ESTABLISHMENT OF EMERGENCY PORTS FOR EVTOL AIRCRAFTS FOR ENHANCING DISASTER RESPONSE AND RELIEF OPERATIONS

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Road disruptions due to disasters can result in low accessibility or isolation of disaster sites. To solve this, we proposed to utilize eVTOL (electric vertical take-off and landing) aircraft to expand air transportation network for better and efficient humanitarian activities. Specifically, we propose to locate emergency ports for eVTOL strategically considering road network vulnerability. A mixed integer programming (MIP) model is formulated to select a suitable location of emergency ports for eVTOL considering road network disruption scenarios caused by disasters. The objective is to minimize the cost of transporting the relief goods and emergency personnel from the airports, that serve as emergency hubs, to disaster sites. Numerical examples with different road disruption scenarios are introduced to illustrate the applicability and feasibility of the proposed method.

Key Words : *disaster response, relief operation, eVTOL aircraft, emergency port, road network disruption, airport*

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 systems1). To alleviate this dilemma, 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 operations2). 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 said disaster3),4). 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 history5).

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.

Given the above background, this study aims to take advantage of the current advancement in technology through the introduction of 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 by finding the optimal location of the emergency ports that can be used as a landing and take-off area considering road network disruptions during disasters.

In the coming years, the use of eVTOL aircrafts, commonly known as drone or air taxis, will be integrated as means of public transportation[6]. By utilizing these eVTOL aircrafts not only during normal conditions but also during disasters, the potential of these Unmanned Aerial Vehicles (UAVs) 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[7]. However, as reviewed in the next section, to the authors' knowledge, there is no study considering road network disruption scenarios in determining the eVTOL port locations.

The rest of sections are organized as follows. In Section 2, we review existing studies focusing the used of unmanned aerial vehicles or drones in disaster management. Section 3 introduces the model formulation and numerical example. Section 4 introduces the results, while Section 5 contains the discussions of the study. Section 6 concludes this paper with major findings and remaining tasks.

2. LITERATURE REVIEW

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 application including intelligence gathering, monitoring, and delivery services[8]. One major advantage of utilizing drones in delivery services is the significant decrease in travel time since drones are not subjected to traffic jams or other road disruptions. Studies including Shavarani et al.[9], Farahani et al. [10], Salama & Srinivas[11], Chauhan et al.[12], Dukkanci et al.[13], Wen & Wu[14], and Liu[15] 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[16]. 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.[17] focused 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. Chowdhury et al.[18], on the other hand, used 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 & Ndoma[19] 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.[20] 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 discreet scenarios. Zhang et al.[16] examined 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.

The advancement in drone technology grew even wider in recent years and one of the most sophisticated advancements is the introduction of electric vertical take-off and landing (eVTOL) aircraft as a new public mobility. New research emerged on the potential of this new type of public transportation particularly its integration with air transportation networks. Rajendran & Srinivas[21] 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[22] proposed several urban airspace concepts based on social, safety, system, and aircraft-related factors. This research specifically focused on identifying the strength and weaknesses of each airspace concept since urban air mobility is very new and there is no airspace design currently implemented. Ale-Ahmad & Mahmassani[23] 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.

In past studies including Choi & Hanaoka[24], Qin et al.[25], Polater[26], Choi & Hanaoka[3], and Arreeras & Arimura[27], improving airport operation during disasters have been a primary topic. While these studies offered solutions to existing problems that the airport face during disaster response, these studies focused solely on airport entities and failed to consider other factors such as road disruptions. 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 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 address during disaster response. With the advantages of the upcoming integration of eVTOL aircrafts as new public transportation in air transportation, airports will become more effective emergency hubs. The potential of the new drone technology leads the current research to further explore the usefulness of eVTOL aircraft not only in normal condition but as an asset that can be used during a disaster to transfer not only relief goods but also emergency personnel to disaster sites.

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.

3. RESEARCH FRAMEWORK

(1) Problem Description

This paper considers a disaster response operation that includes airports, emergency ports (EP), and disaster sites as shown in **Fig.1**. The relief operation starts upon receiving the relief goods 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. 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 air transport which will be reflected by the increase in transportation cost. 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.

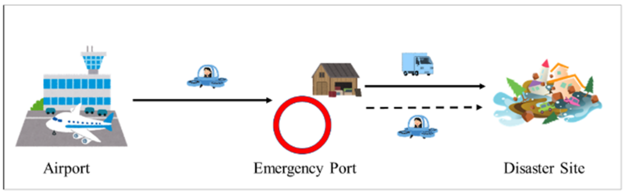

Fig.1 Illustration of Disaster Relief Operation

(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. Studies that developed models based on optimization such as facility location, allocation, assignment, and routing which often aim to minimize travel time and cost or maximize demand, coverage, efficiency, etc. are often used[28)-35)].

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. Based on the network shown in **Fig.2**, the proposed model involves the following indices, parameters, and decision variables.

Set of indices

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

Parameters

F_j	fixed cost for setting up emergency port at candidate location j
C_{ij}^s	Unit transport cost from emergency port j to disaster site i under scenario s
C_{ja}	Unit transport cost from airport a to emergency port j
D_i	Demand at disaster site i
M_j	Capacity of emergency port j
M_a	Capacity of airport a

Decision variables

Y_j	1, if emergency port j is built at candidate location j, 0 otherwise
X_{ij}	Quantity of demand load transferred from emergency port j to disaster site i
X_{ja}	Quantity of demand load transferred from airport a to emergency port j

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

Subject to:

$$\sum_{j=1}^{m} X_{ij} = D_i \qquad for\ all\ i = 1, \dots, n \qquad (2)$$

$$\sum_{i=1}^{n} X_{ij} \le M_j Y_j \qquad for\ all\ j = 1, \dots, m \qquad (3)$$

$$X_{ij} \le D_i Y_j \quad for\ all\ i = 1, \dots, n; j = 1, \dots, m \qquad (4)$$

$$\sum_{j=1}^{m} X_{ja} \le M_a \qquad for\ all\ a = 1, \dots, b \qquad (5)$$

$$\sum_{a=1}^{b} X_{ja} \le M_j \qquad for\ all\ j = 1, \dots, m \qquad (6)$$

$$\sum_{a=1}^{b} M_a \ge \sum_{j=1}^{m} M_j \qquad for\ all\ a = 1, \dots, b; \ j = 1, \dots, m \qquad (7)$$

$$\sum_{a=1}^{b} X_{ja} = \sum_{i=1}^{n} X_{ij} \qquad for\ all\ j = 1, \dots, m \qquad (8)$$

$$X_{ij}, X_{ja} \ge 0 \quad for\ all\ \ a = 1, \dots, b; \ i = 1, \dots, n; \ j = 1, \dots, m \qquad (9)$$

$$Y_j \in \{0,1\} \qquad for\ all\ j = 1, \dots, m \qquad (10)$$

Objective function (1) minimize cost (fixed construction cost, transportation cost). Constraint (2) ensures all demands at disaster site i will be satisfied. Constraint (3) ensures that each established emergency port j has capacity M_j . Constraint (4) ensures all demands at emergency port j will be satisfied based on the demands at disaster site i. Constraint (5) ensures that amount supplied by airport a to emergency ports j does not exceed its capacity M_a. Constraint (6) ensures that the amount supplied by airport a to emergency ports j does not exceed the capacity of the emergency ports j. Constraint (7) ensures that airports a will be able to fulfill the capacity of the emergency ports j. Constraint (8) is the flow conservation constraint for the quantity of goods and services that is transferred from the airport to the disaster sites. Constraint (9) ensures that quantity transferred is non-negative and constrain (10) is the binary constraint to dictate whether the emergency port will be established or not in the candidate locations.

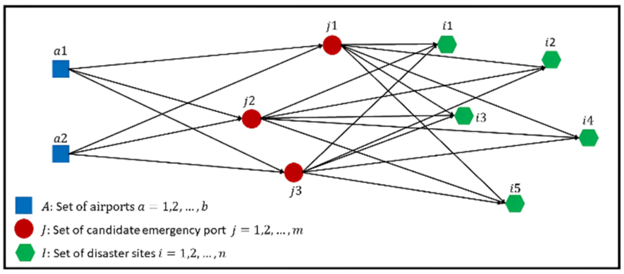

Fig.2 Toy Network Illustration

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 capacity of the eVTOL aircraft and delivery vehicle is not considered; A2) in case there is no shortest path found between the emergency port and disaster site due to road disruption, air transport will be used which is reflected by the increase in transportation cost.

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 **Fig.3**. Network G illustrates the conventional process where goods and services are transferred directly from the airport to the disaster sites.

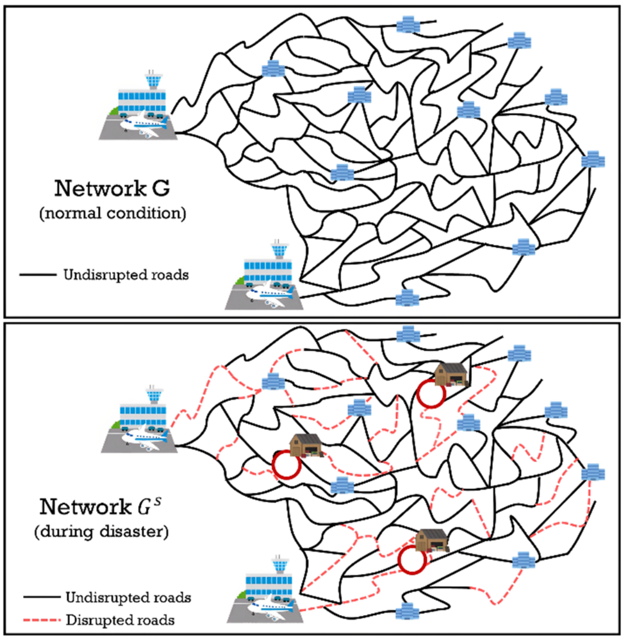

Fig.3 Normal and disrupted network under scenario s

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. 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.

(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 to solve the problem 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.

a) Scenario 0

To illustrate the scenario where no emergency port is established as shown in **Fig.4**, the goods and services received from the airport will be transported directly to the disaster sites using air transport. As such, 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.

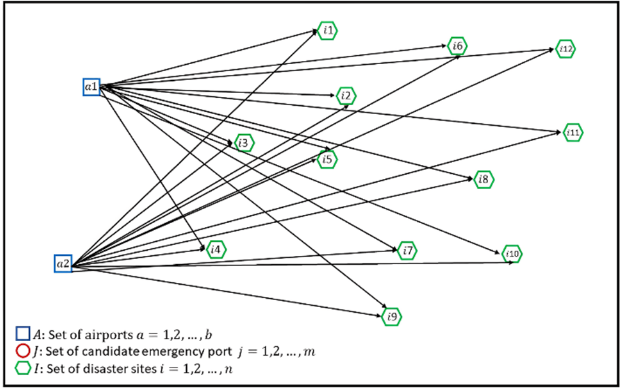

Fig.4 Direct Transportation from Airport a to Disaster site i

$$\min_{\mathrm{X_{ia}}} \sum_{a=1}^{b} \sum_{i=1}^{n} C_{ia} X_{ia} \tag{11}$$

Subject to:

$$\sum_{a=1}^{n} X_{ia} = D_i \qquad for\ all\ i = 1, \ldots, n \tag{12}$$

$$\sum_{i=1}^{n} X_{ia} \leq M_a \qquad for\ all\ a = 1, \ldots, b \tag{13}$$

$$\sum_{i=1}^{n} D_i \leq \sum_{a=1}^{b} M_a \qquad for\ all\ \ a = 1, \ldots, b; \quad i = 1, \ldots, n \tag{14}$$

$$\sum_{a=1}^{b} X_{ia} = \sum_{i=1}^{n} D_i \qquad for\ all\ \ a = 1, \ldots, b; \quad i = 1, \ldots, n \tag{15}$$

$$X_{ia} \geq 0 \qquad for\ all\ \ a = 1, \ldots, b; \quad i = 1, \ldots, n;\ j = 1, \ldots, m \tag{16}$$

Constraint (12) ensures that all demands in disaster

Table 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	-

Table 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

site i can be satisfied. Constraint (13) and (14) are airport a capacity constraints. Constraint (15) is quantity equilibrium constraint while constraint (16) is the non-zero constraint for quantity. **Table 1** shows the parameter values used in scenario 0 to run the optimization.

b) 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 **Fig.5**. Using the parameter values in **Table 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.

c) 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%.

d) Scenario 3

In **Fig.6**, 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.

e) 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 these, transporting goods and services to these sites via land transport is impossible and only air transport is available but at a high cost.

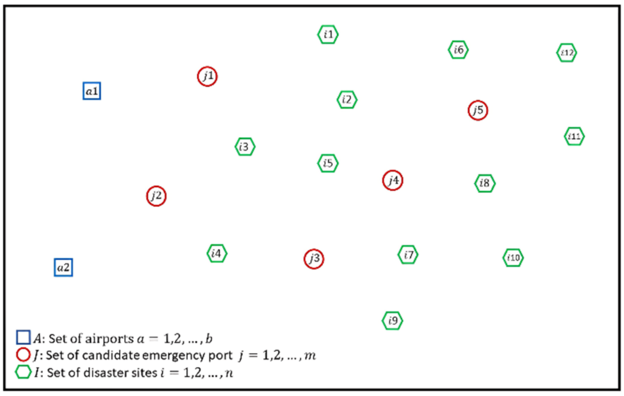

Fig.5 Scenario 1 Problem Illustration

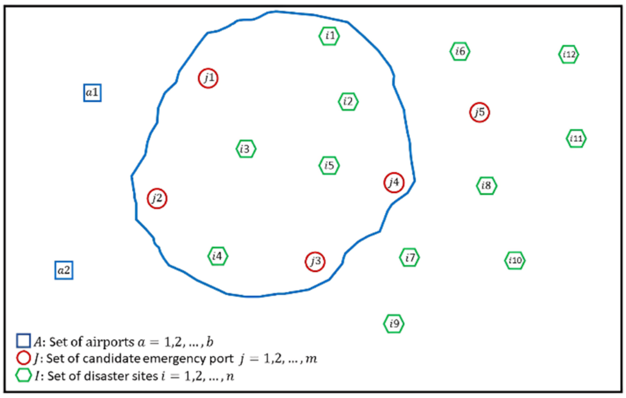

Fig.6 Scenario 3 Problem Illustration

f) Scenario 5

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

4. RESULTS

Table 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*.

Table 3 Result of Scenario 0

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

To visualize the result, **Fig.7** shows the distribution of goods and services from each airport to the different disaster sites.

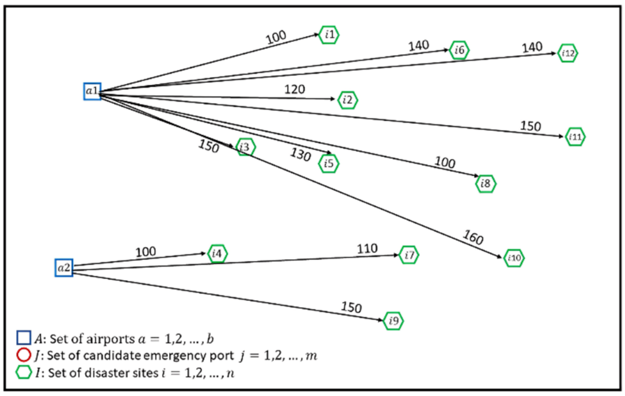

Fig.7 Scenario 0 Optimization Result Illustration

Table 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 (3) 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. **Fig.8** 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*.

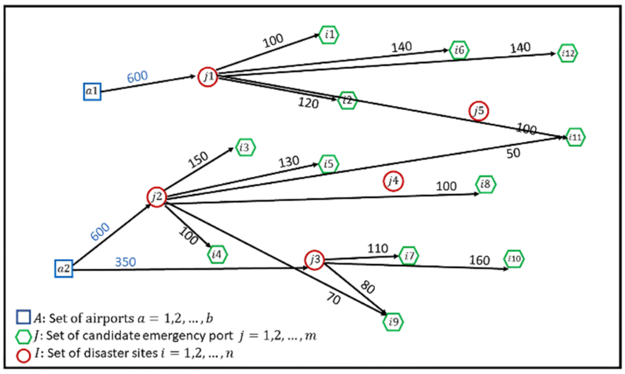

Fig.8 Scenario 1 Optimization Result Illustration

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

Table 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

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.

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.

5. DISCUSSIONS

When comparing the objective function value of Scenario 0 to all other scenarios, the transport cost is very high compared to when emergency ports are built. This implies the importance of building emergency ports for a more efficient and economical humanitarian response since transporting directly from the airport after receiving the relief goods and services yield comparably higher cost. 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 showed 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 near it. 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 shows strength and better serviceability since it connects to more disaster sites based on its capacity. Therefore, for emergency ports in these types of locations, policymakers could consider increasing the capacity to maximize the usage rather than building additional facilities.

6. 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 suitable solution to this problem.

In this study, the effect of road network disruption on the location of the emergency ports was introduced. 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 t disaster areas through emergency ports yields lower transport cost and maximized 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 more 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[36)] implemented using Monte Carlo Simulation analysis can be used. Possible scenarios can include random link failures and targeted link failures such as intentionally removing links with high centrality index or removing links based on road types.

Also, in situations where there are many candidate locations, it is advisable to place additional constraints such as limiting the total number of emergency ports that will be establish or adding a budget constraint since one of the concerns in establishing new facility for policy makers is budget. 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.

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