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Optimum Routing of Aerial Vehicles and Ambulances in Disaster Logistics

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Abstract

One of the most vital aspects of emergency management is planning and improving post-disaster rescue activities and treatment facilities. Reaching the survivors in the shortest time possible and planning the logistics aspect of post-disaster efforts is one of such issues to be handled when performing these operations. This research involves development of mathematical models for both the debris scanning by the utilization of Unmanned Aerial Vehicles in a disaster area and consequently carrying the injured individuals to the treatment facilities by the available ambulances in the shortest possible time. The mathematical model developed for the ambulance routing problem includes unique constraints that are introduced for the first time in the literature. The proposed model is tested on benchmark problems created by using the real data which belongs to the region under investigation. Computational results indicate the efficiency of the proposed model, particularly in small and medium sized problems.

Keywords: disaster logistics, cluster coverage, multi-depot vehicle routing problem, ambulance routing problem, mathematical modeling.

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Introduction

It is often very difficult to project the outcomes of natural disasters. That is why, taking precautions in advance and improving the logistic infrastructure is imperative. Disaster management encompasses all these activities that must be planned ahead. The field attracts many researchers due to its significant impact.

In terms of their nature of occurrence, the disasters can be classified under natural and human disasters [Sahin and Sipahiohlu, 2003]. Natural disasters are caused by the own actions of the nature while human disasters are initiated by the human impact and/or obstruction on nature. Hurricanes, earthquakes and major accidents can be mentioned as such disasters. Earthquakes, among the others are very difficult to foresee as well as their potential impacts in terms of both financial losses and casualties. Thus, taking precautions and improving the applicable infrastructure is particularly important when it comes to the earthquakes. Unlike earthquakes, disasters like hurricanes are a lot easier to forecast through meteorological data which makes it easier to plan and manage. As a result, especially major earthquakes have the potential of resulting with structural collapses and disruption of transportation activities which makes it even more difficult to reach to the survivors during rescue activities while it is imperative to coordinate such activities as fast as possible.

Advanced technology that is available today makes it possible to scan the disaster area in relatively short duration which is important to see the damage and guide the rescue teams. The east region of Turkey that was hit by an earthquake in 2020, was quickly scanned by Manned Reconnaissance Aircraft and Unmanned Aerial Vehicles. The images were transmitted to the Command Center as they were taken. The vehicles scanned 275 locations within a 3-hour time window, significantly contributing to the rescue teams which were able to reach the survivors within the debris caused by the earthquake.

Another critical issue during and after rescue efforts is the transportation of the survivors to the hospitals within the shortest distance. This paper proposes a mathematical model and solution scheme to scan the disaster location using unmanned aerial vehicles and consequently routing the ambulances and other related vehicles to the appropriate hospitals/treatment centers in shortest time possible. The methodology involves two steps. The first step involves the mathematical formulation of vehicle routing to scan the area an initiate the rescue activities as fast as possible in the most efficient manner. The problem is modelled as a cluster coverage problem to route the aerial vehicles. The subsequent step involves routing the ambulances and a mathematical model is proposed by utilizing a multi-warehouse VRP to suggest the quickest transportation of the injured people to the hospitals. Various scenarios are applied to the proposed model, using GAMS software. The data used for the scenarios are generated by visiting the earthquake sites.

The paper is structured in the following way. The first part presents the scope of the study along with the related studies in the literature. The first major contribution of this research is to present a comprehensive review of related literature summarized in Table 1. In the next section, theoretical framework in disaster management is presented. The third section includes problem details as well as the mathematical models formulated for the problem. The last section involves experimental results and the discussion over the findings along with the future direction for subsequent research efforts.

In this study, the problem of ambulance routing has been taken into consideration. This issue can be associated with the following topics in the related literature; disasters, natural disasters, disaster management, disaster logistics, emergency logistics, emergency logistics, humanitarian aid logistics, and earthquake logistics. There are many studies in the literature on the mentioned issues, some of which are given in Table 1

Table 1
Literature review

Author	Method	Content
Yi and Ozdamar [2007]	Mixed integer commodity network flow model	Coordinating logistical support and evacuation processes in disaster response
Gormez [2008]	Model Development	Disaster response and aid center location selection
Gul[2008]	Mixed integer programming	Post-disaster casualty transportation logistics for a possible earthquake
Yuan and Wang [2009]	Model Development – Dijkstra – Ant colony algorithm	Choosing the best way in emergency logistics management
Tanrıoven [2010]	Simulation	Ambulance guidance after disaster
Ozbek [2011]	Bayesian Networks	Prediction system of pre-disaster mitigation and preparedness studies based on Bayesian networks
Unal [2011]	P-median, Floyd Algorithm and AHP	Post-disaster nutrition and shelter location selection model
Hong and Xiaohua [2011]	AHP	Emergency logistics centers location selection
Lin et al. [2011]	Integer Programming Model-Heuristic Approach-Genetic Algorithm	Logistics design for delivery of priority items in disaster relief operations
Doyen [2012]	Random integer programming	Humanitarian supplies logistics
Zhang J. et al. [2013]	Steiner tree-Intelligent algorithm	Multi-objective location model review
Zhang X. et al. [2013]	Amoeboid algorithm	Route selection in emergency logistics management
Roh et al. [2013]	AHP	Humanitarian depot location
Agdas et al. [2014]	SMAA-2	Location of disaster distribution centers
Kalkanci [2014]	Edge Routing	Assigning and routing snow plows to priority routes
Sahin et al. [2014]	Model Development	Containers of relief supplies to run [mobile-temporary] in s possession, the location and number of
Sheu and Pan [2014]	Mixed Integer Linear Programming Model	Design an uninterrupted central emergency supply network
Liberatore et al. [2014]	RecHADS Model	Recovery of transport infrastructure elements and aid distribution planning

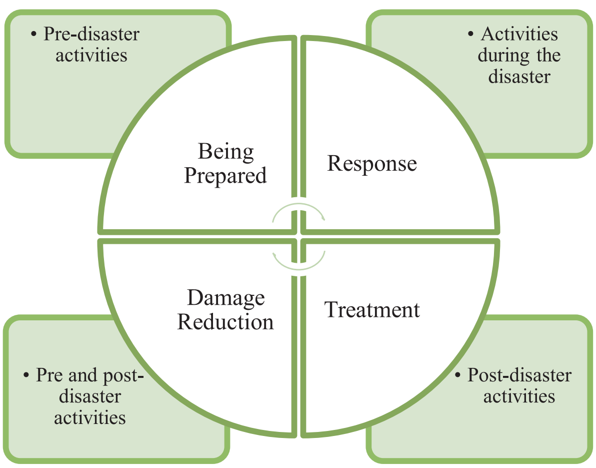
Table 1 *(ending)*

Author	Method	Content
Khojasteh [2014]	Stochastic optimization model	Determining the settlements of medical aid material stores to be used after a disaster
Konu [2014]	Model Development	Multi-product warehouse location determination and pre-positioning of humanitarian elements
Vafaei and Oztaysi [2014]	AHP	Determination of the optimum location of the field hospital
Arslan and Ertem [2015]	Model Development	Using containers, determining the number and location of disaster relief materials instead of stocking them in warehouses
Topal [2015]	Model Development	Transport of disaster relief supplies as soon as possible
He and Liu [2015]	SEIR Model Prediction-Model Development	Building a logistics model with emergency medical demand estimation and aid distribution over the SARS epidemic
Huang et al. [2015]	Uncertainty Theory-4PLROP uncertain programming model	A fourth-party logistics routing optimization with uncertain delivery time in emergencies
Ahmadi et al. [2015]	Stochastic Programming	Multi-store location routing
Ozkapici [2015]	Model Development	Intermodal aid material distribution [sea and road transport]
Peker et al. [2016]	AHS-VIKOR	Location of disaster distribution centers
Ayvaz and Aydin [2016]	Cluster Coverage and P-Median	Disaster logistics warehouse location selection
Uslu [2016]	Stochastic demand multi-warehouse vehicle routing -Model development	Delivering relief supplies as soon as possible after disasters and determining vehicle routes
Tofighi et al. [2016]	Developing a probabilistic-stochastic programming approach	Logistic network design of multiple central warehouses and local distribution centers for potential earthquakes
Ransikarbum and Mason [2016]	Target Programming	Strategic supply distribution and integrated response and recovery for early stage network restoration decisions
Kavlak [2016]	Integer Linear Programming Model	Providing aid materials without handling by a flexible intermodal transport system
Kucuk [2016]	Stochastic programming	Temporary-disaster-response facilities location
Demirdogen et al [2017]	SMAA-2	Location of disaster distribution centers
Ofluoğlu et al. [2017]	ENTROPY-TOPSIS	Disaster logistics warehouse location selection
Yaprak and Merdan [2017]	Stock Control-Demand Analysis	Stock levels of aid materials to be kept in disaster logistics warehouses
Sahin [2017]	Fuzzy VIKOR-Fuzzy TOPSIS	Selection of temporary shelter in case of disaster
Boonmee et al. [2017]	Deterministic , dynamic, stochastic and robust plant location problems	Facility location before and after the disaster
Baskaya et al. [2017]	Model Development	Lateral transfer [number] opportunities, disaster relief facility locations and number, number of relief supplies
Sebath [2017]	Decision Support System	Disaster response facilities [GAM] placement
Haghi et al. [2017]	Multi-purpose programming model	Determination of the locations of health centers and distribution centers
Kaya [2018]	Model Development	Number and location of aid stations in disasters
Kucuk and Cavdur [2018]	Route generation-elimination algorithm and Integer Programming	Post-disaster relief material handling, routing and assigning vehicles to routes
Konu et al. [2018]	Model Development	Pre-positioning aid materials
Wang et al. [2018]	Ideal point algorithm-Ant colony	Urgent material shipment and transportation
Zhang et al. [2018]	Uncertainty Model Development	Multi-area emergency facilities location selection
Roh et al. [2018]	Fuzzy AHP-Fuzzy TOPSIS	Choosing the most suitable warehouse location for international humanitarian organizations
Loree and Aros-Vera [2018]	Model Development	Determining the location of distribution points and allocation of inventory in post-disaster humanitarian logistics
Vahdani et al. [2018]	Model Development-NSGAII and MOPSO algorithms	Two multi-purpose and multi-period geolocation – inventory models for three-level relief chain

Table 1 *(ending)*

Author	Method	Content
Trivedi [2018]	DEMETAL	Choosing a place of shelter for disaster planning
Ozbay [2018]	Mixed integer modeling	Tent – city location selection after the earthquake
Samarah [2018]	Model Development	Warehouse location selection before disaster
Abbasoglu [2019]	Demand Forecast-Facility Layout Model	Location of disaster distribution centers
Sozen [2019]	Model Development- AHP-Conic target programming	Choosing the most suitable disaster logistics system
Zhang et al. [2019]	Stochastic programming model	Emergency resource allocation
Temur et al. [2019]	AHP and P-median Model	Establishing a humanitarian aid distribution center after an earthquake
Suzuki [2019]	Material Convergence [p-method, m-method]	The effect of material convergence on last mile distribution in humanitarian logistics
Cotes and Cantillo [2019]	Model Development	Plant layout for material positioning in the flood area
Maharjan and Hanaoka [2019]	Model Development	Developing a multi-objective location allocation model for disaster response facilities
Acar and Kaya [2019]	Stochastic programming	Network design taking into account the displacement and displacement of mobile hospitals for an expected earthquake
Cavdur and Sebatlı [2019]	Decision Support System - Stochastic programming	Temporary disaster response facility allocation for relief supplies distribution under demand uncertainty
Davoodi and Goli [2019]	Model Development	Prevention of late arrival of aid vehicles to disaster areas in critical situations
Keser [2019]	AHP	Disaster logistics warehouse organization location selection
Dorum [2019]	Model Development	Multi-period , multi-material optimal inventory positioning and routing after natural disaster
Mostajabdaveh [2019]	Mixed integer programming-Genetic algorithm	Selection of shelter in disaster and distribution of aid materials to shelters
Feng et al. [2020]	Model Development	Location of emergency material pools
Budak et al. [2020]	Fuzzy DEMETAL-Fuzzy ANP-Fuzzy TOPSIS	Application of real-time location systems to humanitarian logistics
Oksuz and Satoglu [2020]	Stochastic programming	Determining the location and number of temporary medical centers in case of disaster

Fig. 1. Phases in Disaster Management



Source: [Uslu, 2016].

1. SCIENTIFIC FOUNDATIONS

Although the causes of disasters vary, they all have the potential to have significant life and property damages which require carefully planned and coordinated efforts spanning pre-disaster and post-disaster time window. While pre-disaster measures have the greatest impact in minimizing the casualties and property damages, post-disaster measures are also critical towards the same goal. Disaster management includes the planned efforts to increase awareness of people on the natural conditions in their regions, recognition of the reasons for occurrence, and helping the residents of the region not to be affected if similar situations repeat in the future [Erkal and Degerliyurt, 2009]. Tanyas et al. claims that disaster management should focus on minimizing the damage rather than optimizing the events [Tanyas et al.2013].

Pre-disaster planning and disaster logistics are critical components in disaster management and they will eventually evolve into post-disaster practices [Agdas et al.2014]. Disaster logistics can be defined as the group of studies on the delivery of first aid materials, food supplies, and rescue teams to various points affected by the disaster, transporting the injured people from the area as fast as possible and reaching hospitals for the required treatment [Barbarosoglu et al. 2002].

2. MATERIALS AND METHODS

Erzincan city located on the Northern Anatolia Fault Line is taken into consideration for this research. Post-disaster activities following a destructive earthquake start with scanning the area with the aim of determining the collapsed buildings. The earthquake took place in Elazig in the same region on 2020 is where the aerial vehicles were successfully used and resulted in significant benefits. This study aims to assess the performance of the unmanned aerial vehicles in cluster coverage problem to calculate the optimal number of vehicles to cover the area. The number of aerial vehicles needed to scan the area was calculated for 68 neighborhoods in Erzincan province. Consequently, assignment of injured people to the six hospitals within the same region and ambulance routing problem is discussed in this section.

2.1. Coverage Problem

Cluster coverage problems are usually associated with location decisions. The purpose of using this type of mathematical models is to determine the number of supply facilities that can meet the demand of a set of demand facilities in a way that will minimize the total cost or maximize the area covered. Below is a list of coverage problems (Kara, 2014):

– Highest Space Coverage Problem [Sarikaya et al. 2020]
– Cluster Coverage Problem [Aktas et al. 2011, Sezen and Erben 2019, Ozturk et al. 2013]
– Double Coverage Problem [Catay et al. 2008]
– Reserve Coverage Problem [Catay et al. 2008].

Indices:

i = Index indicating the demand points i = 1, 2, 3, …., T
j = Index indicating facility points j = 1, 2, 3, ….. , S

Parameters:

$$a_{ij}=\begin{cases}1 & \text{if the facility j meets the demand of demand i}\\ 0 & \text{otherwise}\end{cases} \qquad \forall\, i, j$$

$$M_j = \text{fixed of facility j} \quad \forall\, j$$

Decision Variables:

$$x_j=\begin{cases}1 & \text{if facility is is to be establised at j}\\ 0 & \text{if not}\end{cases} \qquad \forall\, j$$

Objective Function:

$$\text{Min} \sum_{j=1}^{S} M_j * x_j \qquad (2.1.1.1)$$

Constraints:

$$\sum_{j=1}^{S} a_{ij} * x_j \geq 1 \quad \forall i \qquad (2.1.1.2)$$

$$x_j \in \{0,1\} \quad \forall j \qquad (2.1.1.3)$$

If the costs are the same for each facility to be opened, the objective function is:

$$\text{Min} \sum_{j=1}^{S} x_j \qquad (2.1.1.4)$$

2.1.1. Cluster Coverage Model

These types of problems are mainly used to determine the number of emergency aid locations and distribution centers in disasters. Mathematical model of the cluster coverage problem is presented as it follows [Aktas et al. 2011]. The provided model is formulated for S facility points and T demand points.

While the aim in Equation 2.1.1.1 is minimizing the total cost, the aim is minimizing the number of facilities to be opened in Equation 2.1.1.4 since facility opening costs are equal. Equation 2.1.1.2 represents the constraint which cuts the inclusion of each demand point of the facilities to be opened. Constraint 2.1.1.3 ensures the decision variables have integer values.

2.1.2. Cluster Coverage Model to Determine the Number of Aerial Vehicles

Number of aerial vehicles to be utilized for scanning purposes after the earthquake, the model presented below is built on the mathematical model discussed in the previous section.

Determining the optimum number of aerial vehicles to be utilized to screen the disaster area is the objective of using this model in the implementation study presented in Section 3.

Indices:

i = Index indicating the neighborhood i = 1, 2, 3 ,…., T

j = Index indicating the neighborhood to be centered for UAVs j = 1, 2, 3 ,… .., S

Parameters:

$$a_{ij}=\begin{cases}1 & \text{if the center neighborhood at point j is covering the neighborhood i}\\ 0 & \text{otherwise}\end{cases}$$

∀ i, j

Decision Variables:

$$x_j=\begin{cases}1 & \text{j point center neighborhood is chosen}\\ 0 & \text{otherwise}\end{cases} \qquad \forall\, j$$

Objective Function:

$$\text{Min} \sum_{j=1}^{S} x_j \qquad (2.1.2 .1)$$

Constraints:

$$\sum_{j=1}^{S} a_{ij} * x_j \geq 1 \quad \forall i \qquad (2.1.2.2)$$

$$x_j \in \{0,1\} \quad \forall j \qquad (2.1.2.3)$$

2.2. Vehicle Routing Problem

Compared to the Traveling Salesman Problem, Vehicle Routing Problem is more challenging due to more constraints and multiple tools. Vehicle routing problems are classified as NP-Hard [Demirtas and Ozdemir, 2017]. This problem type was first introduced by [Dantzig and Ramser 1959], and later this study was developed by [Clarke and Wright 1964] and the classical saving method was introduced. Although there are variations in terms of constraints [Duzakın and Demircioglu 2009], 3 areas emerge. These are:

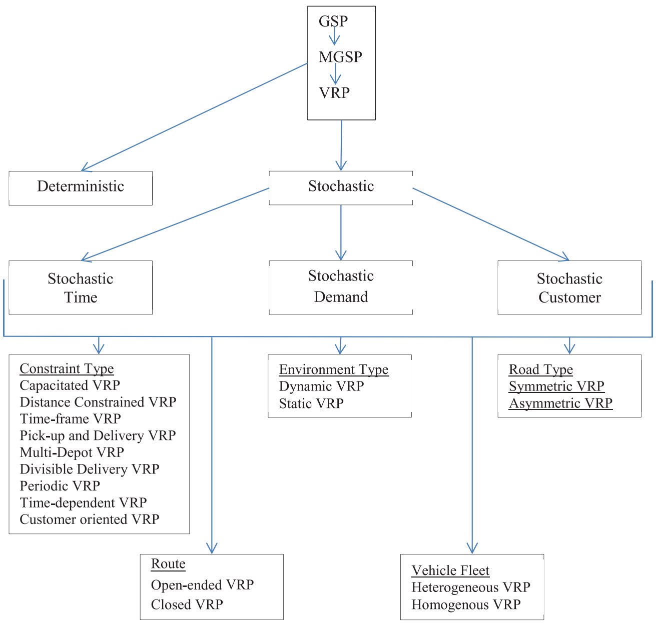
Constraints on current clients
– Constrained time windows for distribution of product/service claims
– Each client has one or more demand constraints

Constraints on the planned vehicles to be utilized
– Limitations on total vehicle time

- Weight or volume constraints of vehicles
- Constraints on legal working hours of vehicle drivers

Other constraints
- Tours exceeding one day length
- Number of tours of the vehicles is more than one restrictions
- Number of facilities to be used is more than one.

Fig. 2. Vehicle routing problem types



Sets;

I: Depots

J: Customers

K: Vehicles

Parameters;

N: Total number of customers

c_{ij}= distance between i and j points i, j Є I U J

v_i= capacity of the depot I, i ЄI

d_j= demand from customer j, j ЄJ

q_k= capacity of vehicle k, k ЄK

Decision variables;

$$x_{ijk}=\begin{cases}1, & \text{if using vehicle k from point i to point j} \\ 0, & \text{otherwise}\end{cases} \qquad I, j \in IUJ$$

$$z_{ij}=\begin{cases}1, & \text{if customer j is assigned to depot} \\ 0, & \text{otherwise}\end{cases}$$

U_{lk}= dummy variable, which is the sub-tour elimination constraint on vehicle/route k

Mathematical Model;

$$\text{Min } Z = \sum_{i\in IUJ}\sum_{j\in IUJ}\sum_{k\in K} x_{ijk}\, c_{ij} \qquad (2.2.1.1)$$

$$\sum_{k\in K}\sum_{i\in IUJ} x_{ijk} = 1 \qquad \forall j\in J \qquad (2.2.1.2)$$

$$U_{lk} - U_{jk} + N x_{ljk} \le N-1 \qquad \forall\, l, j \in J, \forall\, k \in K \qquad (2.2.1.3)$$

$$\sum_{j\in IUJ} x_{ijk} - \sum_{j\in IUJ} x_{jik} = 0 \qquad \forall k\in K, i\in IUJ \qquad (2.2.1.4)$$

$$\sum_{k\in K}\sum_{i\in IUJ} x_{ijk} \le 1 \qquad \forall k\in K \qquad (2.2.1.5)$$

$$\sum_{i\in IUJ}\sum_{j\in J} d_j x_{ijk} \le q_k \qquad \forall k\in K \qquad (2.2.1.6)$$

$$\sum_{j\in J} d_j z_{ij} \le v_i \qquad \forall i\in I \qquad (2.2.1.7)$$

$$-z_{ij} + \sum_{u\in IUJ}(x_{iuk} + x_{ujk}) \le 1 \qquad \forall i\in I, j\in J, k\in K \qquad (2.2.1.8)$$

$$x_{ijk}\in\{0,1\} \quad \forall i\in I, j\in J, k\in K \qquad (2.2.1.9)$$

$$z_{ij}\in\{0,1\} \quad \forall i\in I, j\in J \qquad (2.2.1.10)$$

$$U_{lk} \ge 0 \ \forall l\in J, k\in K \qquad (2.2.1.11)$$

The problem investigated within the scope of this research is closely related to the Multi-Depot Vehicle Routing Problem (MD–VRP), thus MD–VRP is explained in the following section.

2.2.1. Multi-Depot VRP

MD–VRP is a particular case of VRP problem and it aims providing service to multiple clients using multiple facilities in the shortest time and minimum cost possible while finding optimum vehicle routes. Some studies using this problem type appear as follows. [Yilmaz, 2008] made the modeling of the multi-depot VRP with an ant colony algorithm and proposed a solution. [Yildiz, 2011] discussed the problems of VR charts in logistics industry. [Onder, 2011] discussed the bread distribution of Istanbul Public Bakery Facilities as a multi-depot VRP. In his study, [Ozer, 2016] modelled a multi-depot VRP (MD–VRP) to trasport liver transplantation to transplant centers in the shortest time. [Kiziloglu, 2017] studied the stochastic multi-depot VRP with heuristic solutions using a chance constraint approach. [Sadatizamanabad, 2018] utilized a multi-depot VRP in supply chain networks aiming to protect critical facilities. [Ozen, 2020] proposed a mathematical model for an open-ended MD–VRP for the feeder bus network design.

Assigning vehicles to the facilities and clients to the vehicles while ensuring that the demands do not exceed the vehicle capacities are the main constraints for the mathematical model introduced in this study. It is the objective to determine which clients being served from which facility and using which vehicle. It is imperative to decide which patients should be treated in which hospital and transported to the hospital using which vehicle. In the ambulance routing problem discussed in this study, hospitals are referred as depots, the injured people as clients and ambulances as vehicles.

The problem is solved using the mathematical model introduced by [Mirabar, 2010] for the MD–VRP:

The objective function of the model is minimizing the distance traveled. Constraint (2.2.1.1) refers to the assignment of each customer to a single route. (2.2.1.3) expresses the sub-route elimination. (2.2.1.4) shows that each node in the routes has one entry and exit. (2.2.1.5) indicates that each vehicle is dispatched from one and only depot. (2.2.1.6) shows that the demands of the clients on each route are not more than the capacities of the vehicles on the routes. (2.2.1.7) indicates that each customer demand is not more than the capacity of the depot to which it is assigned. The constraint (2.2.1.8) shows that each customer is on the route of the depot to which it is assigned. (2.2.1.9, 10, 11) are the sign constraints of the decision variables.

2.2.2. Mathematical Model Developed for Ambulance Routing Problem

Following the model that [Mirabi, 2010] has proposed for MD–VRP, the mathematical model that is introduced here is provided under this section. The model itself is one of the main contributions of this study to the available literature. Another contribution is the development of another model named ambulance routing problem which is formulated based on this problem. To the best of our knowledge there is no study on the in the literature on ambulance routing problem. Thus, the study is unique in the sense that both the problem itself and the developed mathematical model are new.

Ambulance routing problem discussed within the context of this research aims moving the injured people to the nearest treatment facilities in the fastest way possible given the existing constraints. On the other hand, considering the capacities of the ambulances, it is critical that ambulances make multiple trips and deliver people to the hospitals. Meanwhile, it is considered that ambulances will transport the injured people to different hospitals in case the capacities of the hospitals are full. Fig. 3 illustrates the network of hospitals, ambulances, and wreckage areas in certain areas of the city.

Fig. 3. An example solution to the problem

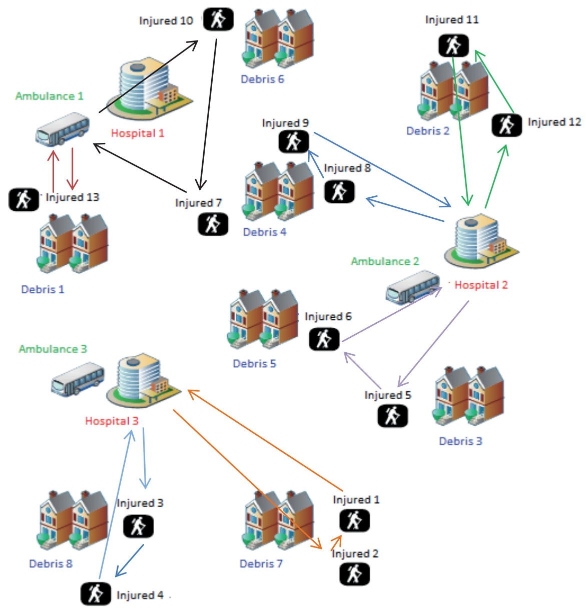


Fig. 3 indicates that there are three hospitals, three ambulances, and thirteen individuals to be taken to the hospitals. The model assumes the hospital capacities are defined and ambulances can transport two individual together. The solution scheme provided in the figure shows that two trips are assigned to the first ambulance, while three trips are assigned to the second, and two trips are assigned to the third ambulance. Another observation is that the seventh and tenth individuals are transported in the first trip while the thirteenth individual is transported on the second trip. Similarly, the remained assignments of injured people to the trips can also be observed in the figure. The solution takes the hospital and ambulance capacities were also taken into account.

The model shown in fig. 3 incorporates various assumptions, constraints, and parameters which are specified as below:

– All injured individuals must be carried to a hospital.
– Suggested solution should satisfy the ambulance and hospital.
– Capacities of the ambulances are assumed to be the same.
– Ambulances can be assigned multiple trips.
– An ambulance can carry the injured individual to the hospitals other than the one that it belongs, but it arrives at the next incident point after stopping at the hospital to which it will carry the patient in the first place to take the necessary equipment.

Index sets;
I: Hospitals
J: Injuries
K: Ambulances
M: Trips

Parameters;
N: Total number of injuries
c_{ij}= distance between i and j points i, j Є I U J
v_i= capacity of hospital i, i ЄI
d_j= demand of injury j, j ЄJ
q_k= capacity of ambulance k, k ЄK
b_m= cost of trip m, m ЄM

Decision variables;

$$x_{mijk}=\begin{cases}1, & \text{if ambulance k is used from point i to point j with trip m}\\ 0, & \text{otherwise}\end{cases} \qquad i,j \in I \cup J$$

$$z_{mij}=\begin{cases}1, & \text{if injured j is transported to hospital i with trip m}\\ 0, & \text{otherwise}\end{cases}$$

$$p_{mijk}=\begin{cases}1, & \text{if ambulance k goes to hospital j from hospital i with trip m}\\ 0, & \text{otherwise}\end{cases}$$

U_{mlk}= dummy variable of sub-tour elimination constraint at k ambulance/route
h_m= variable showing the availability of trip m

Mathematical Model;

$$\text{Min } Z = \sum_{m\in M}\sum_{i\in I\cup J}\sum_{j\in I\cup J}\sum_{k\in K} x_{mijk}\, c_{ij} + \sum_{m\in M}\sum_{i\in I}\sum_{j\in I}\sum_{k\in K} p_{mijk}\, c_{ij} + \sum_{m\in M} h_m b_m \qquad (2.2.2.1)$$

$$\sum_{m\in M}\sum_{k\in K}\sum_{i\in I\cup J} x_{mijk} = 1 \qquad \forall j\in J \qquad (2.2.2.2)$$

$$U_{mlk} - U_{mjk} + N x_{mljk} \le N-1 \quad \forall l,j\in J,\ \forall k\in K,\ \forall m\in M \qquad (2.2.2.3)$$

$$\sum_{j\in I\cup J} x_{mijk} - \sum_{j\in I\cup J} x_{mjik} = 0 \qquad \forall k\in K, i\in I\cup J, m\in M \qquad (2.2.2.4)$$

$$\sum_{k\in K}\sum_{i\in I\cup J} x_{mijk} \le 1 \qquad \forall k\in K, m\in M \qquad (2.2.2.5)$$

$$\sum_{i\in I\cup J}\sum_{j\in J} d_j x_{mijk} \le q_k \qquad \forall k\in K, m\in M \qquad (2.2.2.6)$$

$$\sum_{j\in J} d_j z_{mij} \le v_i \qquad \forall i\in I, m\in M \qquad (2.2.2.7)$$

$$-z_{mij} + \sum_{u\in I\cup J} (x_{miuk} + x_{mujk}) \le 1 \qquad \forall i\in I, j\in J, k\in K, m\in M \qquad (2.2.2.8)$$

$$-1 + \sum_{j\in J} x_{mijk} + \sum_{j\in J} x_{wtjk} - \sum_{o\in M}\sum_{j\in J} x_{oijk} \le p_{mitk} \qquad (2.2.2.9)$$
$$\forall i\in I, t\in I, k\in K, (m,w,o)\in M, \quad i \ne t, m > o > w, m > 1$$

$$x_{mijk} = 0 \quad \forall i\in I, j\in I, k\in K, m\in M \qquad (2.2.2.10)$$

$$\sum_{i\in I}\sum_{j\in J} z_{mij} = h_m \quad \forall m\in M \qquad (2.2.2.11)$$

$$\sum_{i\in I}\sum_{j\in J} z_{mij} * 1000 \ge \sum_{i\in I}\sum_{j\in J} z_{(m+1)ij} \qquad (2.2.2.12)$$

$$x_{mijk}\in\{0,1\} \quad \forall i\in I, j\in J, k\in K, m\in M \qquad (2.2.2.13)$$
$$z_{mij}\in\{0,1\} \quad \forall i\in I, j\in J, m\in M \qquad (2.2.2.14)$$
$$U_{mlk} \ge 0 \quad \forall l\in J, k\in K, m\in M \qquad (2.2.2.15)$$

IMathematical model developed based on the above-mentioned assumptions is provided as it follows:

In the objective function of the model (2.2.2.1), the total travel time, the cost of ambulances going to distant hospitals, and the costs resulting from the additional trips were aimed to be minimized. Constraint (2.2.2.2) implies assigning a single route for each injured. Constraint (2.2.2.3) represents the sub-tour elimination. Constraint (2.2.2.4) means that each node in the routes has a single entry and exit. Constraint (2.2.2.5) means that each ambulance leaves a single hospital. Constraint (2.2.2.6) limits the demands of the injured individuals on each route with the capacities of the ambulances on the routes. Constraint (2.2.2.7) ensures each injured individual demand does not exceed the capacity of the hospital to which it is assigned. Constraint (2.2.2.8) means that each injured person is on the route of the hospital to which they are assigned. Constraint (2.2.2.9) ensures that ambulances are directed to the same and nearest hospital, if possible. Constraint (2.2.2.10) ensures that the transfer between hospitals is not assigned to each other at the relevant time. Constraint (2.2.2.11) allows the trips to be activated gradually. Constraint (2.2.2.12) ensures the assignment of injured people to be transported in the initial trips to a large number of hospitals. (3.2.2.13–2.2.2.14–2.2.2.15) are the constraints limiting the signs of the decision variables.

The developed model is tested on several scenarios and its results are analyzed within the next section.

Table 2.
District clusters obtained from the cluster inclusion problem

Cluster Number (Representation)	Central Clusters	District Numbers Covered
1 (A)	6. Davarlı	6
2 (B)	8. Büyük Çakırman	8
3 (C)	11. Bayrak	11
4 (D)	24. Gazi	1, 2, 5, 10, 12, 14, 15, 16, 20, 21, 22, 24, 31, 43
5 (E)	39. Mengüceli	9, 13, 27, 32, 36, 39, 48, 49, 51, 54, 56, 60, 61, 62, 63, 64
6 (F)	50. Sarıgöl	3, 4, 7, 17, 18, 19, 23, 25, 28, 30, 34, 35, 37, 38, 40, 41, 44, 50, 52, 53, 55, 57, 58, 59, 65, 66
7 (G)	67. Terzibaba	26, 29, 33, 42, 45, 46, 67, 68

3. Research findings

Central district of Erzincan province is used as a benchmark in this research and based on the most recent earthquake in the same region, debris scanning and the most efficient transportation of the injured people to the hospitals are searched. Mathematical models are developed (Sections 3.1.1. and 3.2.1.) for debris scanning and transporting people from incident locations to the hospitals. The following section presents the data used to test the models as well as the information on the implementation.

3.1. Ideal number aerial vehicles

Cluster coverage problem for 68 districts of Erzincan was investigated and the necessary number of UAVs was calculated. The main goal of this problem type is to cover the maximum number of areas using the minimum number of facilities. Treating the unmanned aerial vehicles as facilities, it is aimed to determine the required number of them. To find out the required number of aerial vehicles, the distance matrix of the neighborhoods is generated using Google Maps. The distance values indicate the minutes of the distance traveled by vehicles. The number of aerial vehicles needed to scan the area was determined using the mathematical model in Section 3.1.2, assuming that the aerial vehicles scan distances of 5–10–15–20 minutes.

The solution scheme obtained from Gams software indicates that 17 UAVs are needed for a 5-minute scanning distance while 7 UAVs are required for a 10-minute distance, 2 UAVs for a 15-minute scanning distance, and 2 UAVs for a 20-minute scanning distance. Taking the need for a more detailed scanning after an earthquake into account, 7 UAVs are assumed to be needed in developing datasets in the application stage of ambulance routing problem and the injured individuals are transported to the appropriate districts considering such clusters. The district clusters that occur when 7 UAVs are used are given in table 2.

Datasets are developed based on the mathematical model developed for the ambulance routing problem was tested and presented in the following section.

Table 3
Random distribution of the injured by the district clusters

Trial	Number of Injured	Cluster + District (Number of Injured)
1	10	A6(1)-B8(1)-C11(1)-D1(1)-D2(1)-E9(1)-E13(1)-F3(1)-F4(1)-G26(1)
2	10	A6(1)-B8(1)-C11(1)-D5(1)-D10(1)-E27(1)-E32(1)-F7(1)-F17(1)-G29(1)
3	10	A6(1)-B8(1)-C11(1)-D12(1)-D14(1)-E36(1)-E39(1)-F18(1)-F19(1)-G33(1)
4	10	A6(1)-B8(1)-C11(1)-D15(1)-D16(1)-E48(1)-E49(1)-F23(1)-F25(1)-G42(1)
5	20	A6(1)-B8(1)-C11(1)-D20(1)-D21(1)-E51(2)-E54(2)-E56(2)-F28(2)-F30(2)-F34(2)-F35(2)-G45(1)
6	20	A6(2)-B8(4)-C11(1)-D22(1)-E60(2)-E61(2)-F37(2)-F38(2)-F40(2)-G46(2)
7	20	A6(3)-B8(1)-C11(3)-D24(1)-E62(3)-F41(1)-F44(1)-F50(1)-F53(1)-F55(1)-G67(3)
8	20	A6(4)-B8(4)-C11(4)-D31(1)-D43(1)-E63(1)-E64(1)-F57(1)-F58(1)-F59(1)-G68(1)
9	30	A6(1)-B8(1)-C11(4)-D1(3)-D2(3)- D5(3)- D10(3)-E9(1)-E13(1)-E27(1)- E32(1)-F65(2)-F66(2)-G26(2)-G29(2)
10	30	A6(1)-B8(1)-C11(2)-D12(4)-D14(4)-E36(2)-E39(2)-E48(2)- E49(2)-F3(1)-F4(1)- F7(1)- F18(1)-F19(1)- F23(1)-G33(2)- G42(2)
11	30	A6(1)-B8(1)-C11(1)-D15(3)-D16(3)-D20(3)-E51(3)-E54(3)-E56(3)-F23(1)-F25(1)- F28(1)-G45(3)-G46(1)-G67(1)-G68(1)
12	30	A6(1)-B8(1)-C11(1)-D21(4)-D22(4)-D24(4)-D31(4)-E60(1)-E61(1)-E62(1)-E63(1)-F30(1)-F34(1)-F35(1)-F37(1)-G26(1)- G29(1)-G33(1)
13	40	A6(1)-B8(1)-C11(1)-D1(5)-D2(4)-D5(3)-E9(4)-E13(5)-E39(4)-E51(4)-F65(2)-F66(2)-G45(3)-G46(1)
14	40	A6(2)-B8(4)-C11(2)-D15(4)-D16(4)-D20(4)-D24(4)-E48(2)-F25(4)-F28(4)-F30(4)-G67(2)
15	40	A6(1)-B8(1)-C11(1)-D12(3)-D14(3)- D31(3)- D43(3)-E32(1)-E36(1)-E39(1)- E48(1)-F30(3)-F34(3)-F35(3)-F37(3)-F38(3)-G33(6)
16	40	A6(4)-B8(4)-C11(1)-D20(1)-D21(1)-D22(1)-E60(4)-E61(4)-E62(4)-E63(4)-E64(4)-F17(1)-F18(1)-F19(1)-F23(1)-G68(4)

Table 4
Number of hospitals
and their total capacities

Trial	Number of Hospitals	Total Hospital Capacity
1	1	15
2	1	15
3	1	15
4	1	15
5	2	30
6	2	30
7	2	30
8	2	30
9	3	45
10	3	45
11	3	45
12	3	45
13	3	60
14	3	60
15	3	60
16	3	60

Table 5
Capacity distribution among
three hospitals

Trial	H1	H2	H3
1	15	X	X
2	X	15	X
3	X	X	15
4	15	X	X
5	10	20	X
6	X	14	16
7	12	X	18
8	10	20	X
9	15	15	15
10	10	20	15
11	15	12	18
12	12	15	18
13	20	20	20
14	20	36	4
15	21	3	36
16	4	40	16

Table 6
Distribution of ambulance numbers and capacities
and the number of injuries-trips

Trial	Number of Ambulances	Ambulance Capacity	Number of Injured	Number of Trips
1	2	1	10	5
2	2	2	10	3
3	2	3	10	2
4	2	4	10	2
5	4	1	20	5
6	4	2	20	3
7	4	3	20	2
8	4	4	20	2
9	6	1	30	5
10	6	2	30	3
11	6	3	30	2
12	6	4	30	2
13	8	1	40	5
14	8	2	40	3
15	8	3	40	2
16	8	4	40	2

3.2. Routing Ambulances

Seven district clusters were obtained by applying the mathematical model in section 2.1.2 for 68 districts of Erzincan. The mathematical model in section 2.2.2 has been tested based on these district clusters. The parameters addressed during the model trial are:

– Number of ambulances
– Ambulance capacity
– Number of hospitals
– Hospital capacity
– Number of trips
– Number of injured.

The mathematical model that was developed along with all these datasets and the assumptions was solved using the GAMS software and the computational results are presented in the following section.

4. Conclusion and recommendations

The proposed model was tested and ambulance routing for Erzincan was investigated for smaller examples. In the trial studies, the number of injured was changed to 10–20–30–40 and four trial studies were conducted for each injury cluster. Hospital capacities, ambulance capacities and number of trips varied in each injury cluster. At the same time, the responses of the system were examined by changing the ambulance capacities and the number of trips for the same injured locations in some trial studies. Solution times of the model that was solved with the help of the GAMS and explanations for the solution are provided in table 7.

The findings obtained as a result of the experiments are as follows. As a result of the first trial, the program gave a solution very quickly and the result was the optimum solution. However, in the second attempt, although the program ran for about an hour, it gave an acceptable solution, not an optimum. At the end of the third trial, the program again worked for about an hour, but gave an optimum solution. In the fourth trial, the ambulance capacity was gradually increased and the solution time of the program remained as one hour. The result was not an optimum but an acceptable value. As a result of the increase in the number of injured, only the fifth trial was solved in a short time and gave the optimum solution. However, other trial periods

Table 7. Results and solution times
of ambulance routing in GAMS program

Trial	Result	Solution Time (sec)	Solver Status	Model Status
1	22508	0.170	1	1
2	437	3600.024	3	8
3	201	3339.551	1	1
4	202	3600.014	3	8
5	44794	1.093	1	1
6	772	3600.124	3	8
7	295	3600.143	3	8
8	263	3600.078	3	8
9	67170	5400.505	3	8
10	1048	5400.299	3	8
11	499	5400.309	3	8
12	460	5400.305	3	8
13	89509	10801.429	3	8
14	—	—	—	—
15	595	10800.394	3	8
16	—	—	-	—

increased in direct proportion as a result of the increase in the number of injured. The results obtained were not optimum but acceptable values. The trials were considered as 40 wounded and 3 hospitals at most, but the program did not provide solutions within reasonable periods (around 3 hours for 40 injured) in 14 and 16 trials for randomly assigned injured numbers and locations. According to the trials, the increase in the number of injured and other variables prolonged the solution period of the program. At the same time, almost all of the obtained results received an acceptable value, not an optimum. And again, in case the system becomes complicated, the program could not get results within a reasonable time.

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