ports. Since these facilities need to accommodate eVTOL aircraft and also function as hubs, a considerable amount will also be used during its operation. Currently, no established cost is available therefore changes on this parameter may affect decisions and flow of operation. Results of this analysis can help policy maker in making decisions on locations which may prove to be more beneficial to the overall operation.

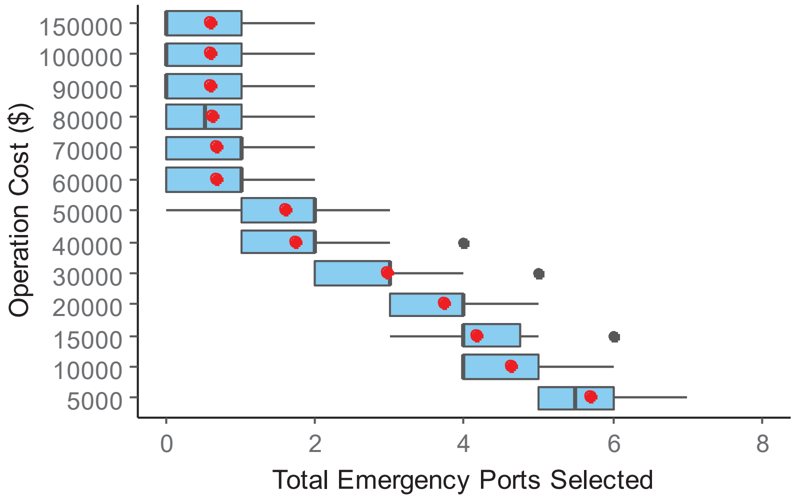
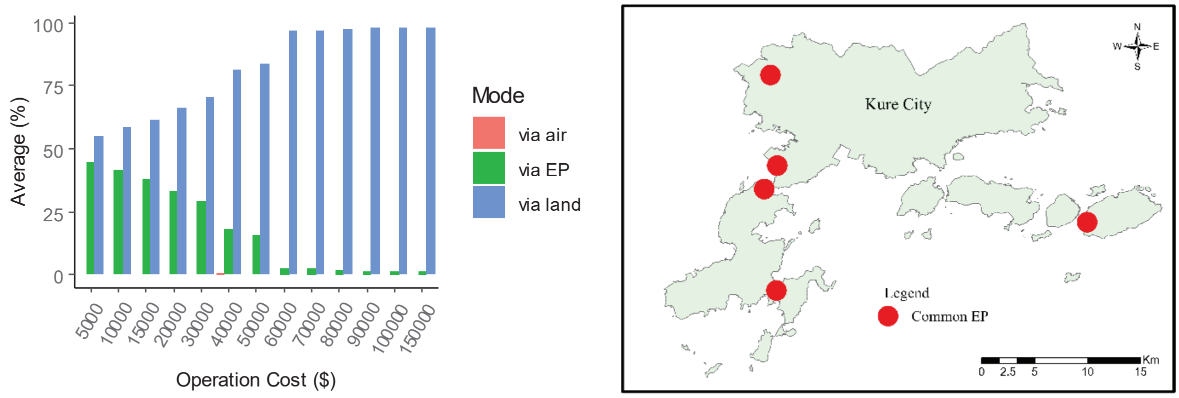


Figure 6-3: Relationship between Operation Cost and Number of EP

Figure 6-3 shows the result of sensitivity analysis conducted for operation cost of emergency ports. As shown, lower operation cost will yield an increase in the number of ports. This promotes the use of eVTOL aircraft in the disaster response. It can also be seen that at some point where the operation cost is very high, the increase in the number of ports selected will be the same. In comparison with the model scenario used in the paper where the operation cost is set to $10,000, when the operation cost is at 9 times, the number of emergency ports chosen starts to stabilize and any increase will have the same effect. This proves the need to establish an emergency port to facilitate relief operations even if the cost is high since it will still yield to a decrease in the overall transportation cost.

In addition, as shown in Figure 6-4 (a), higher operation cost results to more use of land transportation compared to eVTOL aircraft. Also, as shown in Figure 6-4 (b), there are locations which are common regardless of the operation cost. These locations as shown in the map can be used as a guide when considering the cost of operation and limited number of emergency ports are needed.



(a) (b)

Figure 6-4: Comparison between Operation Cost and Location of EP

6.3.3. Change in Demand in DS

The amount of RG units delivered to the disaster shelters may also affect the selection of optimum location of emergency ports. Since emergency ports have limited capacity, each port will only be able to provide service to a certain number of disaster shelters. In case the demand in the nearby disaster shelters is high, additional emergency ports may be needed. In this situation, the location of the emergency ports should be optimum to minimize the cost of transportation.

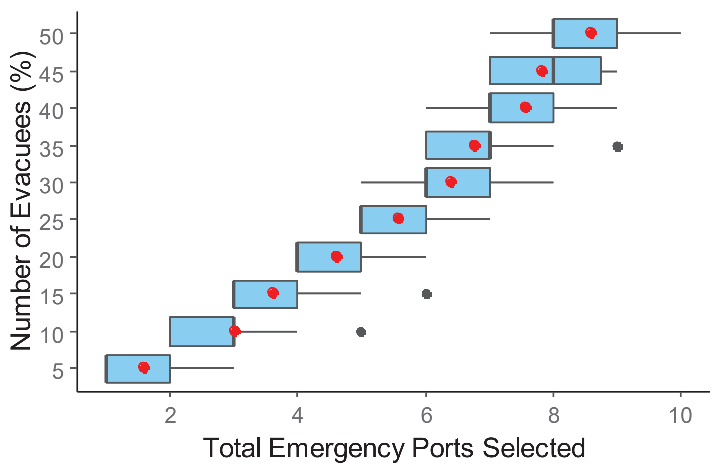
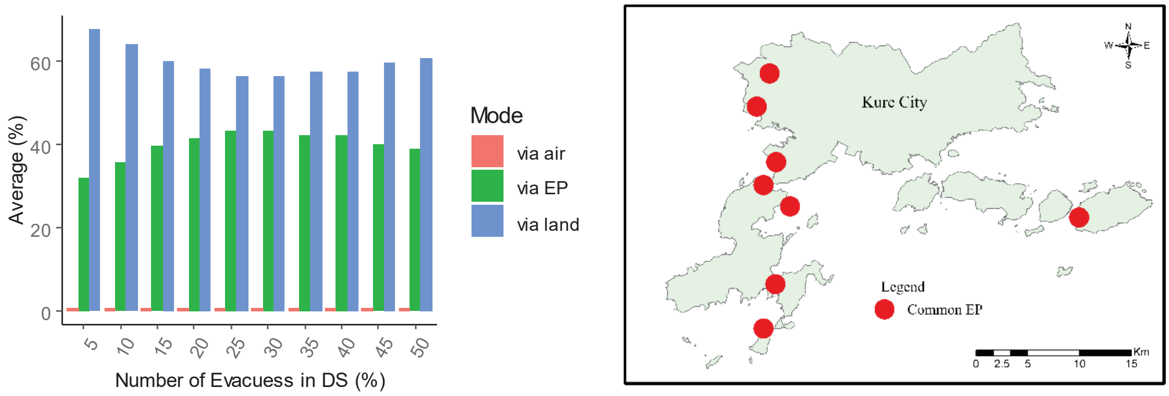


Figure 6-5: Relationship between Demand Change and Number of EP

Figure 6-5 shows the sensitivity analysis between the number of emergency ports selected and the varying demand based on the percentage of population that evacuated to the disaster shelters. In general, the number of emergency ports selected increases as the number of evacuees increases. This is due to the fact that each emergency port has a fixed capacity set in the model and an additional emergecny port will be needed to accommodate an increase in the demand.



(a) (b)

Figure 6-6: Distribution of Transport Mode Considering Number of Evacuees

Figure 6-6 (a) shows the distribution of each mode of transportation used to deliver the relief goods to the disaster shelters. As shown, there is a little variable in the distribution. This can be the effect of the capacity of the emergency ports. The figure shows that when the number of evacuees in the disaster shelter is 30%, the number of trips performed by eVTOL aircraft is at peak. The number of trips gradually decreases as the number of evacuees increases above 30%. One possible reason for this behavior is due to the set value of eVTOL aircraft transportation cost. For this simulation, the land transportation cost was set to $2/km while the eVTOL aircraft transportation cost was set to $2.5/km which is slightly higher in cost. This affects the total transportation cost and as the demand increases up to 30%, the total cost using more eVTOL aircraft is still lower compared to using more land transportation, but as the demand increases beyond 30%, the impact on total transportation cost of the $0.5 difference between the two modes of transportation becomes more significant causing the decrease in the use of eVTOL aircraft and land transportation becomes more favorable because of lower transportation cost. While this is one possible reason, it is recommended to run the same analysis where both the eVTOL aircraft and land transportation cost is the same to further examine the changes that happened in the model.

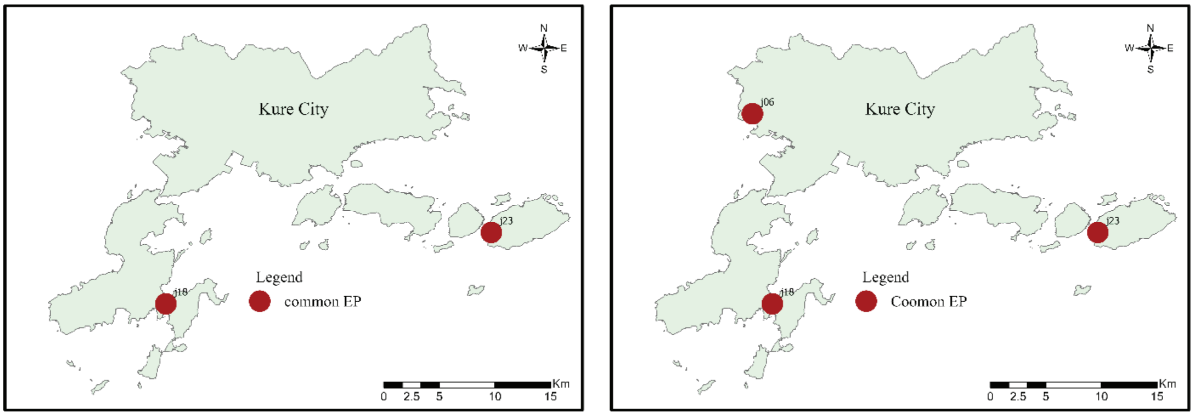
Since capacity was treated in terms of the amount of RG units and the demand was also based on RG units, the capacity of the emergency ports plays a role in the distribution. As shown in Figure 6-6 (b), these disaster shelters are sensitive to the change in the demand as these locations are common regardless of the increase or decrease in the demand on the disaster shelters.

When examining the results of the analysis and the sensitivity analysis, locations which are most likely to be selected when considering road disruptions and overall transportation cost as well as the common selected emergency ports based on the variations in eVTOL transportation cost, operation cost, and demand can be summarized in Table 6-1. This table shows which candidate locations for emergency ports are suitable depending on different considerations and uncertainties.

Table 6-1: List of Common Emergency Ports for Different Considerations

Total Cost wrt to road disruptions	eVTOL Transportation Cost	Operating Cost	Demand
j06	*j04*	*j04*	*j04*
j08	*j12*	*j08*	*j06*
j14	*j18*	*j18*	*j08*
j18	*j23*	*j23*	*j12*
j22	*j24*	*j24*	*j18*
j23			*j20*
			j23
			j24

Using the information in Table 6-1, management can easily decide on which locations to select especially when only a small number of emergency ports can be built.



(a) (b)

Figure 6-7: Location of Common Emergency Ports

As shown in Figure 6-7 (a), when considerations include all aspects considered in this research such as the overall transportation cost with respect to road disruptions and uncertainties brought by changes in eVTOL transportation cost, operation cost, and change in demand, the common location would be *j18* and *j23*. In situations where the major concern is more on the overall transportation cost with respect to road disruptions and the change in demand only, locations *j06, j18,* and *j23* can be selected as shown in Figure 6-7 (b). Other combinations can also be considered depending on the needs and considerations of policy makers.

6.3.4. Isolation Cost

As introduced in the earlier chapter, isolation cost is one of the variables that is hard to determine since it involves a lot of considerations such as location, time, weather condition, population, etc. We can also say that in terms of time, isolation cost may increase proportionally with time since the longer the time spent to meet the demands of the affected population, the greater may be the damage and the demands that needs to be met. In Figure 6-8, we can see that an increase in the isolation cost also cause the total cost to increase. If we interpret this in terms of time, the longer the time spent to meet the demands of the population, the higher will be the overall cost of the operation.

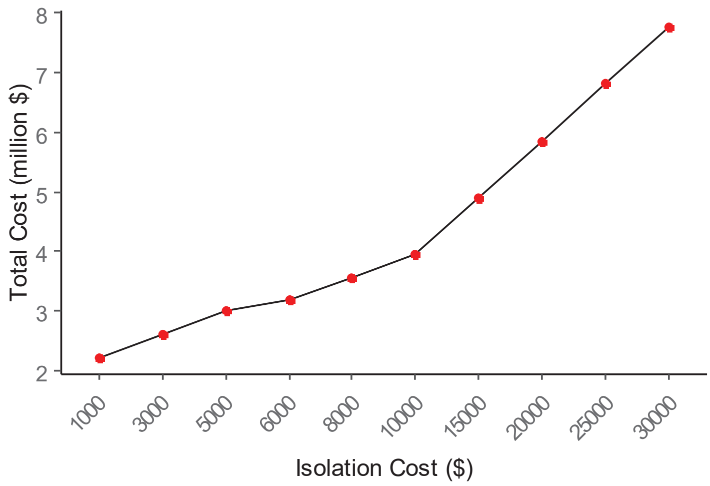


Figure 6-8: Effect of Increasing Isolation Cost

6.3.5. Travel Time Savings and Vehicle Capacity

While reducing the transportation cost of relief goods was the focus of this research, looking at the amount of time that can be saved using eVTOL aircraft and varying vehicle capacity can also be beneficial. Since eVTOL aircraft is not affected by road disruptions, faster travel time can be obtained using this mobility which is also vital during disaster response operations. Also, since the amount of RG that can be transported by each vehicle can affect the amount of time required to meet all the demands, the capacity of each type of vehicle should also be examined. To examine the effect of the varying number of emergency ports and vehicle capacity to the total time of operation, several simulation results introduced in the earlier chapter were compared to the baseline scenario.

To calculate the total time savings for each case, total travel time was compared with the total travel time of baseline scenario. Total travel time was calculated by adding the total time of each mode of transportation that were used. The travel time of each mode was calculated by multiplying the travel time of each mode and the total number of trips performed by each model to satisfy the amount of RG that needs to be transported to each location. Travel time of each mode was calculated by dividing distance with the speed of the vehicle. For this research the speed of the land vehicle used is 40km/hr, while the speed of the emergency helicopter and eVTOL aircraft are 260km/hr and 241km/hr respectively (Kojima et al., 2011; Vertical Aerospace, 2023; Price, 2023). To calculate the number of trips performed by each mode, the number of RG units required in each facility was divided to the capacity of each vehicle. Two comparisons were made as shown in Table 6-2. The first scenario is when the capacity of each vehicle is the same, that is each vehicle can deliver 80 RG units, same capacity of the eVTOL aircraft that was introduced in the earlier chapter. Since land vehicles can have higher capacity, a second comparison was made where the capacity of each land vehicle was set to twice as the initial value which is 160 RG units.

Table 6-2: Comparison of Time Saving Based on the Number of EP

Scenarios	No. of EP	Same Capacity of All Vehicles		Land Vehicle Double Capacity	
		Travel Time (hr)	Time Savings (%)	Travel Time (hr)	Time Savings (%)
Baseline	0	509.47	reference	340.43	33.18
Scenario 2	4	297.46	41.62	207.37	59.30
Scenario 18	5	294.23	42.25	201.60	60.43
Scenario 1	6	287.60	43.55	196.23	61.48
Scenario 74	7	262.51	48.48	180.72	64.53
Scenario 428	8	181.15	64.44	137.97	72.92
Scenario 431	9	165.02	67.61	132.68	73.96
Scenario 476	10	148.10	70.93	113.47	77.73

As shown in Table 6-2, when all relief goods operations are performed by land vehicles only, it took 509.47 hours to finish transporting all the RG to the disaster shelters as compared to the time when emergency ports are introduced and eVTOL aircraft was used to transport a portion of the RG to the disaster shelters. As more emergency ports are added, the total travel time significantly decreased to the point where the total travel time was reduced to more than half. Looking at the percentage of time savings, the use of eVTOL aircraft proves to be very beneficial not only in terms of transportation cost but also in travel time. As the results show, using land vehicles with higher capacity can only lessen the travel time since more RG can be transported at the same time.

While only the capacity of the land vehicle was demonstrated in this example, the same idea also applies to the eVTOL aircraft and emergency helicopters although in real situation, aircraft, in general, has smaller capacity compared to land vehicles. While land vehicle do offer an advantage in terms of larger capacity, looking at the result, the reduction of travel time is more significant when an increase in the number of emergency ports are introduced, in this case, it is still more advantageous to use more eVTOL aircraft to hasten the delivery of RG for longer distances and couple it with land vehicles to reach disaster shelters and for delivering short distance demands.

Note that the calculation of the total travel time and time savings is straightforward and may not totally reflect real situations. This is due to some assumptions that were made and the limitation in the model itself. As mentioned, vehicle routing was not considered in this study and therefore may affect the travel time. Since each vehicle can only visit one location, the amount of RG are fixed and the travel time for smaller number of RG units is the same when the capacity is full compared to where a vehicle can travel to more than one location and the RG can be divided to several location with smaller demand.

Also, since vehicle capacity is also not included in the model, each trip was assumed to be of the same capacity in this case, even if the vehicle can carry more RG, it can only satisfy the demand on one location. Also travel time calculated in this study is only based on one way travel time and since only the travel distance and speed were used other factors such as traffic congestion and loading, unloading, parking, and other activities that takes time was not considered.

6.4. Chapter Conclusions

The sensitivity analysis showed that the number and location of emergency ports may vary due to changes in eVTOL aircraft transportation cost, operation cost, and demand change but some locations are common even with the variation of the said parameters. These locations exhibit characteristics that are tolerant to both the changes in different cost parameters and also to road disruptions since road disruption is also part of the model when the sensitivity analysis was done. Also, isolation cost directly affects the overall cost of transporting relief goods and also dependent on the number of isolated disaster shelters. Since isolation is inevitable, lower isolation cost would be preferable. The total travel time of the whole operation may vary depending on the number of trips performed by each mode as well the vehicle capacity. More trips performed by eVTOL aircraft and larger capacity vehicles are more advantageous to overall operation.

Overall, in can be seen that variation in the cost, demand, travel time, and vehicle capacity play a significant role in choosing a suitable location for emergency ports. Since cost is an important factor in disaster response operation, considering the different cost involved in using the new technology is important. In addition, considering the amount of time that can be saved using the new mobility, reduction in damage caused by disasters can be greatly reduced by timely delivery of RG to the disaster shelters. Using vehicles with higher capacity whenever possible can also be a good consideration not only in terms of travel time but also in terms of transportation cost.

Chapter 7. Conclusions and Recommendation for Future Research

In conclusion, transportation is a primary factor that affects disaster response operations. In particular, land and air transporation is commonly used during disaster response but these mode of transportation have its own deficiencies that can hinder the timely and efficient distribution of relief goods and services to disaster-affected areas. In summary, while looking into these two transportation systems several problems can be identified such as: (1) roads can be disrupted during disaster and can cause increase in travel time due to detouring and low accessibility; (2) land transportation cannot be used to reach isolated places; (3) road disruption patterns are hard to identify before the disruption (4) conventional air transport is expensive; (5) there is low availably of air transport due to complexity in operation; (6) there is a significant increase in demand in air transport that cannot be met; (7) an increase in the use of air transportation will result to additional air, noise pollution and high cost. By finding empirical evidence on road disruption patterns and providing solutions to address road disruptions caused by disasters, a more reliable transportation system can be utilized that can address the problems presented.

Results of the models showed that while both social and natural factors affect the probability of road disruptions and duration of road recovery, natural factors are more dominant with respect to road disruptions, while social factors are the major contributing factor in the duration of road recovery. By providing an insight to better locations, new road infrastructure can be made more resilient to disasters and this can be a basis for future road infrastructure investments and policies.

By focusing on road disruptions, this study introduced another model considering air transportation not as a replacement but as a compliment mode of transportation during disaster response. As mentioned above, while this mode of transportation helps, it also have shortcomings. In the proposed model, the use of new air mobility called eVTOL aircraft was introduced to overcome the said shortcomings not only on the side of air transportation but also in the land transportation specifically road disruptions. Results of the model introduced showed that the new concept presented in the form of facility establishment, is an effective way to solve the existing problems.

With the given parameters, suitable locations for emergency ports considering both the transport cost as well as the condition of the road network was identified by the model. Additionally, the location of the emergency ports has very little variation for each scenario with an average of six emergency ports per scenario. Total cost varies depending on the number of emergency ports chosen as well as the mode of transportation used. The higher number of isolated disaster shelters serviced by conventional air transport such as helicopters results to a higher cost. There is an overall reduction of 8.64% in the number of isolated disaster shelters when the emergency port is introduced in the network. The distribution of transportation mode used to deliver goods and services to the disaster shelters comprised of 53.55% by land, 43.78% via emergency ports, and 0.67% via air (helicopter). While transport cost using eVTOL shows that lower cost promotes the use of eVTOL using emergency ports, in some situations, the need to establish emergency port can still lessen the overall cost of operation since place isolation serviced by conventional air transport still incurs higher cost when isolation cost is considered.

Also, from the results, several advantages can be derived by utilizing eVTOL in a coordinated transportation network in humanitarian logistics, such as the reduction of isolated areas that resulted from road disruptions. By combining land and air networks, the disadvantages of each mode of transport is complemented by the other. This proves that coordination between air transportation and land transportation would yield better disaster response.

The results of this research can help future researchers who would further explore the potential of eVTOL aircraft in disaster response operations in an integrated air-land transportation model. Several areas of improvement suggested for future works includes the use of vehicle routing (VR) model for both air and land transportation of relief goods since currently, only one-to-one distribution was used. This can reflect more realistic scenario particularly in the use of land transportation since generally, land vehicles used for transporting relief goods have higher capacity compared to helicopters and eVTOL aircraft. This can also reflect a change in the transportation cost since visiting one or more disaster shelters using a single vehicle will have a different value compared to a single vehicle visiting a single disaster site.

Also, in this study, only relief goods were demonstrated in terms of transporting while eVTOL aircraft has also the capability to transfer emergency personnel. In this case, further study can extend this model to divide the allocation in terms of both goods and emergency personnel. This may also affect the computation of capacity of the facilities and may also be challenging when added to the vehicle routing since the demand may also be affected. Another improvement may include the change in the demand. Currently only the disaster shelter evacuees were considered in the study, the model can be extended by taking into consideration how to satisfy the remainder of the population which are also affected by the disaster. In this case, the demand side have to change to suit the needs in the model.

Additionally, when treating the model and focusing only on vehicle capacity, the total transportation cost may greatly vary when the capacity of eVTOL aircraft and land transportation vehicle is taken into consideration. The increase in capacity especially for eVTOL aircraft may prove to be more beneficial and economical as an emergency transport during relief operations. As such, further studies addressing this area can be done to test the feasibility of larger eVTOL aircraft since it also proves that there is a huge increase in time savings when there is an increase in the use of these aircraft.

Additional analysis using the model can also be examined such as finding which areas or road links can cause an increase in the total cost or lowers the accessibility and increase isolation rate. As these concerns where not addressed in the current study, further research can be done in this area that can help policy makers to develop plans for infrastructure development where emergency ports as well as critical link locations are considered at the same time. Also, since only the top four highest cost was introduced in the study, additional analysis on the range of total cost can be done to identify possible patterns that cause the variation in the cost and to find more details that can help understand what factors can be considered that can help lower the total cost of operations.

For technical considerations, additional technical constraints can also be considered in the future studies. Currently, battery capacity was considered to be proportional to travel distance of eVTOL aircraft but since other factors may affect battery consumption such as payload weight, environmental condition, and others, it may also be good to include a more detailed battery capacity constraint. Another technical constraint that can be considered are the environmental limitations of eVTOL aircraft such as wind tolerance and terrain considerations. In the current study, these limitations were not considered since it is assumed that weather condition is favorable during the operation and there is no flight cancellation. It is also assumed that the chosen locations are suitable to receive the eVTOL aircraft, so terrain limitations were not considered. Travel speed may also be considered as another constraint since it can also be affected by other variables such as weather condition and payload weight.

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