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A mathematical model to optimize debris clearance problem in the disaster response phase: A case study

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Abstract

The post-disaster response phase aims to reduce casualties by accessing critical areas to transfer relief aid, search and rescue operations to the injured as soon as possible. Debris from the disaster blocks roads and prevents rescue teams from reaching critical areas. It is crucial to decide which routes should be cleared for relief aid transportation to reduce the negative effects of the disaster. In this study, a model for debris removal is presented to minimize access time to critical areas such as hospitals and maximize coverage of the areas. The AUGMECON 2 method has been used to solve this problem. Also, the efficiency of this solution method in Tehran has been studied, and its results have been analyzed. The results of this study indicate the importance of considering a comprehensive plan and several sites for debris removal in the disaster response phase.

Keywords: Debris removal, emergency relief, disaster management

1- Introduction

A disaster is an event that can cause physical damage, destruction of buildings, loss of life, or significant changes in the natural environment (Tavakoli, Rabbani and Bozorgi-Amiri, 2017). According to the American Red Cross, a disaster can be defined as a natural or human-made occurrence, which creates some trouble for humans and causes human suffering that victims cannot relieve themselves. The type of disasters has been shown in Fig with details (Wang, Hsieh and Huang, 2018).

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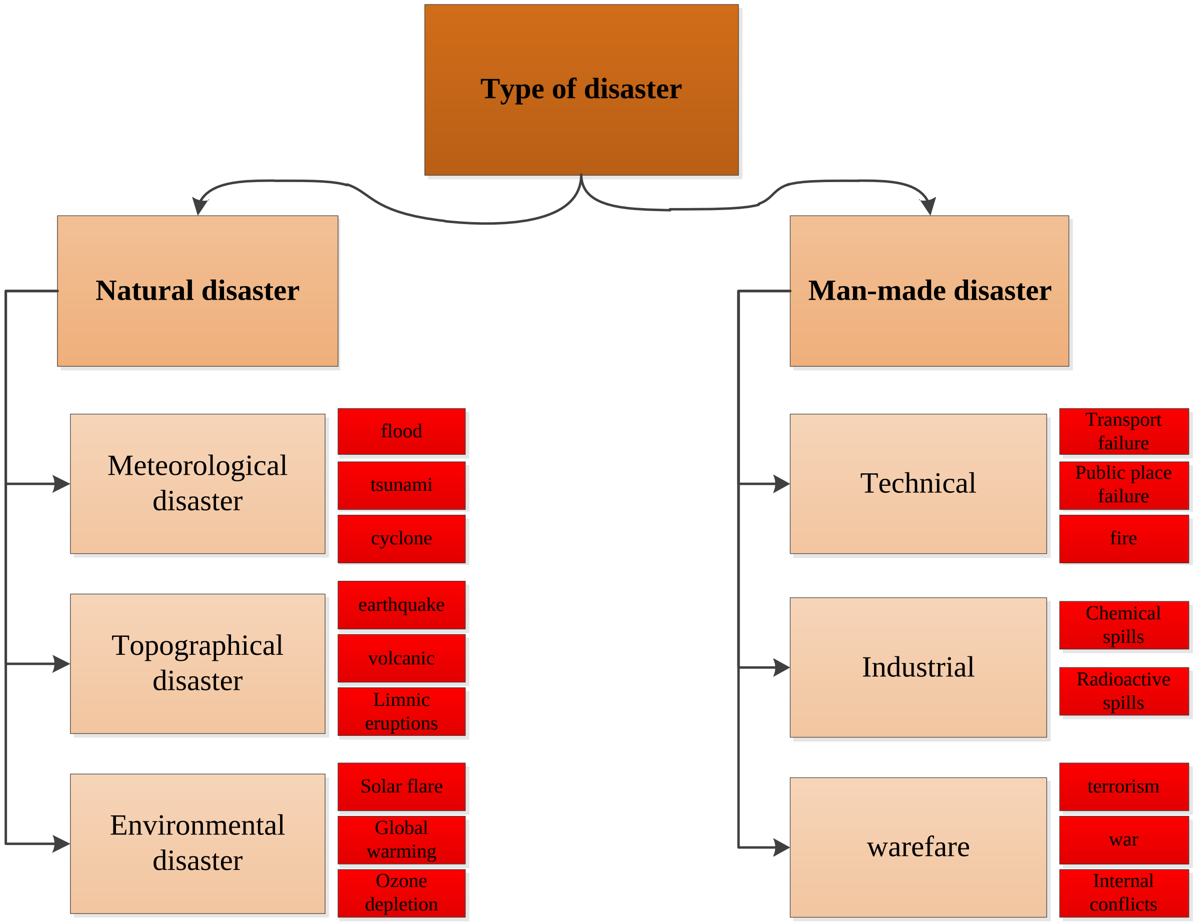

Fig 1. Types of disaster

Earthquake is one of the most critical disasters inevitable. According to the International Institute of Seismology and Earthquake Engineering in Iran, more than fifteen destructive earthquakes have occurred since 2008 in this country that caused many deaths and financial losses. For this reason, Iran is among the top ten countries in the world at risk of natural disasters.

The Haiti earthquakes in North America, Indonesia earthquakes and tsunamis, China's Tangshan earthquakes, Bam earthquakes, Lorestan floods are all reminiscent of the natural disasters that have hit some communities and countries. Many people are losing their lives, property, and family every year due to natural or human disasters. Especially in underdeveloped and developing countries, the impact of these events is more significant because these countries lack preventive strategies to prevent, warn, mitigate, and control disasters (Moe and Pathranarakul, 2006). However, it may not be feasible to stop hazardous events. Also, efficient disaster management will be an obstacle (Bang, 2014). As mentioned earlier, disasters occur in four phases, as shown in Fig . Disaster preparedness refers to actions taken to prepare for and diminish the effects of disasters. That is, to predict and stop any disasters, decrease their impact on vulnerable populations, and respond effectively to their outcomes. In response to a disaster, the Post-disaster initiatives to achieve early recovery and rehabilitation of affected fatalities and communities include Response, Recovery, and Reconstruction. Furthermore, mitigation defines a sustained action that reduces or expurgates long-term risk to people and property from natural hazards and their effects. The mitigation phase of emergency management differs from the other phases in that it focuses on long-term measures for reducing or eliminating the risk.

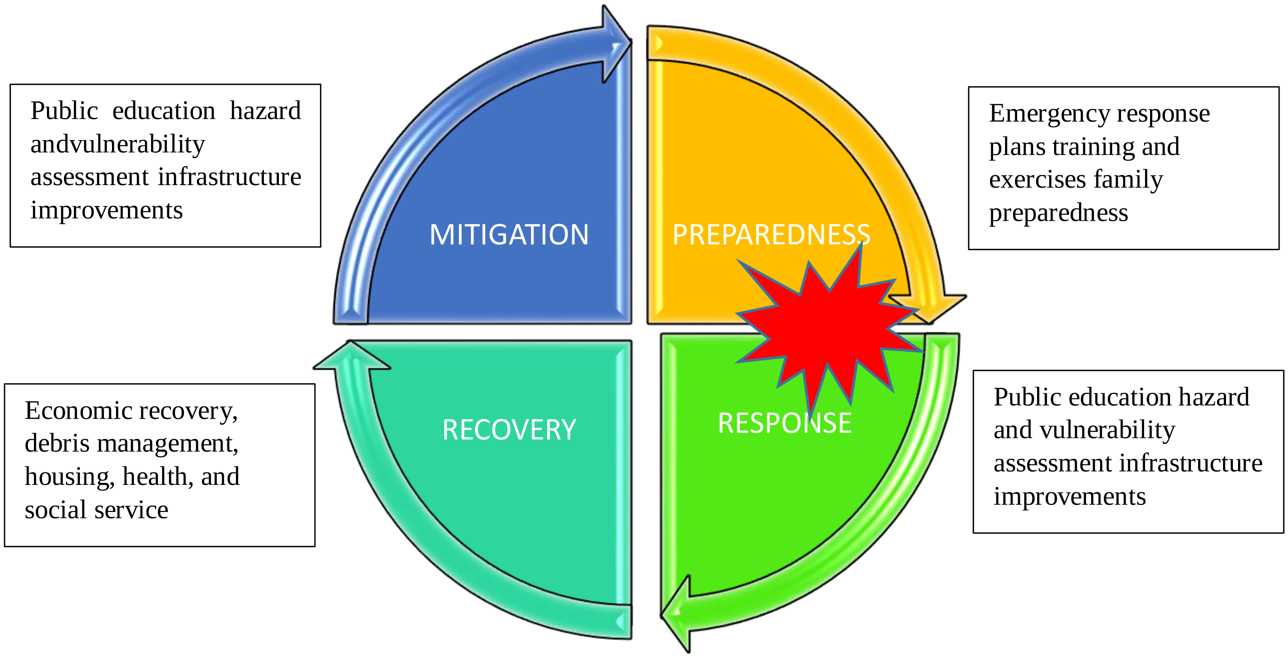

Fig 2. Disaster cycle

Experiences from past events show that much of the relief phase is related to logistics. For example, During the Haiti earthquake in 2010, the airport's lack of fuel and limited ramp space prevented humanitarian flights from entering (Murphy, 2010), or The debris may block part or all of the waterways and create undesirable hydraulic conditions that will cause the foundation of the docks and bridge ditches to be destroyed and other structural damage (Chang and Shen, 1979). So getting rid of debris is an important issue that can result in high costs or even new disasters if not acted.

Thus, a fast reaction after a disaster is significant. If we have a calculated and planned response after a disaster, we will avoid any cost of living and finance.

These questions arise if an accident occurs and the roads are blocked.

1. What is the path to reach essential places?

2. How to clear blocked paths from debris?

3. How to access the affected areas in the shortest possible time?

To answer these questions, we propose a mathematical two-objective model for the clearance of debris caused by disasters. Objective functions of the model are minimizing the time to reach the critical node and maximize coverage of the areas. An important question that arises is road structures that we named arc by which priority should clean? So should take attention to attributes introduced from expert comments for road clearance and prioritize the road with high priority. For more realism, we consider weight for nodes that distinguishes the nodes' importances from each other. The carriers of transfer debris will be heterogeneous; also, their capacity and cost will be different.

The study continues as follows: section 2 provides an overview of the literature relevant to the problem. In section 3, we will detail the problem at hand. Section 4 indicates the solution method and section 5 looks at a case study's numerical examples and sensitivity analysis. Finally, in section 6, the references of research are shown.

2- Literature review

The research on disaster management can be divided into three sections: pre-disaster, during a disaster, and post-disaster. Cities at risk of natural disasters need to plan and be prepared before disaster strikes, for example, Cities located at fault and earthquake zones like Tokyo, Jakarta, and Manila. Discussions on this topic fall into the pre-disaster area. Fig shows a selection of activities to be made before, during, and after a disaster.

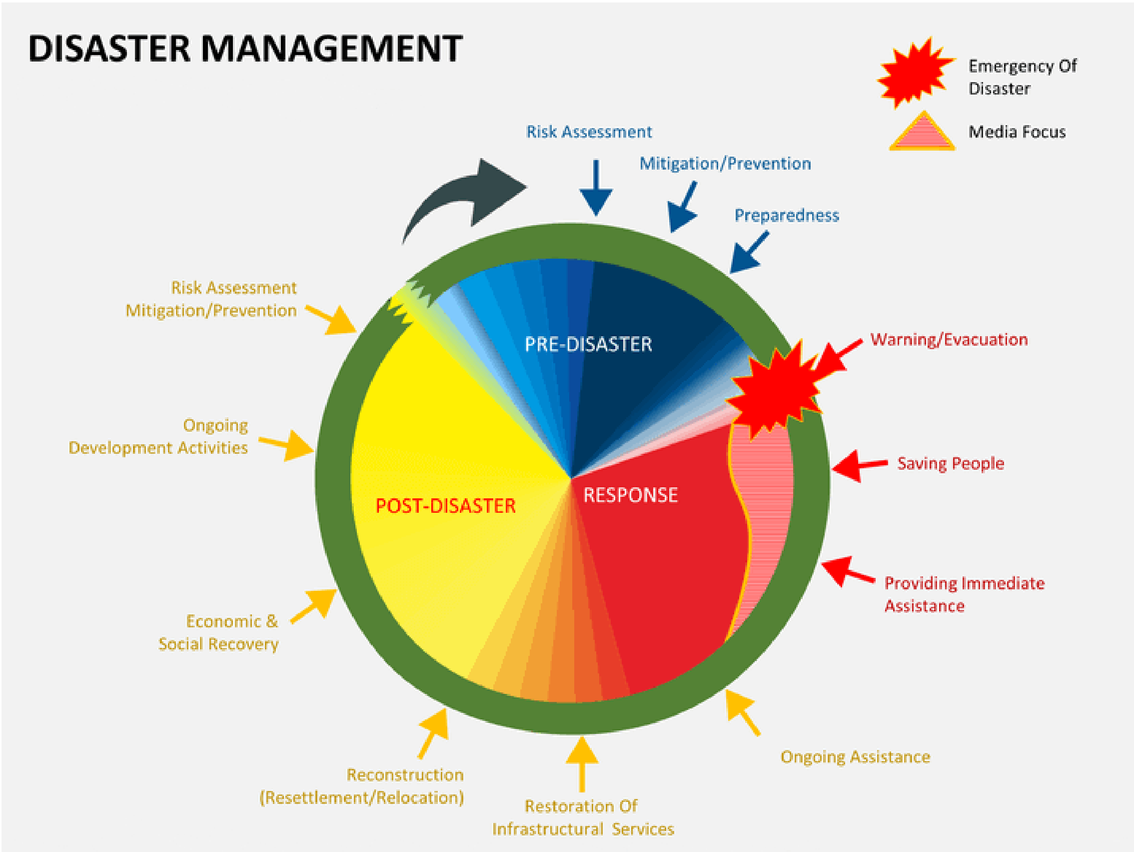

Fig 3. General scheme of disaster management (www.sketchbubble.com)

2-1- Pre-disaster

Pre-disaster activities focus on reducing the property and human losses caused by a potential hazard. Some researchers are looking for methods to reduce disaster risk by identifying and assessing the threats, assessing the vulnerability of critical, prioritizing risk reduction measures based on strategy, etc. Moe and Pathranarakul (2006) introduced an integrated approach to successful and effective disaster management in this context. The integrated approach includes active and reactive strategies to manage disasters before, during, and after the period. In times of disaster, the integrated approach has a high impact on saving lives. Their paper also provides a framework for the impact of crisis management - identifying a set of appropriate and successful crisis factors for disaster management. The research of Perry (2007) Discusses the use of advanced technologies ineffective crisis management systems. New technologies for disaster management systems include sirens, amateur radio, and community radio and SMS services. But the leading technologies include satellite radio, Information and Communication Technology (ICT), Internet of Things (IoT), big data, and deep learning. They discussed the strengths and weaknesses of possible solutions for effective disaster management using multiple technologies and presented a wide range of technologies for effective disaster management.

Wei et al. (2008) introduced the decision support system. Using modern technology, the system delivers human decision-making to reduce multi-functional artificial use, debris flow monitoring, information transfer, disaster and prediction and alarm, disaster forecasting, evacuation, and rescue. As a result, this system can be used to estimate natural disasters and hazard zone and rescue that increase the degree of response to natural disasters. Due to natural disasters in Japan and the damages they caused, Hirayama et al. (2010) developed an estimation method for assessing waste from disasters such as floods and earthquakes. Their method allows for proper planning before the accident to give a proper response during the accident. (Grzeda, Mazzuchi and Sarkani, 2014) have noted in their research that one of the essential components for disaster planning and preparation for them is identifying and selecting interim disaster debris management sites. And a pre-disaster approach in identifying the most likely sites based on the number of locational constraints would significantly contribute to disaster debris management planning. At the end of this study, a binary cluster analysis method was used to identify potential debris management sites in a case study in Hamilton County, Indiana. Crowley (2017) studied about effects of the debris management plans before disaster and Comparison between the counties that do and do not these plans. They tried to identification the Advantages of pre-disaster debris management plans. Félix, Monteiro, and Feio (2020) provided a technique for estimating temporary housing unit demands before disaster based on the modified Mercalli Scale, with the goal of forecasting requirements in terms of space and resources to supply interim dwelling units following hypothetical earthquake damage and destruction scenarios. Monzón, Liberatore, and Vitoriano (2020) proposed a pre-disaster Humanitarian Logistics stochastic model that optimizes the prepositioning of helping distribution centers and the strengthening of path sections to guarantee that the maximum number of people impacted may get assistance as quickly as possible. According to their suggested stochastic model, the demand in disaster-affected areas and the transportation network's status are unpredictable. Their technique has been tested in a real-world case study based on the 2018 storm system that struck Mozambique's Nampula Province. Modica, Paleari, and Rampa (2021) in Their research study Since there is a lack of readiness for dealing with disaster debris, the goal is to look into how the present Italian regulatory framework may be improved to improve communities' ability to deal with earthquake debris. They concentrate on a study area that is growing more important as the quantity and severity of natural catastrophes increase but is yet underappreciated. Rezaei et al. (2021) studied an order allocation and supplier selection model with disruption and environmental risks of each region such as earthquakes, floods, hurricanes, etc., in a centralized supply chain.

2-2- During and post-disaster

Some scholars have examined the issues during and after the disasters and made suggestions to improve them. Salamati Nia and Kulatunga (2017) have addressed the issue of hospital disaster management during disasters. In the event of any disaster, it is important for hospitals to stay healthy. Therefore, it is essential to be aware of the necessary actions for the event of a disaster to take them if necessary. In this study, they suggest appropriate measures in the light of previous disasters that are useful in maintaining the hospital and serving the population during the disaster. Mohamadi and Yaghoubi, (2016) presented a multi-objective location-allocation model to select the best hospitals' locations for the quick reaction for treating injured people and the best locations as depots for medicines and medical equipment. Sabouhi, Heydari, and Bozorgi-Amiri, (2016) introduced a multi-objective model for scheduling and routing vehicles in the post-disaster phase to maximize vehicles' total arrived time and minimize the number of vehicles. After a disaster, debris clearance and selecting the right way are the most important issues for accessing vulnerable areas and cleaning and handling them. The following are some of the studies by researchers in this field.

Humanitarian logistics has paid much attention to post-crisis issues (for example, Danesh Alagheh Band, Aghsami and Rabbani (2020), and Setiabudi and Wydiadana (2019)'s article); however, the issue of debris clearance has been less favored than other issues. Debris Clearance is a comprehensive issue that is not just about natural disasters, such as Fan et al. (2016)'s article was on space debris and how to eliminate it. They pointed to a laser-based approach and introduced it. Or in another article, waste from construction is seen as debris (Ram, Kishore, and Kalidindi, 2020). Federici, Zavoli and Colasurdo (2021) studies looked at how to construct the best active debris removal mission possible. The mission aim was to maximize the cumulative score of the cleared debris, which was assigned a quantitative value based on its threat level. The optimization problem, similar to a Time-Dependent Orienteering Problem, was stated as a graph search problem, and an optimum tree search method was used to solve it.

Considering uncertainty, with the multi-period nature of the problem, can add significant complexity and make accurate methods impossible for real-world examples. To overcome this Çelik, Ergun and Keskinocak (2015) proposed a heuristic that relaxed the multi-period nature of the decision-making process and developed solution methods that incorporated regional information updates. They characterized the situations that employing regional updates improve the solutions. Fetter and Rakes (2012) presented a quantitative model with recycling motivations for locating temporary disposal and storage reduction (TDSR) facilities. They aimed was to support disaster debris cleanup operations to identify the differences between typical solid waste disposal and disaster debris cleanup and develop a facility location model that incorporates the Federal Emergency Management Agency's (FEMA) new recycling motivations and assists disaster management coordinators in locating TDSR facilities. Fetter and Rakes (2013) presented a multi-objective and mixed-integer model to help decision-makers allocate resources in debris clearance operations after the disaster. That incorporates the unique assumptions, objectives, and constraints of post-disaster debris clearance. Habib and Sarkar (2017) researched in a two phases framework provided for sustainable debris management during the response phase of disasters. In the first phase, using a combination of multi-criteria decision-making techniques (ANP and fuzzy TOPSIS), they selected the best suitable locations among available places as Temporary Disaster Debris Management Site. In the second phase, they developed a framework of the debris allocation optimization model in which fuzzy possibilistic programming can be used to deal with high-level uncertainty during post-disaster environments. Ajam, Akbari and Salman (2019) presented an after-disaster route clearance problem to determine an optimization route for work troops responsible for clearing the block roads. To determine the total time and minimize the running time, they proposed a mixed integer model to minimize the total time of reaching the critical location. They also developed a heuristic method to solve the proposed model on a transformed network and a lower bounding method to evaluate the optimality gaps. Furthermore, they developed a metaheuristic method based on GRASP and VNS. Momeni et al. (2019) developed a humanitarian relief supply chain model considering repair groups, reliability of route, and monitoring operation before distributing relief items in different steps. Aydin (2020) research about finding a landfilling area for debris of earthquakes in Istanbul to decrease the earthquakes' effects by considering the renovation of old buildings and creating an optimal plan to reuse or recycle the debris during the subversion of the old buildings. And finally, they developed a stochastic multi-objective mathematical model to combine environmental and social matters. Hooper (2019) investigated the dynamics of debris clearance by studying how organizations' reactions to the 2010 Haiti earthquake. According to studies by Sharma et al. (2019), the most important factors for locating temporary blood facilities in the post-disaster term are response, time, and easy accessibility. The purpose of this study was to find suitable locations for temporary blood centers. They located these centers by considering the shortest distance from the hospital. They calculated the optimal number of blood centers using the Tabu search and considering the cost component. In addition, they used a Bayesian belief network to prioritize the factors for locating the temporary blood facilities. (Abazari, Aghsami and Rabbani, 2020) Introduced a mixed-integer nonlinear problem with four objective functions considering uncertain parameters. That model determines the number of relief items that should be transported to demand points after a disaster occurs. This model's objective functions, minimize the distance traveled by relief items, total costs, and the maximum time between relief items and demand points. Akbari and Salman, (2017) research the arc routing problem to address road clearance problems after a disaster. They introduced an efficient solution to produce a coordinated program for road clearance teams. Their model ensures that no clearance teams cross the closed roads unless the roads are cleared. In addition, they proposed a metaheuristic that is based on a MIP-relaxation and a local search algorithm. Given that disaster relief activities are disrupted by the presence of damaged roads, Sanci and Daskin (2019) Presented a model to perform rescue distribution and network repair activities simultaneously. To do this, they proposed a two-stage stochastic programming model. They then proposed a sample average approximation way with concentration sets adapted from Rosing and ReVelle (1997) Heuristic Concentration to efficiently solve the proposed model. Sayarshad, Du, and Gao (2020) offered a queuing model for a dynamic debris clearance problem, which allowed them to analyze clearing equipment requests and response times under uncertainty. They employed a method for creating a dependent Dirichlet process that benefited the inherent relationships between a Poisson and a Dirichlet process, allowing for a more realistic calculation of belief probabilities. In the aftermath of a disaster, study of Cheng, Zhu, Costa, and Thompson (2021) evaluated a waste clean-up system that included demolition, waste collection from customer nodes to temporary hazard waste management places, processing at temporary disaster waste management sites, and transportation of the trash to last disposal locations. A multi-objective mixed integer model was created to reduce the entire clean-up cost and time and tackle the problem. Three distinct techniques were created and tested using fake cases and a genuine case study. Their findings showed that the proposed models might produce near to optimum answers in a reasonable amount of time. (Cheng, Zhu, Costa, Thompson, and Huang, (2021) created a model that considers the use of Temporary Disaster Garbage Management Sites, which may hold and process garbage before transporting it to ultimate disposal sites, to reduce the cost and time of disaster garbage clean-up. Their research offers a mixed-integer program using a Genetic Algorithm to model and solves the problem. Finally, computational tests revealed that the proposed GA's performance is stable, that using Temporary Disaster Waste Management Sites can reduce total garbage clean-up cost and time.

As the occurrence of natural disasters or accidents causes the obstruction or interruption of road traffic connectivity and influences the transportation of necessary materials, especially for cross-regional delivery under emergencies, COVID-19 forced government managers to establish cross-regional quarantine roadblocks to reduce the risk of virus transmission caused by cross-regional transportation. According to this, Wang, Peng and Xu (2021) built a bi-objective mixed-integer programming model based on state–space-time networks to optimize truck routes to fulfill customer requests for vital supplies at the lowest cost and fastest emergency response time possible with restricted transportation resources. They suggested a two-stage hybrid heuristic approach to identify good-quality solutions to the problem. They used a 3D k-means clustering technique that took into account time and space indices to get their clustering findings. They tested the effectiveness of the suggested model and algorithm on a real-world situation in China.

It seems in the previous study about debris removal in the post-disaster phase; little attention has been paid to the importance of places and priority of debris removal. This issue makes inadequate priorities to clear the blocked road and deal with the disaster-affect area when a disaster occurs.

In this literature review, we have seen a series of studies of disaster by researchers. In this study, we intend to address one goal that matters post-disaster and in the disaster response stage. That is, reducing access time to critical areas after disasters such as earthquakes despite roads blocked by debris. In this regard, we intend to consider cases that have not been addressed in previous studies. Our areas in this study have different priorities because it is better than prioritizing the regions in the real problem. By doing this, we can handle more essential areas sooner. So in this study, we want to reach an optimized route. This optimal route is under the influence of many items as the weight of the areas, block arc, transferring times, etc.

3- Problem description

We must know that the main purpose of disaster management is to minimize the negative impacts and prevent the loss of life of the human. In this context, the existence of systematic debris removal at the response stage is critical (Şahin, 2013). That is why the issue of debris clearance is important. After disasters such as earthquakes, floods, storms, tsunamis, etc., roads connecting to important centers such as hospitals, firefighters, and other important centers like houses that have been damaged, and some were there. We want to reach the affected areas by road. In serious cases, these damages are such that they have to be repaired and prepared for crossing to reach important centers. The critical centers are called critical nodes, and the paths represent the arcs of a network. This network or graph covers the entire system under study. In order to optimize time and cost, it is important to decide on which path to reach the critical nodes and decide on the route to be taken. All of this is "debris clearance in response phase".

In the aforementioned network, after the disaster occurs and some of the arches (roads) are blocked, we assume that the affected arches are known, and we are aware of them. The model decides which one to use to reach critical nodes.

G = (N, A) is a complete symmetric graph in which N is the set of nodes, which contains the set of non-critical nodes (NC) and the set of critical nodes (C). A represents the set of grid arcs. s represents the supply point. The time required to cross the arc (i, j) is t_{ij}, and the parameter I_{ij} gets set to 0 if the arc (i, j) is blocked. Otherwise, it gets a value of 1. The time spent trying to clean a blocked arc is measured in time is shown by c_{ij} for the arc (i, j). So the required time to cross the blocked arc (i, j) is $t_{ij} + c_{ij}$ for the first time. We assume that a blocked arc will remain open after clearing and will not be blocked again. A certain number of vehicles are stationed at zero time. Each of these vehicles begins to scroll through the arcs to the critical nodes after the disaster (Berktaş, Kara and Karaşan, 2016). The transport capacity at the time of debris clearance is limited. Because trucks have a certain capacity depending on their type, this capacity is by weight. That is the maximum portable weight. These carriers are heterogeneous.

Nodes are weighted according to their importance, which determines their priority. And the budget allocated to the removal work is limited. This budget constraint brings us closer to reality and simulates the crises and hardships of a real disaster in our model. Because one of the most important issues after a disaster occurs is sufficient funding. Otherwise, rescue and displacement work will be slow, and losses will be higher. Our major goal is to minimize the time needed to clear the road leading to reach the critical node as quickly as possible and maximize access to damaged areas and routes between them. We will try to achieve this by providing a mathematical model.

3-1- Problem setting of debris removal in the response phase

Quick handling of damaged areas is an essential duty in the urban management system. Because with the help of fast processing, relief can be accelerated, and more financial and human losses can be prevented. Experiences showed in many cases after an accident occurred and buildings and houses, road structures also face some problems. Road structure such as city streets, transport roads, bridges, culverts and etc. has a vital role in disposal, rescue, recovery, and reconstruction after an accident occurred (Gajanayake et al., 2018). At this moment, the road structure needs to be cleaned until receiving aid and transporting the injured.

In this study, we addressed the issue of debris clearance from road structures. From now on, we named road structure, arc and block road structure, blocked arc. Consider the network in figure 4. In this network, there are 3 nodes $\{i, j, k\}$ that connect to each other with arcs (j, k) and (i, k) and (i, j). This network is a complete and symmetric graph $G = (N, A)$. N expresses nodes, and nodes can be critical (C) or non-critical (NC). Critical nodes are the nodes that must be addressed. And non-critical nodes are the node that isn't necessary to address them, but they exist. For simplicity in modeling, we duplicated graph G according to graph $G' = (N', A')$ as shown in figure 5. New nodes (i', j', k') indicate the nodes that was visited before.

The critical nodes are different in terms of location and access. The importance of areas can be different together and determines the priority of addressing the needs for areas. For this reason, the areas have different priorities. Experts introduce attributes that, with them, we can weigh the areas. Therefore, we can consider different weights for them, and this weight shows the weight of each node relative to other nodes. The method to achieving weights is indicated in the next part.

In the following, we will address the proposed model for clearing debris from the blocked arc. Our goals are minimizing the time to reach each node and maximize the coverage of nodes and the volume of debris. We considering the weight of nodes when we minimize the reach time; by this way, we can reach to nodes that have high weight early. And with maximizing coverage, we can access more nodes as much as possible. For this reason, we will develop the model with two goals shown in the model.

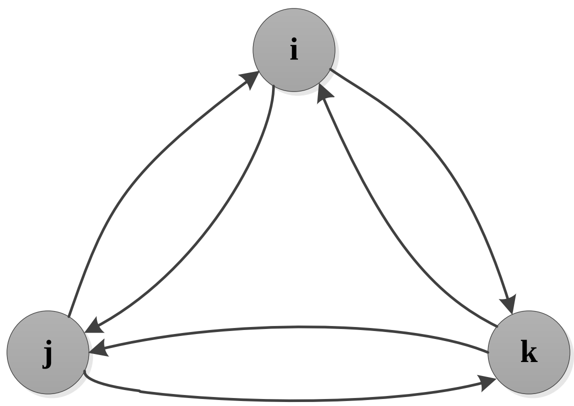

Fig 4. Original network G=(N,A) (Berktaş, Kara and Karaşan, 2016)

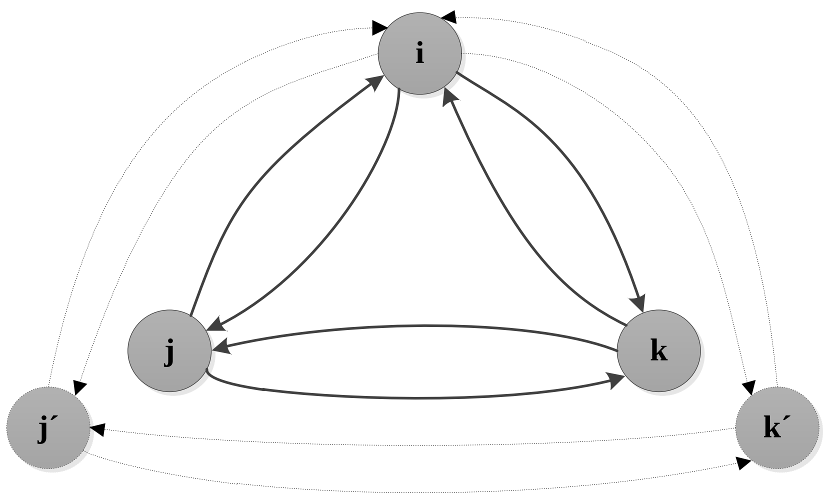

Fig 5. New network where dotted nodes and arc are artificial (Berktaş, Kara and Karaşan, 2016)

3-2- Model assumption

1- Arcs have different weights, and they have priority over each other.

2- Requirement budget calculate in the model, and at the end, we can compare the calculated budget with the available budget.

3- We can use different types of vehicles with different capacities and costs.

4- Nodes are divided according to whether they are critical or non-critical. Critical nodes should be visited, but it is not necessary to visit non-critical nodes.

5- Vehicles start at the station and never return.

6- Blocked arc and time to remove them are known.

7- The time to remove the arc is trapezoidal fuzzy, and this time, regardless of the type of vehicle.

3-3- Nomenclature

notation:

S	Stations
C	Critical nodes
C'	Duplicate critical nodes
NC	Noncritical nodes
N'	Duplicate nodes
NC'	$NC \cup C'$ original noncritical nodes and duplicate critical nodes
V	Vehicles

Parameters:

cap_v	Capacity of vehicle type V
de_{ij}	Quantity of debris in the arc (i, j)
$cost_{ijv}$	Cost of clearance of the arc (i, j) by vehicle $v \in V$
t_{ij}	Time need to transfer the arc (i, j)
ct_{ij}	Time need to clearance the arc (i, j)
I_{ij}	$\begin{cases} 0, & \text{if arc } (i,j) \text{ is blocked} \\ 1, & \text{otherwise} \end{cases}$
w_k	Weight of each node $k \in C$
τ_c	Sum of critical nodes
vc_v	Cost of vehicle type $v \in V$

Variables:

y_{klv}	$\begin{cases} 1, & \text{if } l \in C \text{ is the first critical node visited after } k \in C \\ 0, & \text{otherwise} \end{cases}$

x_{ijv}^{k}	$\begin{cases}1, & \text{if } (i,j) \in A' \text{ is traversed while going to } k \in C \text{ from the prior critical node} \\ 0, & \text{otherwise}\end{cases}$
v_{ijv}^{k}	$\begin{cases}1, & \text{if (i, j) } \in \text{A}' \text{ is cleaned to reach critical node k} \in \text{C} \\ 0, & \text{otherwise}\end{cases}$
a_{klv}	$\begin{cases}1, & \text{if } l \in C \text{ is visited after } k \in C \text{ } 1 \\ 0, & \text{otherwise}\end{cases}$
r_{kv}	Time that node $k \in c$ is reached by vehicle v.
C_{kv}	Time spent to reach node k ∈ C\{s} from the prior critical node by vehicle $v \in V$ (the time required for debris removal not included).
n_v	number of vehicles required from type $v \in V$
$budget$	Budget required for removal the arcs

3-4- Mathematical model

$$\min \sum_{\forall v \in V} \sum_{k \in c \setminus s} w_k r_{kv} \tag{1}$$

$$\max \sum_{ij,k \in c \setminus s} \sum_{v \in V} x_{ijvk} de_{i,j} / \tau_c \tag{2}$$

s.t.

$$\sum_{j \in NC' \cup \{l\}} x_{kjv}^{l} = y_{klv} \qquad \forall\, k,l \in C, k \neq l \tag{3}$$

$$\sum_{i \in N'} x_{ijv}^{k} - \sum_{h \in NC' \cup \{k\}} x_{jhv}^{k} = 0 \qquad \forall\, k \in C, \forall\, j \in NC' \tag{4}$$

$$\sum_{i \in N'} x_{ilv}^{l} = 1 \qquad \forall\, l \in C \setminus \{s\} \tag{5}$$

$$C_{l,v} = \sum_{i,j \in N'} x_{ijv}^{l} \tilde{t}_{ij} \qquad \forall l \in C \setminus \{s\} \tag{6}$$

$$\sum_{\forall v \in V} (y_{klv} + y_{lkv}) \leq 1 \qquad \forall k,l \in C, k \neq l \tag{7}$$

$$\sum_{v \in V} \sum_{k \epsilon C : k \neq l} y_{klv} = 1 \qquad \forall l \in C \setminus \{s\} \tag{8}$$

$$\sum_{v \in V} \sum_{k \epsilon C, l \epsilon C \setminus \{s\} : k \neq l} \sum_{l \in C} y_{klv} = |\tau_c \setminus \{s\}| \tag{9}$$

$$\sum_{v \in V} \sum_{l \epsilon C : k \neq l} y_{klv} \leq 1 \qquad \forall k \in C \tag{10}$$

$$a_{klv} \geq y_{klv} \qquad \forall k, l \in C, v \in V \qquad (11)$$

$$a_{klv} + a_{lkv} = 1 \qquad \forall k, l \in C, v \in V, k \neq l \qquad (12)$$

$$a_{mlv} \geq a_{mkv} + y_{klv} - 1 \qquad \forall k, l, m \in C, \forall\, v \in V, k \neq l \qquad (13)$$

$$a_{slv}=1 \qquad \forall l \in C\backslash\{s\}, \forall v \in V \qquad (14)$$

$$r_{sv} = 0 \qquad \forall v \in V \qquad (15)$$

$$r_{lv} \geq r_{kv} + c_{lv} + \sum_{i,j \epsilon N: i<j} v_{ijv}^{k} ct_{ij} - (1 - y_{klv})M \qquad \forall k \in C, \forall l \in C\backslash\{s\} \qquad (16)$$

$$\sum_{v \in V} \sum_{l \epsilon C\backslash\{s\}} v_{ijv}^{l} \leq 1 - I_{ij} \qquad \forall i, j \in N: i < j \qquad (17)$$

$$2 - \sum_{\forall v \in V} v_{ijv}^{l} \geq \sum_{\forall v \in V} x_{ijv}^{k} + x_{jiv}^{k} + x_{i'jv}^{k} + x_{ji'v}^{k} + x_{j'iv}^{k} + x_{ij'v}^{k} + x_{i'j'v}^{k} + x_{j'i'v}^{k} + a_{klv} \qquad \forall i, j, k, l \in C: i < j, I_{ij} = 0, k \neq l \qquad (18)$$

$$2 - \sum_{\forall v \in V} v_{ijv}^{l} \geq \sum_{\forall v \in V} x_{ijv}^{k} + x_{jiv}^{k} + x_{i'jv}^{k} + x_{ji'v}^{k} + a_{klv} \qquad \forall i, k, l \in C, j \in NC: i < j, I_{ij} = 0, k \neq l, \forall v \in V \qquad (19)$$

$$2 - \sum_{\forall v \in V} v_{jiv}^{l} \geq \sum_{\forall v \in V} x_{ijv}^{k} + x_{jiv}^{k} + x_{i'jv}^{k} + x_{ji'v}^{k} + a_{klv} \qquad \forall i, k, l \in C, j \in NC: i > j, I_{ij} = 0, k \neq l, \forall v \in V \qquad (20)$$

$$2 - \sum_{\forall v \in V} v_{ijv}^{l} \geq \sum_{\forall v \in V} x_{ijv}^{k} + x_{jiv}^{k} + a_{klv} \qquad \forall k, l \in C, i, j \in NC: i < j, I_{ij} = 0, k \neq l, \forall v \in V \qquad (21)$$

$$|\tau_c\backslash\{s\}| \sum_{k \epsilon C\backslash\{s\}} v_{ijv}^{k} \geq \sum_{k \epsilon C\backslash\{s\}} (x_{ijv}^{k} + x_{jiv}^{k} + x_{i'jv}^{k} + x_{ji'v}^{k} + x_{j'iv}^{k} + x_{ij'v}^{k} + x_{i'j'v}^{k} + x_{j'i'v}^{k}) \qquad \forall i, j \in C\backslash\{s\}: I_{ij} = 0, i < j \qquad (22)$$

$$|\tau_c\backslash\{s\}| \sum_{k \epsilon C\backslash\{s\}} v_{ijv}^{k} \geq \sum_{k \epsilon C\backslash\{s\}} (x_{ijv}^{k} + x_{jiv}^{k} + x_{i'jv}^{k} + x_{ji'v}^{k}) \qquad \forall i \in C\backslash\{s\}, j \in NC: I_{ij} = 0, i < j \qquad (23)$$

$$|\tau_c\backslash\{s\}| \sum_{k \epsilon C\backslash\{s\}} v_{jiv}^{k} \geq \sum_{k \epsilon C\backslash\{s\}} (x_{ijv}^{k} + x_{jiv}^{k} + x_{i'jv}^{k} + x_{ji'v}^{k}) \qquad \forall i \in C\backslash\{s\}, j \in NC: I_{ij} = 0, i > j \qquad (24)$$

$$|\tau_c\backslash\{s\}| \sum_{k \epsilon C\backslash\{s\}} v_{ijv}^{k} \geq \sum_{k \epsilon C\backslash\{s\}} (x_{ijv}^{k} + x_{jiv}^{k}) \qquad \forall i, j \in NC: I_{ij} = 0, i < j \qquad (25)$$

$$de_{ij} \times v_{ijv}^{k} \leq n_v \times cap_v \qquad (i\ j) \in A', k \in C, \forall v \in V \qquad (26)$$

$$cost_{ij} \times y_{klv} + vc_v \times n_v \leq budget \qquad (i\ j) \in A', k \in C, \forall v \in V \qquad (27)$$

$x_{ijv}^{k} \epsilon (0,1)$	$\forall i,j \in N', \forall k \in C, \forall v \in V$ (28)
$v_{ijv}^{k} \epsilon (0,1)$	$\forall i,j \in N, \forall k \in C, \forall v \in V$ (29)
$a_{klv}, y_{klv} \epsilon (0,1)$	$\forall k,l \in C, \forall v \in V$ (30)
$r_{kv}, C_{kv} \geq 0$	$\forall k \in C, \forall v \in V$ (31)

The objective function (1) indicates weighting the arcs, and this objective minimizes the time to reach the nodes. The objective function (2) maximize coverage of injured areas and routes between them.

If critical node l is visited after critical node k by vehicle$v$, then constraints (3) assures that vehicle v leaves k to go$l$. So vehicle v can go to l from k directly or with intermediate node$j \in NC$. If the vehicle uses an intermediate node, constraint (4) assures that vehicle v leaves$j$. In other words, this constraint ensures that enter to j is equal to exit the$j$. In this constraint, $\sum_{i \in N'} x_{ijv}^{k}$ is overall nodes since the vehicle can depart from any node, and $\sum_{h \in NC' \cup \{k\}} x_{jhv}^{k}$ is over all noncritical nodes and the targeted critical.

Constraint (5) guarantees that all critical nodes are visited. Constraint (6) calculates the transfer time of going to critical node l from the previous critical node by vehicle$v$. Constraint (7) says either critical node l precedes k or k precedes$l$, or they are not consecutively visited critical nodes. Constraint (8) expresses that each critical node except stations has a previous critical node. Constraint (9) restricts the whole number of devolutions to the number of critical nodes we need to reach by vehicle$v$. Constraint (10) points out that it is possible to have a substitute critical node or not. This is needed because of the variable a_{klv} and constraint (12), which assures either $k \in C$ is visited before $l \in C$ or contrariwise.

By constraint (11), if critical node k is visited just before $l \in C$ by vehicle$v$, then k is visited before$l$, and by constraint (13) we satisfy that any $m \in C$ which is visited before k by vehicle v is also visited before$l$. Constraints (14) and (15) are guaranteed that the station nodes are the start nodes. Constraint (16) removes sub-tours between critical nodes and assigns visiting times, including the time spent on debris removal. So, if the arc (i,j) is cleared of any debris while going to critical node k by vehicle$v$, its cleaning time c_{ij} is added to r_{kv}. Constraint (17) assures that arcs will be clean only once and only if they are blocked.

We can prevent a blocked arc from being cleaned in later usage by constraints (18) - (21). For example, if critical node k is visited before critical node l and if a blocked arc (i,j) or one of its artificial versions has been traversed while going to k, then that arc cannot be cleaned while going to l. Constraints (22) - (25) guarantee that a blocked arc is cleaned while going to a critical node to be traversed to reach any critical node. Hence the blocked arc (i,j) is cleaned if it is used at least once. With constraints (18) - (25), we make sure, if the blocked arc (i,j) is used, it is cleaned once, and debris is deleted on its first usage. With (26) we can know that how many vehicles from type v we need. And with (27) we know how much budget we require. And finally, equations (28) - (31) specifies the type and range of variables.

3-5- Fuzzy approach

Given that there is a fuzzy parameter in constraint (8), we will explain that in this section. And we show that what we do with this fuzzy parameter. This parameter is $\tilde{t}_{ij}$ and indicates the transferring time of the arc(i,j). We convert fuzzy constraints to a certain one. For this, we can use Jimenez method (Jiménez, Arenas and Bilbao, 2007).

3-5-1- Jimenez method

If $\tilde{t}$ is a trapezoidal fuzzy number, membership function of $\tilde{t}$ is according as follow:

$$\mu_{\tilde{t}}^{(x)} = \begin{cases} f_t^{(x)} = \dfrac{x - t_1}{t_2 - t_1} & t_1 \le x \le t \\ 1 & t_2 \le x \le t_3 \\ g_t^{(x)} = \dfrac{t_4 - x}{t_4 - t_3} & t_3 \le x \le t_4 \\ 0 & o.w \end{cases} \qquad \tilde{t} = (t_1, t_2, t_3, t_4)$$

According to this method, the expectation interval and expected value of a trapezoidal fuzzy number calculate as follow:

$$I(\tilde{t}) = [E_1^t, E_2^t] = \left[\int_0^1 f_t^{-1}(x)\,dx, \int_0^1 g_t^{-1}(x)\,dx\right] = [\frac{1}{2}(t_1 + t_2), \frac{1}{2}(t_3 + t_4)]$$

$$EV(\tilde{t}) = \frac{E_1^t + E_2^t}{2} = \frac{t_1 + t_2 + t_3 + t_4}{4}$$

So constraint (6) change to constraint (6′)

$$C_{l,v} = \sum_{i,j \in N'} x_{ijv}^l \tilde{t}_{ij} \qquad \forall l \in C \backslash \{s\} \qquad (6)$$

$$C_{l,v} = \sum_{i,j \in N'} x_{ijv}^l ((1 - \beta) E_2^t(i,j) + \beta E_1^t(i,j)) \qquad \forall l \in C \backslash \{s\} \qquad (6')$$

3-6- Weighting the nodes

Earlier it was pointed that for fast handling of important nodes, we can use weighted nodes. We use the multi-attribute decision-making technique (MADM) for weighting nodes according to the importance of debris clearance. Therefore we used the group Analytical Hierarchy Process (group AHP), one of the standard techniques in weighting attributes. In this method, for giving importance to areas, we must determine attributes first step. In the second step, we form pairwise comparisons with the help of an expert (Balaji, Santhanakrishnan and Dinesh, 2019). In group AHP we used the opinion of several experts. In this method, after developing the hierarchical model, we go to creating matrices. Experts compare the attributes two by two and form the matrix of the pairwise comparisons of attributes like this matrix:

$$A = \begin{vmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{vmatrix}$$

These matrices of pairwise comparisons indicate the importance of each attribute relative to the other and can be measured based on the values of table 1. Then we use geometric mean for compile matrices of each expert to reach the weights of nodes as equation (32). All these can be done by expert choice software.

$$GM = \sqrt[n]{\prod_{i=1}^{n} X_i} \tag{32}$$

Table 1. Fundamental scale of AHP (Leal, 2020)

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

In MADM, selecting standard and appropriate attributes is vital (Llamazares, 2019). We used four attributes from important attributes introduced by Federal Emergency Management Agency (FEMA) for prioritizing areas for removing debris that as Table :

Table 2. Basic factors considered for areas

Content	**Basic factors**
Accessibility	Places due to proximity to centers such as fire bridge, police, red cross, etc. are on the way to the service vehicles of these centers.
Direction	Places that are proximity to hospitals, clinics, doctor buildings, emergency rooms, and other medical centers.
Congestion	Density locations such as education centers, shopping centers, etc.
Justice issue	Deprived and low-income areas for environmental isolation, justice issue because we help them.

These attributes are handling by experts and paired comparison matrix formed with the group AHP method. Moreover, in the proposed model, weighted nodes are needed in the first objective function. As we said before, we try to weigh nodes Using a pairwise matrix where reflects experts' opinions. After following the previous steps, we will achieve a result like table 3.

Table 3. Weight of nodes

Nodes	Weights
Node 1	w_1
Node 2	w_2
Node 3	w_3
Node 4	w_4
Node 5	w_5

4- Solution method

In this section, we will address solving the proposed model. We solved small and medium-size problems by an exact method using GAMS software. Due to the high nonlinear degree of the model and high solution time using the exact method, we propose the Grasshopper Optimization Algorithm (GOA) as a new metaheuristic method for large-size problems.

The proposed model in this study is a multi-objective model, so we used the AUGMECON 2 to solve this model.

4-1- AUGMECON 2

The AUGMECON 2 is a generation method of ε constraint method. This method is used for multi-objective and MIP models. The AUGMECON 2 enhances the ε constraint method for generating the Pareto's optimal solutions. This method addresses some weak points in the payoff table.

The following model is the general model of AUGMECON 2. Where e_y is the parameter for the specific iteration drawn from the grid points of the yth objective functions, S_p is the surplus variables of the pth constraints, and r_p is the ranges of the respective objective functions (Mavrotas and Florios, 2013).

$$\max(f_1(x) + eps \times (\frac{S_2}{r_2} \times 10^0 + \frac{S_3}{r_3} \times 10^{-1} + \cdots + \frac{S_p}{r_p} \times 10^{-(p-2)})) \quad (32)$$

s.t.

$$f_y(x) - S_y = e_y \qquad \forall\, y \in \{2, \dots, p\} \quad (34)$$

$$x \in S, S_p \in R^+ \; and \; eps \in [10^{-6}, 10^{-3}]$$

The steps of the AUGMECON 2 are as follow:

1. With using the lexicography method, calculate the amount of the final result table.

2. Choose one of the objective functions as the main objective function of the problem.

3. Elicit the worst and the best amount of each objective function in the final result table.

4. Calculate the domain of each secondary objective function.

5. Divide the domain of secondary objective functions due to the number of Pareto's answers into a predetermined number.

6. Create a model like the above model (equations (32) and (34)). Put your main objective function as the objective function of the model and the other objective in constrain (34).

7. Solve this model for e_p. The result for each e_p is one of the Pareto's answer of problem.

8. Report Pareto's answers.

4-2- Grasshopper optimization algorithm (GOA)

The living of grasshoppers in nature inspires GOA. We often observe grasshoppers in nature individually, but they are the biggest swarm of insects in creation. Like other natural inspired algorithms, the search process of GOA is divided into two types: exploration and exploitation. The search agents are encouraged to move suddenly in exploration. But in exploitation, they tend to move locally (Saremi, Mirjalili and Lewis, 2017).

According to researches of (Saremi, Mirjalili and Lewis, 2017):

The mathematical model that have similar behavior with GOA is as follow (35):

$$X_i = S_i + G_i + A_i \tag{35}$$

Equation (36) can rewrite by considering random behavior as follow (36):

$$X_i = r_1 S_i + r_2 G_i + r_3 A_i \tag{36}$$

Where r_1, r_2 and r_3 are random number in $[0,1]$. Also, the other factors are calculable from the following equations:

$$S_i = \sum_{\substack{j=1 \\ j \neq i}}^{N} s(d_{ij})\widehat{d_{ij}} \tag{37}$$

$$d_{ij} = \left|X_j - X_i\right| \tag{38}$$

$$\widehat{d_{ij}} = (X_j - X_i)/d_{ij} \tag{39}$$

$$s(r) = f e^{-r/l} - e^{-r} \tag{40}$$

That d_{ij} is the distance between grasshopper i-th and j-th, $\widehat{d_{ij}}$ indicate the unit vector from i-th until j-th grasshopper. Also, s demonstrates social forces, f demonstrates the intensity of attraction, and l demonstrates the attractive length scale. It should be noted that function s cannot apply strong forces between grasshoppers with large distances between them. Figure 6 illustrates a conceptual model of interactions between grasshoppers and the comfort zone using the function s.

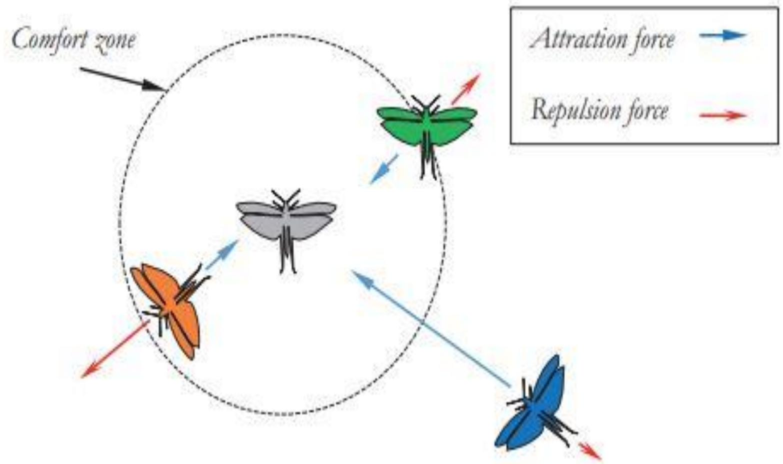

Fig 6. conceptual model of grasshoppers and comfort zone (Saremi, Mirjalili and Lewis, 2017)

Gravity forces of grasshopper (G_i) can calculate as following:

$$G_i = -g\widehat{e_g} \tag{41}$$

Where g is the gravitational constant, and $\widehat{e_g}$ is a unity vector towards the earth's center.

A_i can calculated as follow:

$$A_i = -u\widehat{e_w} \tag{42}$$

Where *u* indicate a constant drift and $\widehat{e_w}$ indicate a unity vector in the direction of the wind.

So, Equation (35) can rewrite as follow:

$$X_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} s\left(\left|X_i - X_J\right|\right)\frac{X_i - X_J}{d_{ij}} - g\widehat{e_g} + u\widehat{e_w} \tag{43}$$

N is the number of grasshoppers.

We cannot use this mathematical model directly to solve optimization problems because the grasshoppers reach the comfort zone quickly, and the congestion does not gather at a specific point. Instead, we can use equation (44) to solve optimization problems as a modified version of equation (43) that is as follows:

$$X_i^d = c\left(\sum_{\substack{j=1 \\ j\neq i}}^{N} c\frac{ub_d - lb_d}{2} s(\left|X_j^d - X_i^d\right|)\frac{X_j - X_i}{d_{ij}}\right) + \widehat{T_d} \tag{44}$$

Where ub_d and lb_d are upper and lower bound in the d-th dimension, respectively. $\widehat{T_d}$ is the best-found value of the d-th dimension, and c is updating with the Equation (45) to increase exploitation and reduce exploration proportional to the number of iteration:

$$c = cmax - l\frac{cmax - cmin}{L} \tag{45}$$

Where l denotes the current iteration, $cmax$ indicates the maximum value, $cmin$ indicates the minimum value, and L marks the maximum number of iteration.

Finally, GOA's Pseudo illustrates in figure 7.

```
Initialize the swarm X_i(i=1, 2, ..., n);
Initialize cmax, cmin and maximum number of iterations
Calculate the fitness of each search agent
T= the best search agent
while (l ≤ Max number of iterations)
   Update c using Equation (48)
   for each search agent
        Normalize the distance between grasshoppers in [1,4]
        Update the position of the current search agent by the Equation (47)
        Bring the current search agent back if it goes outside the boundaries
   end for
   Update T if there is a better solution
   l=l+1
end while
return T
```

Fig 7. Pseudo codes of the GOA (Saremi, Mirjalili and Lewis, 2017)

5- Case study

In this section, we will examine the model to prove its correct operation. For this goal, we consider small and medium-size cases, implement them in the model, and discuss how they work in sections 5-1 and 5-2. The small and medium-size model used the AUGMECON 2 method by generalized algebraic modeling system (GAMS) software's CPLEX on Lenovo laptop with 2.5 GHZ intel CORE i7 CPU and 4 GB RAM, which resulted in the optimal solution.

5-1- Small size problem

For the small size example, we consider five nodes in Tehran. According to figure 9, the communication roads between nodes i1 and i2, i2 and i3, i4, and i5 are blocked by debris. We have to handle every critical node, and we know that the removal operation takes time and money. In these five nodes, we have four critical nodes and one non-critical node. We prioritized all critical nodes except station's node based on attributes introduced in section 3.6. After applying the opinion of 15 experts, we achieve this pairwise comparisons matrix:

	accessibility	*Direction*	*Congestion*	*Justicissue*
accessibility	–	1.035	2.354	4.069
Direction	0.966	–	2.876	4.868
Congestion	0.425	0.348	–	2.327
Justicissue	0.246	0.205	0.430	–

And also, we form four pairwise comparisons matrices of nodes according to each attribute. Figure 8 illustrates the Software environment of expert choice and the consequence of weighing with the AHP method.

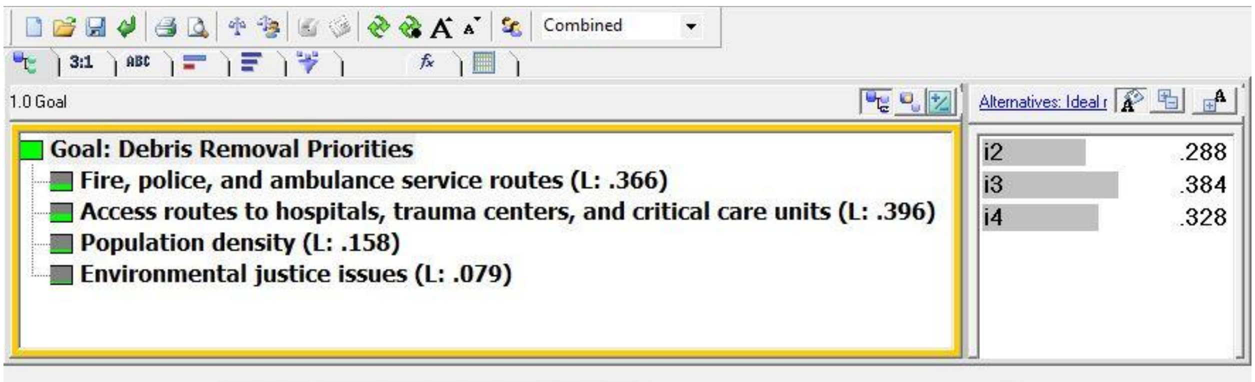

Fig 8. Environment of expert choice software

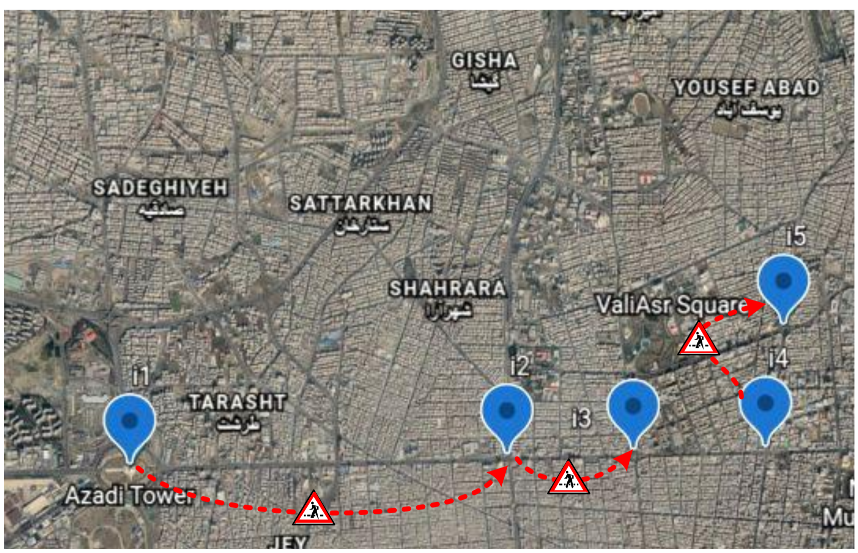

Fig 9. Location of critical and non-critical points in the map of Tehran for small size example

Icon  with red arrows indicates block road. After obtaining information like the amount of debris of road, the clearance time of each block road, etc., we solve the problem. The results from solving this problem are as figure 10. Actually, the yellow arrows in this picture indicate a relation between critical nods. According to the results, trucks cross from the blocked road between node i2 and node i3. So, we had to clear that road. Moreover, we cover all of the existing critical nodes. By using aumecon2 we get Pareto's answer that is visible in figure 11.

Fig. 10 Optimal movement of trucks in the network

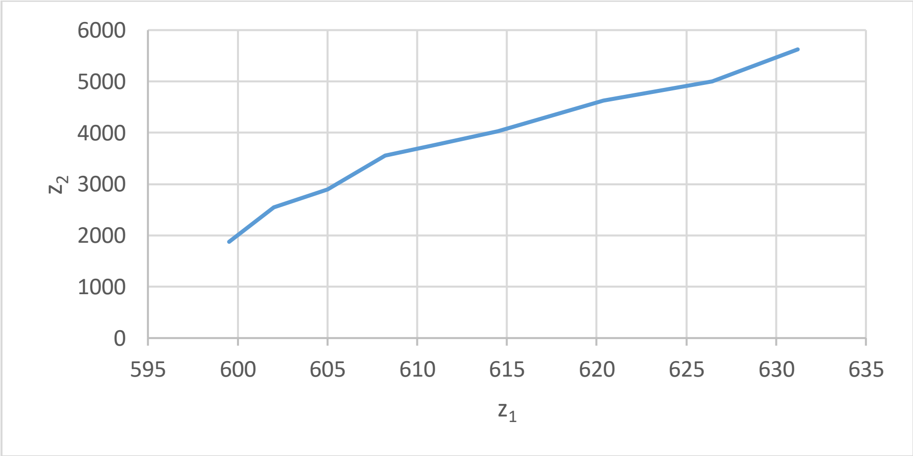

Fig 11. Pareto's answers

5-2- Medium size

For medium size, we expanded the small size problem and considered seven nodes. According to figure 12, the communication roads between nodes i1 and i2, i2 and i3, i4 and i5, i6 and i7 are blocked with debris. Nodes i1 to i6 are critical, and nodes i7 is non-critical.

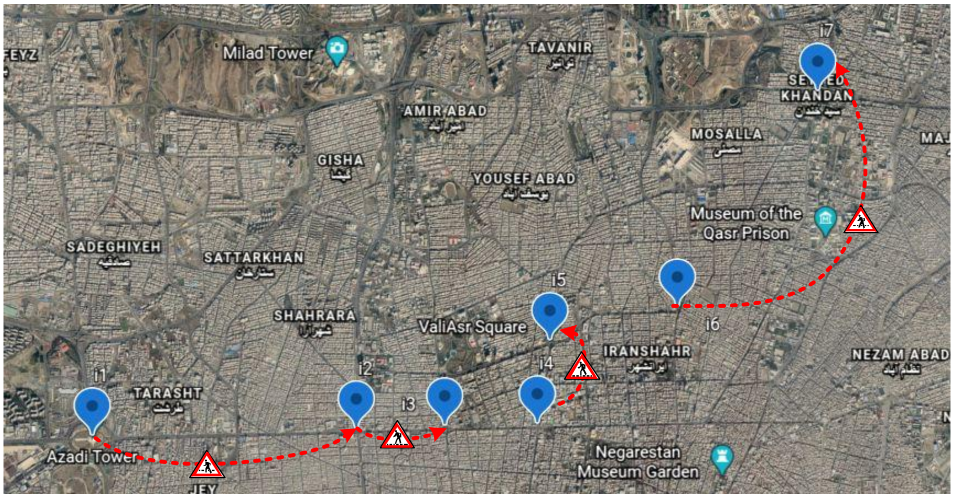

Fig 12. Location of critical and non-critical points in the map of Tehran for medium size example

Weight of critical nodes that extraction by AHP is as Table . This table expected that trucks visit all critical nodes at the end. After solving the model, we arrive at Pareto's answer that is shown in figure 13. Also, the final answer includes of trucks route illustrated in figure 13. In the end, we had to clean the debris between nodes i2 and i3 and between i6 and i7. We didn't need to clean other block roads.

Table 4. Weight of each critical node

Critical node	i2	i3	i4	i5	i6
Weight	0.174	0.236	0.201	0.218	0.171

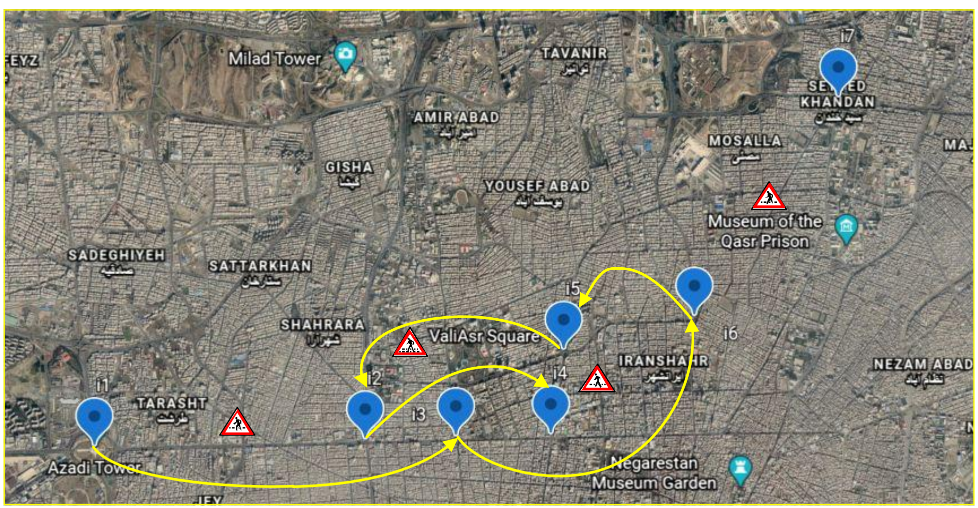

Fig 13. The optimal movement of trucks in the network

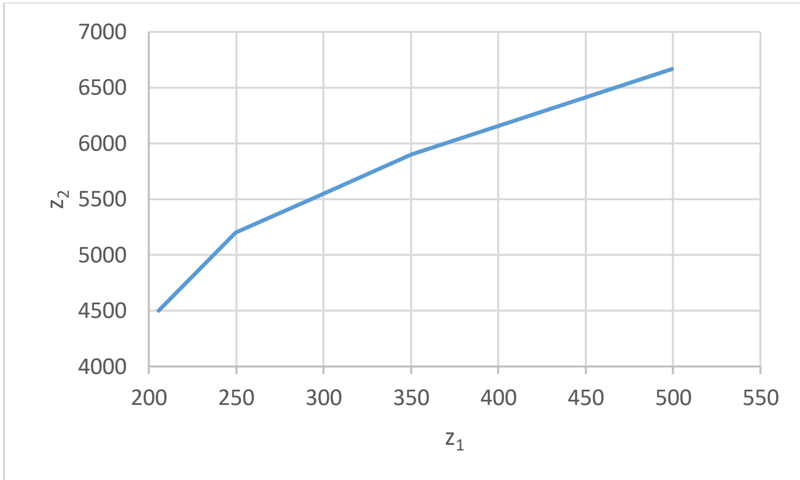

Fig 14. Chart of Pareto's answer

5-3- Validation of GOA

Solving the proposed model using the exact method according to figure 15 with increasing dimensions of the problem takes a lot of time. Hence, we need to use meta-heuristic algorithms for large-size problem. In this study, we propose the Grasshopper Optimization Algorithm (GOA) for accelerated responses. To examine how the algorithm responds and the effects on the problem answer, we considered 6 test problems. Therefore, we solved the model using both GAMS software as an exact method and GOA as a meta-heuristic method. Table 's results illustrate that the answers obtained from meta-heuristic are different from the solutions obtained from the exact method. On the other hand, the speed to get answers in meta-heuristic is much faster than the exact method. So, using a meta-heuristic method is recommended. Also, figure 16 shows the convergence of the GA algorithm to the optimal solution.

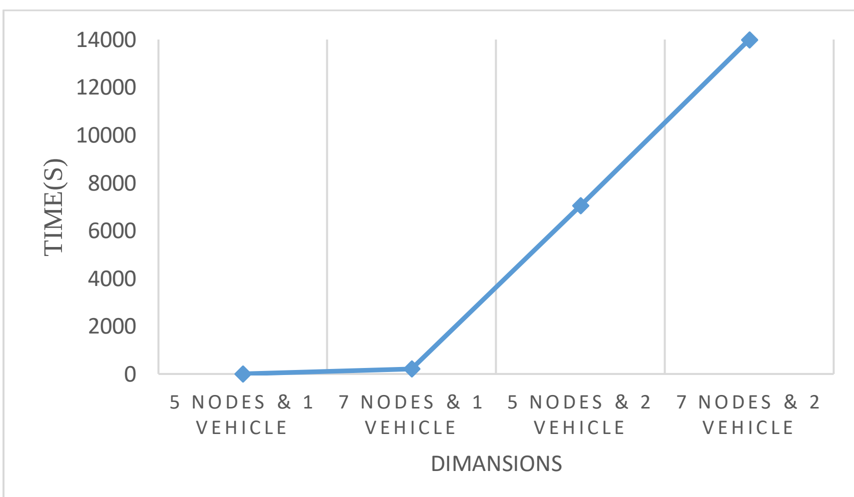

Fig 15. Elapsed time

Table 5. Numerical result of exact and meta-heuristic method

Solution method	Exact method or GAMS				GOA				GAP[1]%		
Variables / problems	Optimal value of z_1	Optimal value of z_2	$budget$	CPU TIME(S)	Optimal value of z_1	Optimal value of z_2	$budget$	CPU TIME(S)	Difference of optimal value of z_1	Difference of optimal value of z_2	Difference of $budget$
Test problem 1	1388.21	6375	80100	2.47	1450.12	5952	80250	2.03	4.46	6.64	0.19
Test problem 2	1438.16	6800	419600	297.14	1602.967	6695.76	429005	19.73	11.46	1.53	2.24
Test problem 3	804.321	2950	7740	1027.81	1001.23	2567	7850	22.72	24.48	12.98	1.42
Test problem 4	908.188	6333.333	14880	371.17	928	6123.51	15600	19.89	2.18	3.31	4.84
Test problem 5	437.123	5100	17560	264.61	486.91	5002.49	16900	19.58	4.53	1.91	8.61
Test problem 6	992.173	4200	8100	403.34	1079.95	3780.19	8500	20.16	8.45	10	4.94

[1] $GAP = |GOA - GAMS|/GAMS$

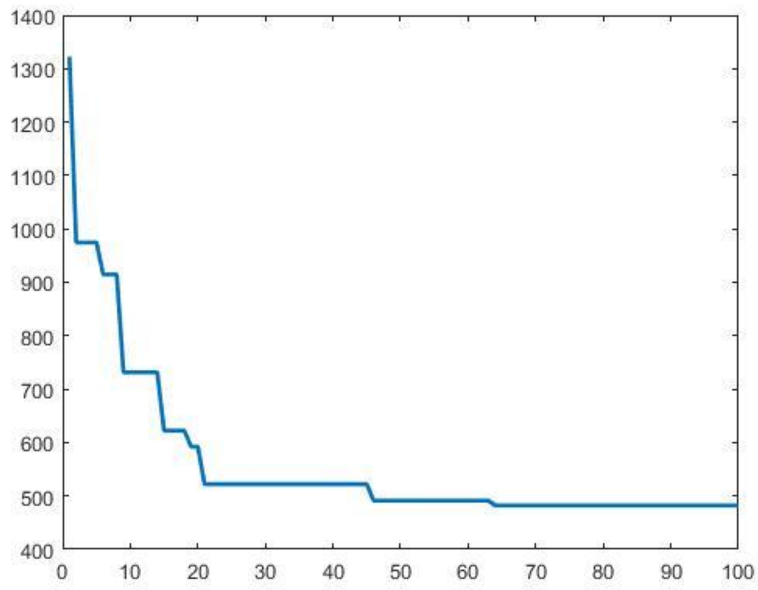

Fig 16. Convergence of GOA to the optimal solution for test problem 5

5-4- Model validation

To ensure the model's validity, we made changes to some variables to see if our predicted results will happen. So, in follow, we investigate the effect of changing transportation time and changing amount of debris on time to reach potential nodes and vehicle's number.

5-4-1- The effect of changing transportation time on time to reach potential nodes

If the time of transferring between two nodes increases on our road, then the total time to reach the final nodes will increase. Also, divers of this issue occur. It means that if transferring time between two nodes in our road decreases, the total time to reach final nodes will decrease. So, when transferring time between every node increase (decrease), we expected that the time to reach the node $k \in c$ would increase (decrease). To ensure how the model works in this issue and analyze the effect of changing transportation time on total time to reach potential nodes, we change the amount of transferring time with different ratios. We doubled the time by 0.5, 1.5, and 2. The results are illustrated in figure 17. According to this chart, as expected, increasing transferring time results in increasing time to reach critical nodes and conversely.

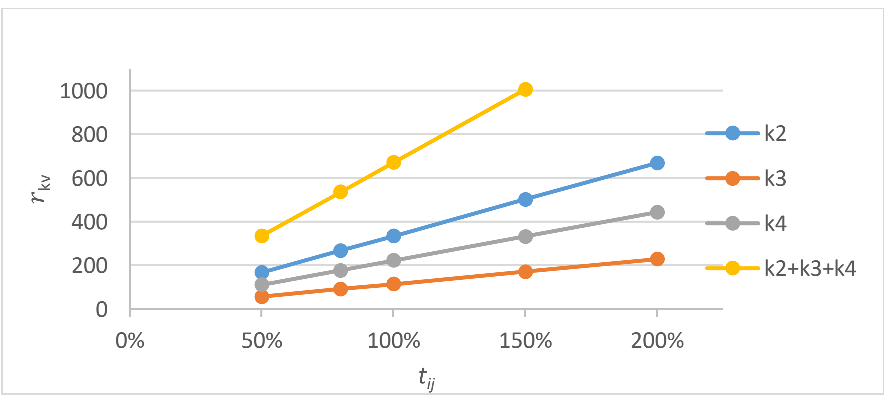

Fig. 17 Change the t_{ij} on the r_{kv}

5-4-2- The effect of changing amount of debris on the number of vehicles

We investigated the effect of changing the amount of debris on the number of vehicles. We expected that with increasing the amount of debris, our need for vehicles would increase. So after applying change to the amount of debris, we found the number of vehicles will increase (figure 18).

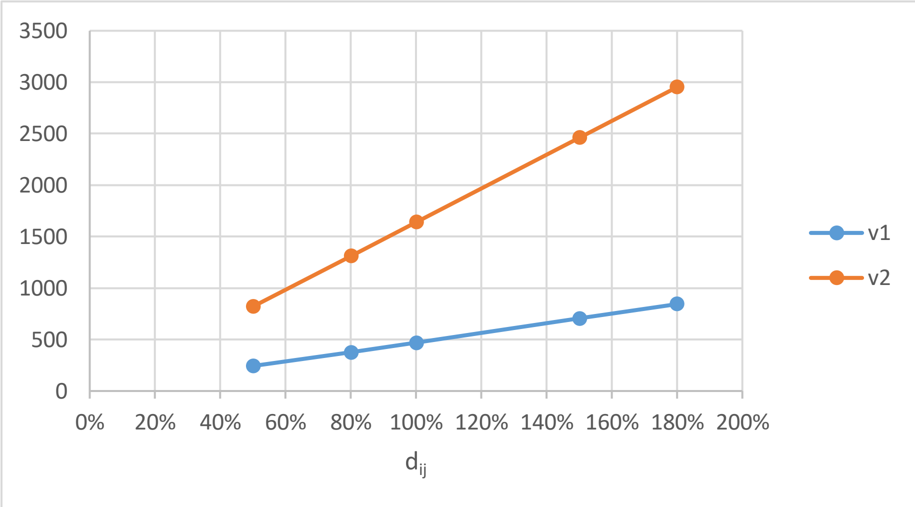

Fig 18. Change the dij on the v1 and v2

As illustrated in figure 17 and figure 18, we found that the mathematical model works as well as possible.

5-5- Sensitivity analysis

A sensitivity analysis of the model can provide useful insight. In this section, we consider an assumption example for model performance validation, and then with changing data, we can analyze the model.

5-5-1- The effect of the amount of debris on budget

We know that an increasing amount of debris causes an increasing number of vehicles and decreases the budget. After analyzing with changing the amount of debris, we receive figure 19.

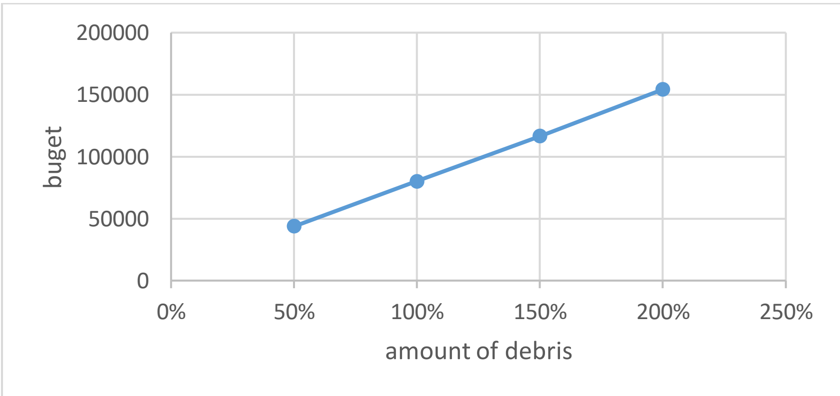

Fig 19. Change amount of debris on the budget

5-5-2- The effect of clearance cost on the budget

The same test on the effect of the clearance costs shows that, as the clearance costs increase, the budget changes ascending (figure 20).

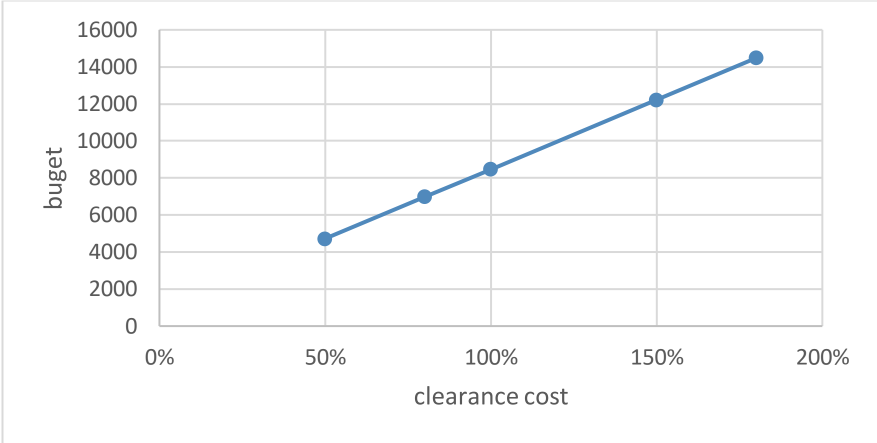

Fig 20. Change the cij on the budget

5-5-3- The effect of cost and capacity of vehicles on required budget

To find the relation between cost and capacity with the required budget, we solved the model severally by three scenarios as follow:

1. Cost of vehicles with different capacities is slightly different from each other.

2. The cost of vehicles is very different.

3. The difference in the cost of trucks with each other is normal. Neither low nor high.

For better understanding, the results are giving in Table , Table , and as shown in

Table , the cost and capacity of cars together are effective in budgeting. If the first or third scenario establishes, we choose a vehicle with more big capacity. But if the second scenario creates, we must calculate which vehicle is appropriate for us. We explain more about this in section 5-4.

Table 6. Results of scenario 1

Scenario 1			
vehicle	Cost of vehicle	Capacity of vehicle	Required budget
v1	10	5	22500
v2	11	20	11625
v3	12	50	9300
v4	13	100	8475

Table 7. Results of scenario 2

Scenario 2			
vehicle	Cost of vehicles	Capacity of vehicle	Required budget
v1	10	5	22500
v2	15	20	13125
v3	35	50	12750
v4	75	100	13125

Table 8. Results of scenario 3

Scenario 3			
vehicle	Cost of vehicle	Capacity of vehicle	Required budget
v1	15	5	30000
v2	30	20	18750
v3	40	50	13500
v4	50	100	11250

5-6- Managerial insight

Various management recommendations can be made to improve performance while a disaster occurred. For example, according to research, we can consider temporary debris management sites between the roads if we face a limit on the number of trucks. Furthermore, for more efficiency, we can increase these sites' capacity until as maximum as possible or add some equipment (like landfilling, incineration, and shredding of waste) to decrease debris volume (Kim, Deshmukh and risk, 2018).

Moreover, according to the numerical analysis, there are some other ways that municipality managers can use them to achieve the best function which other studies have paid less attention to that are as follow:

If the different size of vehicles exists in same renting cost, choosing between the most voluminous is economical. This way, due to the high capacity of the vehicles, we need fewer of them, and thus our final cost is reduced. So, we need a fewer budget. But in the real world, the probability of different truck prices being equal is close to zero. So, let's look at another scenario. If the cost of different types of vehicles is close to each other or not significantly different from each other, like scenario one and scenario 3, choosing between the most voluminous is economical. This issue was tested, and the results are illustrated in Table and

Table . According to these tables, for optimally selecting, we must choose vehicle type 4 because it has the most vehicle capacity. But if Scenario 2 is established, we must calculate to find which choice is more economical for us, and without calculating total cost, we cannot make the right decision. For example, in Table , we can use the proposed model with 4 types of vehicles severally if we want to minimize the required budget. Considering the amount of budget, we can make decisions. In this example, we must choose the third type of vehicle for reducing the budget while there are two options with less cost and an option with more capacity. So, according to the above, deciding on the optimal vehicle type choice depends on how to divide the trucks.

According to part 5-5-2, debris removal costs directly depend on the required budget, and we want to reach all critical nodes. So if the road between two critical nodes is blocked, we must decide to remove the block arc or use a long way. So in deciding to choose the next nodes, we must calculate which one is optimal. The proposed model with the weight of nodes, amount of debris, clearance time, and clearance cost decide to choose the way optimally. Because an increase in transportation time leads to an increase in reaching time to nodes, we must speed up the availability of debris collection trucks to destroyed areas by applying traffic restrictions after disasters occurred. For this purpose, Curfew regulations of personal vehicles can be used.

After a disaster occurs, we may face budget and facilities shortages. One way to help us in this situation is to remove debris in the form of step by step. In this way, debris removal will only open the ambulances and fire truck route in the first stage. In the next stages, deeper cleaning will be done. So we can handle more nodes in a shorter time.

Eventually, we can say managers can allocate the proposed budget using the proposed model in this study, according to the type of disaster, power, and amount of that, and also estimation of the volume of debris and costs such as clearance and transportation costs.

6-Conclusions

One of the crucial issues after a disaster is debris management. Many studies paid to collect debris to clear blocked paths in the reconstruction phase. But clearing debris to rescue, save lives, and prevent more severe accidents in high-risk areas is an important issue we addressed in this study. We developed a multi-objective model for the debris clearance problem. Our aims are minimizing the time of reach to each critical node and maximizing coverage to areas. In these problems, our goal is not just clearance the roads; we have to reach different nodes from the shortest and cheapest route to eliminate more life-threatening dangers. Also, for considering the importance of nodes for prioritizing addressing them, we gave weight to them. For weighting them, we asked some experts and used the AHP method. Finally, to investigate the model's response rate, we considered some case studies in Tehran and solved them with the AUGMECON 2 method. We also used GOA as a meta-heuristic method, solved some test problems, and compared the results of the meta-heuristic and exact method. We can consider this problem with uncertain information like debris and a limited budget for future research in this area. Considering congestion in the nodes with the queuing system (Mohtashami et al., 2020) would be interesting for future research. Also, we can use other meta-heuristic algorithms and compare them with each other. Besides, we can investigate this problem with the time window.

References

Abazari, S. R., Aghsami, A. and Rabbani, M. (2020) "Prepositioning and distributing relief items in humanitarian logistics with uncertain parameters," *Socio-Economic Planning Sciences*. Elsevier Ltd, p. 100933. doi: 10.1016/j.seps.2020.100933.

Ajam, M., Akbari, V. and Salman, F. S. (2019) "Minimizing latency in post-disaster road clearance operations," *European Journal of Operational Research*. Elsevier B.V., 277(3), pp. 1098–1112. doi: 10.1016/j.ejor.2019.03.024.

Akbari, V. and Salman, F. S. (2017) "Multi-vehicle synchronized arc routing problem to restore post-disaster network connectivity," *European Journal of Operational Research*. Elsevier B.V., 257(2), pp. 625–640. doi: 10.1016/j.ejor.2016.07.043.

Aydin, N. (2020) "Designing reverse logistics network of end-of-life-buildings as preparedness to disasters under uncertainty," *Journal of Cleaner Production*. Elsevier Ltd, 256, p. 120341. doi: 10.1016/j.jclepro.2020.120341.

Balaji, M., Santhanakrishnan, S. and Dinesh, S. N. (2019) "An application of analytic hierarchy process in vehicle routing problem," *Periodica Polytechnica Transportation Engineering*. Budapest University of Technology and Economics, 47(3), pp. 196–205. doi: 10.3311/PPtr.10701.

Bang, H. N. (2014) "General overview of the disaster management framework in Cameroon," *Disasters*. Blackwell Publishing Ltd, 38(3), pp. 562–586. doi: 10.1111/disa.12061.

Berktaş, N., Kara, B. Y. and Karaşan, O. E. (2016) "Solution methodologies for debris removal in disaster response," *EURO Journal on Computational Optimization*. Springer Verlag, 4(3–4), pp. 403–445. doi: 10.1007/s13675-016-0063-1.

Çelik, M., Ergun, Ö. and Keskinocak, P. (2015) "The post-disaster debris clearance problem under incomplete information," *Operations Research*. INFORMS Inst.for Operations Res.and the Management Sciences, 63(1), pp. 65–85. doi: 10.1287/opre.2014.1342.

Chang, F. and Shen, H. W. (1979) "DEBRIS PROBLEMS IN THE RIVER ENVIRONMENT."

Cheng, C., Zhu, R., Costa, A. M., & Thompson, R. G. (2021). Optimisation of waste clean-up after large-scale disasters. *Waste Management*, *119*, 1-10.

Cheng, C., Zhu, R., Costa, A. M., Thompson, R. G., & Huang, X. (2021). Multi-period two-echelon location routing problem for disaster waste clean-up. *Transportmetrica A: Transport Science*, 1-31.

Crowley, J. (2017) "A measurement of the effectiveness and efficiency of pre-disaster debris management plans," *Waste Management*. Elsevier Ltd, 62, pp. 262–273. doi: 10.1016/j.wasman.2017.02.004.

Danesh Alagheh Band, T.S., Aghsami, A. and Rabbani, M., 2020. A Post-disaster Assessment Routing Multi-objective Problem under Uncertain Parameters. *International Journal of Engineering*, *33*(12), pp.2503-2508.

Fan, G. C. *et al.* (2016) "Research on the scheme and key technologies of space debris clearance with space-based laser," *Journal of Beijing Institute of Technology (English Edition)*. Beijing Institute of Technology, 25, pp. 156–160. doi: 10.15918/j.jbit1004-0579.201625.S231.

Federici, L., Zavoli, A., & Colasurdo, G. (2021). On the use of A* search for active debris removal mission planning. Journal of Space Safety Engineering.

Félix, D., Monteiro, D., & Feio, A. (2020). Estimating the needs for temporary accommodation units to improve pre-disaster urban planning in seismic risk cities. *Sustainable Cities and Society*, *61*, 102276.

Fetter, G. and Rakes, T. (2012) "Incorporating recycling into post-disaster debris disposal," *Socio-Economic Planning Sciences*. Pergamon, 46(1), pp. 14–22. doi: 10.1016/j.seps.2011.10.001.

Fetter, G. and Rakes, T. R. (2013) "An equity approach to contractor assignment in post-disaster debris disposal operations," *International Journal of Emergency Management*, 9(2), p. 170. doi: 10.1504/IJEM.2013.055167.

Gajanayake, A. *et al.* (2018) "Community adaptation to cope with disaster related road structure failure," in *Procedia Engineering*. Elsevier Ltd, pp. 1355–1362. doi: 10.1016/j.proeng.2018.01.175.

Grzeda, S., Mazzuchi, T. A. and Sarkani, S. (2014) "Temporary disaster debris management site identification using binomial cluster analysis and GIS," *Disasters*. Blackwell Publishing Ltd, 38(2), pp. 398–419. doi: 10.1111/disa.12040.

Habib, M. S. and Sarkar, B. (2017) "An Integrated Location-Allocation Model for Temporary Disaster Debris Management under an Uncertain Environment," *Sustainability*. MDPI AG, 9(5), p. 716. doi: 10.3390/su9050716.

HIRAYAMA and N. (2010) "Establishment of Disaster Debris Management Based on Quantitative Estimation Using Natural Hazard Maps, Waste Management and the Environment V," *WIT Transactions on Ecology and the Environment*, 40, pp. 167–178.

Hooper, M. (2019) "When Diverse Norms Meet Weak Plans: The Organizational Dynamics of Urban Rubble Clearance in Post-Earthquake Haiti," *International Journal of Urban and Regional Research*. Blackwell Publishing Ltd, 43(2), pp. 292–312. doi: 10.1111/1468-2427.12696.

Jiménez, M., Arenas, M. and Bilbao, A. (2007) "Linear programming with fuzzy parameters: an interactive method resolution," *European Journal*.

Kim, J., Deshmukh, A. and risk, M. H.- (2018) "A framework for assessing the resilience of a disaster debris management system," *International journal of disaster*. Available at: https://www.sciencedirect.com/science/article/pii/S2212420917303643 (Accessed: November 8, 2020).

Leal, J. E. (2020) "AHP-express: A simplified version of the analytical hierarchy process method," *MethodsX*. Elsevier B.V., 7. doi: 10.1016/j.mex.2019.11.021.

Mavrotas, G. and Florios, K. (2013) "An improved version of the augmented s-constraint method (AUGMECON2) for finding the exact pareto set in multi-objective integer programming problems," *Applied Mathematics and Computation*. Elsevier Inc., 219(18), pp. 9652–9669. doi: 10.1016/j.amc.2013.03.002.

Modica, M., Paleari, S., & Rampa, A. (2021). Enhancing preparedness for managing debris from earthquakes: lessons from Italy. *Natural Hazards*, *105*(2), 1395-1412.

Moe, T. L. and Pathranarakul, P. (2006) "An integrated approach to natural disaster management: Public project management and its critical success factors," *Disaster Prevention and Management: An International Journal*. Emerald Group Publishing Ltd., 15(3), pp. 396–413. doi: 10.1108/09653560610669882.

Mohamadi, A. and Yaghoubi, S. (2016) "A new stochastic location-allocation emergency medical services healthcare system model during major disaster," *Journal of Industrial and Systems Engineering*. Iranian Institute of Industrial Engineering, 9(special issue on location allocation and hub modeling), pp. 85–99. Available at: http://www.jise.ir/article_15110.html (Accessed: December 31, 2020).

Mohtashami, Z., Aghsami, A. and Jolai, F., 2020. A green closed loop supply chain design using queuing system for reducing environmental impact and energy consumption. *Journal of cleaner production*, *242*, p.118452.

Momeni, B., Aghsami, A. and Rabbani, M., 2019. Designing Humanitarian Relief Supply Chains by Considering the Reliability of Route, Repair Groups and Monitoring Route. *Advances in Industrial Engineering*, *53*(4), pp.93-126.

Monzón, J., Liberatore, F., & Vitoriano, B. (2020). A mathematical pre-disaster model with uncertainty and multiple criteria for facility location and network fortification. *Mathematics*, *8*(4), 529.

Murphy, D. (2010) "Haiti earthquake: Small Port-au-Prince airport strained by aid demand - CSMonitor.com."

Perry, M. (2007) "Natural disaster management planning: A study of logistics managers responding to the tsunami," *International Journal of Physical Distribution and Logistics Management*. Emerald Group Publishing Limited, pp. 409–433. doi: 10.1108/09600030710758455.

Ram, V. G., Kishore, K. C. and Kalidindi, S. N. (2020) "Environmental benefits of construction and demolition debris recycling: Evidence from an Indian case study using life cycle assessment," *Journal of Cleaner Production*. Elsevier Ltd, 255, p. 120258. doi: 10.1016/j.jclepro.2020.120258.

Rezaei, A., Aghsami, A. and Rabbani, M., 2021. Supplier selection and order allocation model with disruption and environmental risks in centralized supply chain. *International Journal of System Assurance Engineering and Management*, pp.1-37.

Rosing, K. E. and ReVelle, C. S. (1997) "Heuristic concentration: Two stage solution construction," *European Journal of Operational Research*. Elsevier, 97(1), pp. 75–86. doi: 10.1016/S0377-2217(96)00100-2.

Sabouhi, F., Heydari, M. and Bozorgi-Amiri, A. (2016) "Multi-objective routing and scheduling for relief distribution with split delivery in post-disaster response," *Journal of Industrial and Systems Engineering*. Iranian Institute of Industrial Engineering, 9(3), pp. 17–27. Available at: http://www.jise.ir/article_14559.html (Accessed: December 31, 2020).

Şahin, H. (2013) "Debris removal during disaster response phase : a case for Turkey." Bilkent University.

Salamati Nia, S. P. and Kulatunga, U. (2017) "Safety and security of hospitals during natural disasters: Challenges of disaster managers," *International Journal of Safety and Security Engineering*. WITPress, 7(2), pp. 234–246. doi: 10.2495/SAFE-V7-N2-234-246.

Sanci, E. and Daskin, M. S. (2019) "Integrating location and network restoration decisions in relief networks under uncertainty," *European Journal of Operational Research*. Elsevier B.V., 279(2), pp. 335–350. doi: 10.1016/j.ejor.2019.06.012.

Saremi, S., Mirjalili, S. and Lewis, A. (2017) "Grasshopper Optimisation Algorithm: Theory and application," *Advances in Engineering Software*. Elsevier Ltd, 105, pp. 30–47. doi: 10.1016/j.advengsoft.2017.01.004.

Sayarshad, H. R., Du, X., & Gao, H. O. (2020). Dynamic post-disaster debris clearance problem with re-positioning of clearance equipment items under partially observable information. *Transportation research part B: methodological*, *138*, 352-372.

Setiabudi, D. H. and Wydiadana, I. G. A. (2019) "Humanitarian logistics information system for natural disaster: A case study on East Java, under the coordination of Indonesian red cross," in *ACM International Conference Proceeding Series*. Association for Computing Machinery, pp. 86–92. doi: 10.1145/3355402.3355418.

Sharma, B. *et al.* (2019) "Dynamic temporary blood facility location-allocation during and post-disaster periods," *Annals of Operations Research*. Springer, 283(1–2), pp. 705–736. doi: 10.1007/s10479-017-2680-3.

Tavakoli, S., Rabbani, M. and Bozorgi-Amiri, A. (2017) "Providing an Optimization Model for Debris Clearance Problem During Disaster Response," *Journal of Crisis Management*.

Wang, W.-C., Hsieh, M.-C. and Huang, C.-H. (2018) "Applying Prim's Algorithm to Identify Isolated Areas for Natural Disaster Prevention and Protection," *Engineering*. Scientific Research Publishing, Inc, 10(07), pp. 417–431. doi: 10.4236/eng.2018.107029.

Wang, Y., Peng, S., & Xu, M. (2021). Emergency logistics network design based on space–time resource configuration. *Knowledge-Based Systems*, *223*, 107041.

Wei, F. *et al.* (2008) "A decision support system for debris-flow hazard mitigation in towns based on numerical simulation: A case study at Dongchuan, Yunnan Province," *International Journal of Risk Assessment and Management*. Inderscience Publishers, 8(4), pp. 373–383. doi: 10.1504/IJRAM.2008.019014.