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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 studies is the development and examination of post-disaster search and rescue activities and treatment facilities. One of such issues to be considered while performing these operations is to reach the disaster victims within minimum time and to plan disaster logistics in the most efficient manner possible. In this study, the problem of planning debris scanning activities with Unmanned Aerial Vehicles after an earthquake and transporting the injured people to the hospitals by ambulances within minimum time was discussed, and mathematical models were developed to solve the problem. The ambulance routing problem and the mathematical model to be used in the solution to the problem are discussed for the first time in the literature. The developed model was tested on the problem sets created by taking into account the data of the province under investigation.

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

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# Оптимальная маршрутизация воздушных судов и машин скорой помощи в логистике при стихийных бедствиях

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## Аннотация

Одним из наиболее важных аспектов исследований по управлению рисками и чрезвычайными ситуациями является разработка и изучение поисково-спасательных мероприятий и очистных сооружений после стихийных бедствий. Одним из вопросов, которые необходимо учитывать при выполнении этих операций, является обеспечение доступа к жертвам стихийных бедствий в минимальные сроки и планирование логистики в случае стихийных бедствий наиболее эффективным способом. В данном исследовании рассматривается проблема планирования работ по спасению с помощью беспилотных летательных аппаратов после землетрясения и транспортировки пострадавших людей в больницы на машинах скорой помощи за минимальное время. Для решения этой проблемы были разработаны и предложены математические модели. Впервые рассматривается задача маршрутизации скорой помощи и математическая модель, которая будет использоваться для решения этой задачи. Разработанная модель была протестирована на множествах задач, созданных с учетом реальных данных исследуемой провинции Турции.

**Ключевые слова:** логистика при стихийных бедствиях, кластерный охват, задача маршрутизации транспортных средств с несколькими депо, задача маршрутизации скорой помощи, математическое моделирование.

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## Introduction

It is very difficult to predict the devastating damage caused by disasters. For this reason, it is necessary to take urgent precautions beforehand, during and after the disaster, to improve conditions and to plan for logistics. This makes it necessary to understand the concepts of disaster management and amnesty logistics thoroughly and to increase the importance of the studies on these concepts.

Disasters are divided into two groups as natural and human in terms of their occurrence [Sahin, Sipahiohlu, 2003]. While natural disasters occur as a result of nature's own actions, human disasters occur as a result of the increase of people's effects on nature. Earthquakes, storms, floods, hurricanes, avalanches and landslides are important natural disasters. Outbreaks, fires and transport accidents appear as human disasters. Earthquakes, like all other disasters, are situations that are very difficult to predict and they result in loss of life and property. Taking necessary precautions before an earthquake can be life-saving in case of an earthquake. Likewise, it is known that if the instructions to be applied during an earthquake are followed, the survival probability of people increases. However, even if all these measures are taken and implemented, there may be structures collapsed after a severe earthquake with a very high intensity and earthquake survivors struggling to survive. In such cases, it is vital to benefit from search and rescue as well as health services as quickly as possible.

The effective and rapid execution of search and rescue activities is possible by scanning the area where the earthquake occurred in a short time as well as determining the damage. In the earthquake that occurred on Friday, January 24, 2020 at 20.55 in Elazig, images were taken in a short period of 25 minutes with Unmanned Aerial Vehicles (UAV) and Manned Reconnaissance Aircraft (MRA) and transferred to the Gendarmerie Command Center. In addition, the MRA and UAVs used to scan 275 different points in 3 hours, making a very important contribution to search and rescue efforts. Later, the dead and wounded were reached through search and rescue efforts from earthquake debris.

One of the most important issues after the search and rescue efforts is the treatment of the injured and the transfer to the nearest hospitals in the shortest time. This research involves scanning the city center with UAVs and routing the restricted number of ambulances to the assigned hospitals in the minimum duration. In the first part of the study, the problem of UAV routing was focused on in order to scan for debris and start search and rescue studies quickly and efficiently. The mathematical model of the cluster coverage problem was used while routing the UAV. In the second part, the ambulance routing problem was discussed and a new mathematical model was developed by using the multi-warehouse vehicle routing problem in the literature in order to provide the fastest treatment for injured people who were reached through search and rescue studies. The developed model was then tested on different scenarios with the help of the GAMS program. While developing the scenarios, the data is created by visiting the wreckage sites of Elazig province, which is on the earthquake zone and was shaken by a magnitude of 6.8 earthquake that caused 41 dead, 1466 injured and major damage on January 24, 2019.

In the first part of the study, the purpose and scope is specified, and the information about the studies in the literature on the subject is provided. The first major contribution of this study is to provide a comprehensive review of related literature summarized in table 1. In the second part, theoretical foundations such as disaster, disaster management, disaster logistics, and disaster types are mentioned. In the third part, the details of the problem

Table 1
Literature review

| Author | Method | Content |
|---|---|---|
| [Yi, 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, 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, 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 et al., 2013a] | Steiner tree-Intelligent algorithm | Multi-objective location model review |
| [Zhang et al., 2013b] | 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 |
| [Sheu, 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 |
| [Kara, 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, Oztaysi, 2014] | AHP | Determination of the optimum location of the field hospital |
| [Arslan, 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, 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 |

Table 1 *(ending)*

| Author | Method | Content |
|---|---|---|
| [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, 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, 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, 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 |
| [Sebatli, 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, 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, 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 |
| [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, Cantillo, 2019] | Model Development | Plant layout for material positioning in the flood area |
| [Maharjan, Hanaoka, 2019] | Model Development | Developing a multi-objective location allocation model for disaster response facilities |
| [Acar, Kaya, 2019] | Stochastic programming | Network design taking into account the displacement and displacement of mobile hospitals for an expected earthquake |
| [Cavdur, Sebatlı, 2019] | Decision Support System - Stochastic programming | Temporary disaster response facility allocation for relief supplies distribution under demand uncertainty |
| [Davoodi, 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, Satoglu, 2020] | Stochastic programming | Determining the location and number of temporary medical centers in case of disaster |

dealt with in the study are expressed and the mathematical models developed for the problem are introduced. In the fourth chapter, the research findings were shared, while the general evaluation of the study and information about future studies are presented in the last chapter.

Turkey is located on the world's most earthquake generating Alps-Himalayan seismic zone. This is the main cause of earthquakes in the country. Since earthquakes are not known in advance, people can only take the necessary precautions before an earthquake and the measures that should be applied during an earthquake with the best possibility. Even if all kinds of precautions are taken, the destructiveness and intensity of earthquakes can be very high. In other words, it makes debris scanning, logistics and health services much more important after an earthquake. For the stated reasons, UAV and ambulance routing have been chosen as the subject of this research. The scope of this study consists of the neighborhoods of the central district of Elazig province.

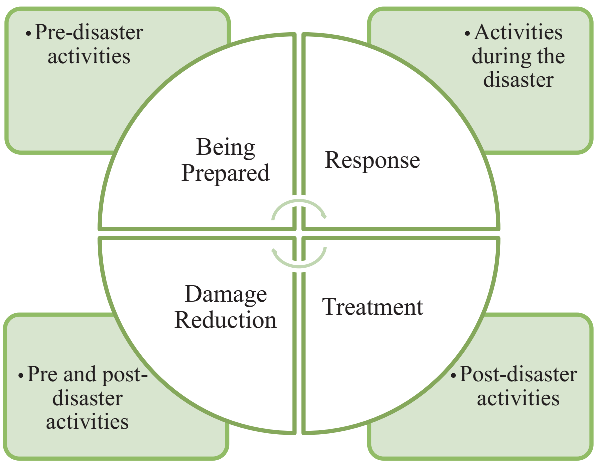
In this study, the problem of ambulance routing has been taken into consideration. This issue is related to the following topics in the relevant literature about disasters, natural disasters, disaster management, disaster logistics, emergency logistics, emergency logistics, humanitarian aid logistics, and earthquake logistics. There are many studies in the literature on the mentioned issues, some of which are given in table 1.

## 1. Scientific foundations

Disasters are caused by nature and human beings in terms of their types and cause loss of life and property. Regardless of the cause and source, it is necessary to minimize such losses. This includes disaster management measures to be implemented. At the same time, as disasters cannot be prevented, post-disaster logistics activities are also important in preventing significant casualties.

Disaster management involves the tasks carried out in order to make people aware of natural conditions that occur in the region they live in, to recognize the reasons for these situations in detail and to help them not to be affected in the face of repetition of such situations [Erkal, Degerliyurt, 2009].

Fig. 1. Phases in disaster management




*Source:* [Uslu, 2016].

In order for disaster management to be successful, it should aim at minimizing the damage rather than optimizing the events [Tanyas et al., 2013].

One of the most important issues in disaster management is pre-disaster planning and disaster logistics, which will turn into a post-disaster practice [Agdas et al., 2014].

Disaster logistics is expressed as the collection of studies on the transportation of first aid materials, equipment, food and beverage and search and rescue teams that may be in need of all kinds to very scattered points, removing the injured from the scene very quickly and taking them to health institutions for necessary treatment [Barbarosoglu et al., 2002].

## 2. Materials and methods

In this study, Elazig province, which is located on an earthquake zone, is taken into consideration. The first thing to do right after a severe and destructive earthquake is to scan the area where the earthquake occurred and to determine the places of debris. After the earthquake in the city on January 24, 2020, debris scanning was carried out with IKU and UAVs and very significant benefits were achieved. In this study, it is aimed to evaluate the UAVs in the cluster coverage problem and find the required number of UAVs. Using the mathematical model of the cluster coverage problem, the number of UAVs required to be used in screening was determined by evaluating the UAVs within 38 neighborhoods of the central district of the province. Then, taking into account the characteristics of 6 hospitals and multiple ambulance types in the central district of the province, the problem of assigning the injured to the hospital and routing the ambulances were discussed. Details on the related problems are given in the sections below.

### 2.1. Coverage problems

Coverage models are mostly used for location problems. While there are a certain number of customers (target/city/demand points) in the coverage models, it is aimed to determine the number of facilities (supply points) that will meet the needs of all of them in a way that will have the least cost or the largest coverage area.

Some of the coverage problems are given below [Kara, 2014]:

– cluster coverage problem [Aktas et al., 2011; Ozturk et al., 2013; Sezen, Erben 2019];
– highest space coverage problem [Sarikaya et al., 2020];
– double coverage problem [Catay et al., 2008];
– reserve coverage problem [Catay et al., 2008];
– reliable coverage problem.

#### 2.1.1. Cluster coverage problem

Cluster coverage is a type of model developed to respond to all demand points of the supply points planned to be established with the least cost. The most common use of cluster coverage models is to determine the number of emergency aid stations and distribution centers in case of disasters.

Cluster coverage Model is provided below [Aktas et al., 2011].

The written model is given for T demand points and S facility points.

Indices:

*i* = Index indicating the demand points i = 1, 2, 3, …., T

*j* = Index indicating facility points j = 1, 2, 3, ….. , S

Parameters:

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

$M_j$ = fixed of facility j $\forall$ j

Decision Variables:

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

Objective Function:

$$\text{Min} \sum_{j=1}^{S} M_j * x_j \qquad (3.1.1.1)$$

Constraints:

$$\sum_{j=1}^{S} a_{ij} * x_j \geq 1 \quad \forall i \qquad (3.1.1.2)$$

$$x_j \in \{0,1\} \quad \forall j \qquad (3.1.1.3)$$

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

$$\text{Min} \sum_{j=1}^{S} x_j \qquad (3.1.1.4)$$

While the aim in Equation 3.1.1.1 is to minimize the total cost, the aim is to minimize the number of facilities to be opened in Equation 3.1.1.4 since facility opening costs are equal. Equation 3.1.1.2 is the constraint that cuts the inclusion of each demand point of the facilities to be opened. Finally, 3.1.1.3 is the constraint of the decision variable to be an integer.

### 2.1.2. Cluster coverage model for determining the number of UAVs

Considering the mathematical model in the previous section, the following mathematical model has been established to determine the number of UAVs to be used in screening activities after the earthquake.

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:

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

Decision Variables:

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

Objective Function:

$$\text{Min} \sum_{j=1}^{S} x_j \qquad (3.1.2\ .1)$$

Constraints:

$$\sum_{j=1}^{S} a_{ij} * x_j \geq 1 \quad \forall i \qquad (3.1.2.2)$$

$$x_j \in \{0,1\} \quad \forall j \qquad (3.1.2.3)$$

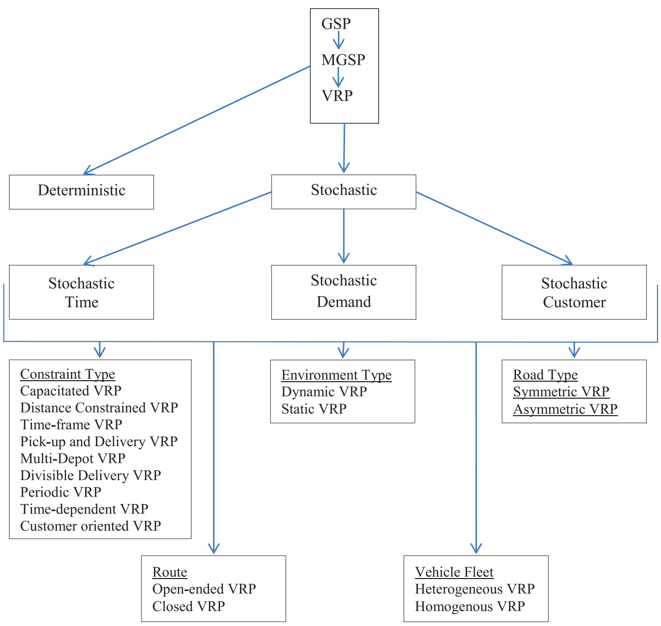
Using this model in the implementation study in Section 4, it was intended to determine the ideal number of UAVs to be used in screening activity for the province.

## 2.2. Vehicle routing problem

It is a much more difficult problem in terms of VRP solution with more constraints and multiple tools than the Traveling Salesman Problem (TSP). Again, the fact that VRP problems are static or dynamic does not prevent them from being included in the NP-Hard group [Demirtas, Ozdemir, 2017]. VRP was initially discussed by [Dantzig, Ramser, 1959], and later this study was developed by [Clarke, Wright, 1964] and the classical saving method was introduced. Although it varies in terms of VRP constraints [Duzakın, Demircioglu, 2009], 3 areas emerge. These are:

1) restrictions on the vehicles planned to be used
   – capacity constraints of vehicles in terms of weight or volume,
   – constraints on total vehicle time,
   – restrictions on legal working hours of vehicle drivers;
2) restrictions on existing customers
   – each customer has one or more product demand constraints,
   – limited time frames constraints for distribution of product claims;
3) other constraints
   – number of tours of the vehicles is more than one, the same vehicle returns to the warehouse on the same day and leaves for another road restrictions,
   – tours exceeding one day in terms of length,
   – the number of depots to be used is more than one.

Fig. 2. Vehicle routing problem types




It was determined that the problem dealt with in the scope of this study is related to the Multi-Depot Vehicle Routing Problem (MD-VRP) and the information about the MD-VRP is stated in the next section.

### 2.2.1. Multi-depot vehicle routing problem

In general, MD-VRP is a type of problem that deals with providing service to many customers from more than one warehouse in the shortest possible time and cost and determining vehicle routes. Some studies using this problem type appear as follows [Yilmaz, 2008] made the modeling of the multi-depot vehicle routing problem with the ant colony algorithm and proposed a solution. [Yildiz, 2011] discussed the problems of vehicle routing charts in the transportation sector. [Onder, 2011] discussed the bread distribution of Istanbul Public Bakery Factories as a multi-depot vehicle routing problem. In his study [Ozer, 2016] benefited from the problem of multi-depot vehicle routing to take liver transplantation to transplant centers in a short time [Kiziloglu, 2017] investigated the stochastic multi-depot vehicle routing problem with heuristic solutions under the chance constraint approach [Sadatizamanabad, 2018] used the multi- depot vehicle routing problem in supply chain networks and aimed to protect critical facilities [Ozen, 2020] developed the mathematical model of the open-ended multi-depot vehicle routing problem for the feeder bus network design.

In this problem, the assignment of the vehicles to the depot, the assignment of the customers to the vehicles and the customer demands not exceeding the vehicle capacities appear as important constraints. In line with these constraints, it is important to decide which customers should be served from which depot and with which vehicle. Within the scope of the subject dealt with in this study, it is important to determine which injured people will be served from which hospital and by which ambulance. In the ambulance routing problem addressed here, hospitals are considered as depots, the wounded as customers and ambulances as vehicles.

To solve the problem discussed in this study, following mathematical model developed by [Mirabi et al., 2010] for the MD-VRP was benefited from:

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;

$$\text{Min } Z = \sum_{i \in IUJ} \sum_{j \in IUJ} \sum_{k \in K} x_{ijk} c_{ij} \qquad (3.2.1.1)$$

$$\sum_{k \in K} \sum_{i \in IUJ} x_{ijk} = 1 \qquad \forall j \in J \qquad (3.2.1.2)$$

$$U_{lk} - U_{jk} + N x_{ljk} \leq N-1 \qquad \forall\, l, j \in J, \forall\, k \in K \qquad (3.2.1.3)$$

$$\sum_{j \in IUJ} x_{ijk} - \sum_{j \in IUJ} x_{jik} = 0 \qquad \forall k \in K, i \in IUJ \qquad (3.2.1.4)$$

$$\sum_{k \in K} \sum_{i \in IUJ} x_{ijk} \leq 1 \qquad \forall k \in K \qquad (3.2.1.5)$$

$$\sum_{i \in IUJ} \sum_{j \in J} d_j x_{ijk} \leq q_k \qquad \forall k \in K \qquad (3.2.1.6)$$

$$\sum_{j \in J} d_j z_{ij} \leq v_i \qquad \forall i \in I \qquad (3.2.1.7)$$

$$-z_{ij} + \sum_{u \in IUJ} (x_{iuk} + x_{ujk}) \leq 1 \qquad \forall i \in I, j \in J, k \in K \qquad (3.2.1.8)$$

$$x_{ijk} \in \{0,1\} \quad \forall i \in I, j \in J, k \in K \qquad (3.2.1.9)$$

$$z_{ij} \in \{0,1\} \quad \forall i \in I, j \in J \qquad (3.2.1.10)$$

$$U_{lk} \geq 0 \;\forall l \in J, k \in K \qquad (3.2.1.11)$$

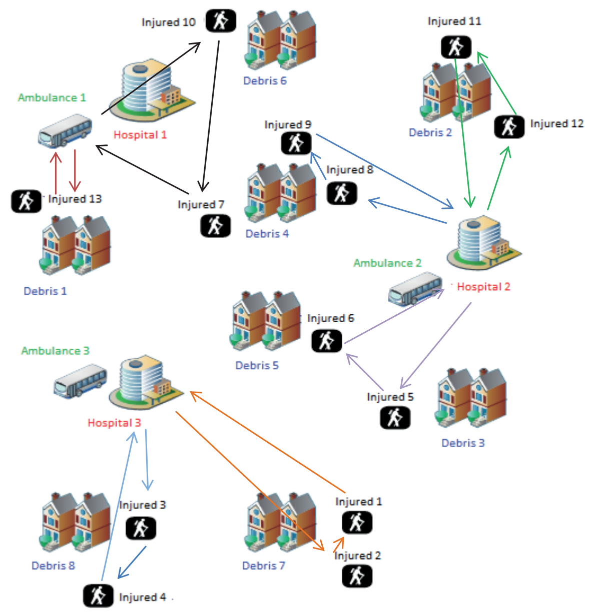
The objective function of the model is to minimize the distance traveled. Constraint (3.2.1.1) refers to the assignment of each customer to a single route (3.2.1.3) expresses the sub-route elimination (3.2.1.4) means that each node in the routes has a single entry and exit (3.2.1.5) means that each vehicle is dispatched from a single depot (3.2.1.6) means that the demands of the customers on each route do not exceed the capacities of the vehicles on the routes (3.2.1.7) means that each customer demand should not exceed the capacity of the depot to which it is assigned. The constraint numbered (3.2.1.8) means that each customer is on the route of the depot to which it is assigned (3.2.1.9, 10, 11) are the sign constraints for the decision variables.

### 2.2.2. Mathematical model developed for ambulance routing problem

Based on the mathematical model that [Mirabi et al., 2010] has developed for the multi-depot vehicle routing problem, the mathematical model that has been developed within this research, is presented in this section. This new model is the first major contribution of this research to the related literature. Another contribution is the introduction of a new type of problem called ambulance routing problem which has been developed based on this problem. It has been discovered that there is no study on the ambulance routing problem in the literature. For this reason, it has been determined that this study is different from other studies in the literature in terms of both the problem and the proposed mathematical model.

Ambulance routing problem covered within the context of this study aims to deliver the injured ones to the nearby hospitals in the most effective manner given the existing constraints. However, when ambulance capacities are considered, it is important that ambulances make more than one trip and deliver the other injured people to hospitals. At the same time, it is considered that ambulances will transport the injured to different hospitals in case the hospital capacities are over. fig. 3 shows the hospitals, ambulances, and casualty locations in some parts of the city.

Fig. 3. An example solution to the problem



In the sample problem presented in fig. 3, it can be observed that there are 3 hospitals, 3 ambulances and 13 injured. Here, it is assumed that each ambulance can carry a maximum of 2 patients at once and capacities for each hospital are defined. According to the solution presented in this figure, "1st ambulance has 2 trips", "2nd ambulance has 3 trips" and "3rd ambulance has 2 trips". The 1st ambulance carries the 7th and 10th individuals on the first trip, and the 13th on the 2nd trip. The second ambulance carries the 5th and 6th individuals on the first trip, the 11th and 12th ones on the 2nd trip, and the 8th and 9th on the 3rd trip. Finally, the 3rd ambulance carries the 3rd and 4th injured people on the first trip, and the 1st and 2nd on the 2nd trip. Ambulance and hospital capacities were also taken into consideration while performing the solution.

The problem in fig. 3 includes many constraints, parameters, and assumptions in it. The constraints, parameters, and assumptions considered in this study are specified below:

– Every patient must be transported to a hospital.
– Routing should be carried out without exceeding the hospital and ambulance capacities.
– Ambulance capacities were assumed to be equal (1–2–3 or 4).
– Ambulances can make more than one trip.
– It is assumed that it is possible for an ambulance to transport the injured to the hospitals other than the hospitals to which it belongs, but it arrives at the next injury location after stopping at the hospital to which it will transport in the first place and taking the relevant equipment. For example, the first ambulance departing from the first hospital can take the 5th and 7th patients, and after returning to the first hospital, they can go on a second trip to transport the injured in the system to the nearest hospital. In this case, the injured people can go to the other hospital (for example the second hospital) first to get the relevant equipment, then reach the relevant injury locations (for example the 3rd and 8th injured) and return to the second hospital. In this case, the total mission route for the first ambulance is as follows: First trip: 1st hospital – 5th injured, 7th injured – 1st hospital. Second trip: 2nd hospital – 3rd injured – 8th injured – 2nd hospital. In this way, it was aimed to create a full tour for ambulances and to terminate their duties in the hospitals they started. In this case, it is aimed to reflect the hospital changes of the ambulances to the objective function.

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;

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

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

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

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

$$\text{Min } Z = \sum_{m \in M}\sum_{i \in IUJ}\sum_{j \in IUJ}\sum_{k \in K} x_{mijk}\, c_{ij} + \sum_{m \in M}\sum_{i \in I}\sum_{j \in I}\sum_{k \in K} p_{mijk}\, c_{ij} + \sum_{m \in M} h_m b_m \quad (3.2.2.1)$$

$$\sum_{m \in M}\sum_{k \in K}\sum_{i \in IUJ} x_{mijk} = 1 \quad \forall j \in J \quad (3.2.2.2)$$

$$U_{mlk} - U_{mjk} + N x_{mljk} \leq N-1 \quad \forall l, j \in J,\ \forall k \in K,\ \forall m \in M \quad (3.2.2.3)$$

$$\sum_{j \in IUJ} x_{mijk} - \sum_{j \in IUJ} x_{mjik} = 0 \quad \forall k \in K, i \in IUJ, m \in M \quad (3.2.2.4)$$

$$\sum_{k \in K}\sum_{i \in IUJ} x_{mijk} \leq 1 \quad \forall k \in K, m \in M \quad (3.2.2.5)$$

$$\sum_{i \in IUJ}\sum_{j \in J} d_j x_{mijk} \leq q_k \quad \forall k \in K, m \in M \quad (3.2.2.6)$$

$$\sum_{j \in J} d_j z_{mij} \leq v_i \quad \forall i \in I, m \in M \quad (3.2.2.7)$$

$$-z_{mij} + \sum_{u \in IUJ} (x_{miuk} + x_{mujk}) \leq 1 \quad \forall i \in I, j \in J, k \in K, m \in M \quad (3.2.2.8)$$

$$-1 + \sum_{j \in J} x_{mijk} + \sum_{j \in J} x_{wtjk} - \sum_{o \in M}\sum_{j \in J} x_{oijk} \leq p_{mitk} \quad (3.2.2.9)$$

$$\forall i \in I, t \in I, k \in K, (m, w, o) \in M, \quad i \neq t, m > o > w, m > 1$$

$$x_{mijk} = 0 \quad \forall i \in I, j \in I, k \in K, m \in M \quad (3.2.2.10)$$

$$\sum_{i \in I}\sum_{j \in J} z_{mij} = h_m \quad \forall m \in M \quad (3.2.2.11)$$

$$\sum_{i \in I}\sum_{j \in J} z_{mij} * 1000 \geq \sum_{i \in I}\sum_{j \in J} z_{(m+1)ij} \quad (3.2.2.12)$$

$$x_{mijk} \in \{0,1\} \quad \forall i \in I, j \in J, k \in K, m \in M \quad (3.2.2.13)$$

$$z_{mij} \in \{0,1\} \quad \forall i \in I, j \in J, m \in M \quad (3.2.2.14)$$

$$U_{mlk} \geq 0 \quad \forall l \in J, k \in K, m \in M \quad (3.2.2.15)$$

Information on the mathematical model developed under these assumptions is given below:

In the objective function of the model (3.2.2.1), the total duty time, the cost of ambulances going to distant hospitals, and the costs arising from the additional trips were tried to be minimized. Constraint (3.2.2.2) implies assigning a single route for each injured. Constraint (3.2.2.3) represents the sub-tour elimination. Constraint (3.2.2.4) means that each node in the routes has a single entry and exit. Constraint 93.2.2.5) means that each ambulance leaves a single hospital. Constraint (3.2.2.6) means that the demands of the injured on each route do not exceed the capacities of the ambulances on the routes. Constraint (3.2.2.7) means that each injured demand should not exceed the capacity of the hospital to which it is assigned. Constraint (3.2.2.8) means that each injured person is on the route of the hospital to which they are assigned. Constraint (3.2.2.9) ensures that ambulances are directed to the same and nearest hospital, if possible. Constraint (3.2.2.10) ensures that the transfer between hospitals is not assigned to each other at the relevant time. Constraint (3.2.2.11) allows the trips to be activated gradually. Constraint (3.2.2.12) ensures the assignment of injured people to be transported in the initial trips to a large number of hospitals. (3.2.2.13–3.2.2.14–3.2.2.15) are the constraints limiting the signs of the decision variables.

In the next section, the developed model is tested on various scenarios and its results are analyzed.

## 3. Research findings

In this study, the central district of Erzincan province has been taken into account and the debris scanning and the most efficient transportation of the injured from under the debris to the hospitals are emphasized, based on the previous earthquake. Two different mathematical models, Sections (3.1.1, 3.2.1) have been developed for debris scanning and rescuing the injured from under debris and transferring them to the hospitals. The developed model was tested by taking into account the data in the district and the information regarding the implementation study is given in the following sections.

### 3.1. Determining the ideal number of UAVs

Within the scope of the thesis, the cluster coverage problem for 68 districts of Erzincan province was addressed and the required number of UAVs was tried to be determined. The purpose

Table 2. District clusters obtained as a result of solving 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 |

of cluster coverage problems is to serve the maximum number of areas with the minimum number of facilities. Based on this idea, UAVs are considered as facilities and it is aimed to find the required number. In determining the required number of UAVs, the distances between the neighborhoods were calculated using the Google Maps application. Relevant distances represent the value in minutes of the distance traveled by vehicles. While solving the problem, assuming that the UAVs scan distances of 5–10–15–20 minutes, the number of UAVs required for scanning was aimed to be found with the mathematical model in Section 3.1.2.

As a result of solving the relevant model with the Gams software, it was determined that it requires 17 UAVs for a 5-minute scanning distance, 7 UAVs for a 10-minute scanning distance, 2 UAVs for a 15-minute scanning distance, and 2 UAVs for a 20-minute scanning distance. Considering the need for a more detailed scanning after an earthquake, 7 UAVs are assumed to be needed in developing data sets in the application phase of ambulance routing problem and the injured individuals are distributed to the districts considering these clusters. The district clusters that occur when 7 UAVs are used are given in table 2.

In the next section, data sets were prepared based on the obtained sets and the mathematical model developed for the ambulance routing problem was tested.

### 3.2. Routing ambulances

While routing the ambulances, 7 district clusters were obtained by applying the mathematical model in section 3.1.2 for 68 districts of Erzincan province. Based on these district clusters, the mathematical model in section 3.2.2 has been tested. The parameters addressed during the model trial are:

– number of hospitals,
– hospital capacity,
– number of ambulances,
– ambulance capacity,
– number of injured,
– number of trips.

Information on these parameters is provided below.

**Number of the injured:** The number of injuries in the problem sets varies between 10 and 40, and as the number of injured increases, the time to solve the problem and its reaction

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) |

to the results needs to be determined. In addition, the injuries are distributed randomly to different locations in the city center and real geographical data of the region are used while determining the locations of the injured. The casualties were randomly allocated to the districts in the clusters determined during the cluster coverage stage, and the condition that each cluster should have at least one injured was added. For the scenario of UAVs on the 10-minute scan, it is assumed that the injured ones are distributed to the districts within the 7 clusters determined under the assumption of 7 UAVs are required. The injuries distributed randomly to clusters and districts under 16 trials are shown in table 3.

**Number of hospitals:** Three were established considering the hospitals in the province. While creating the relevant distance matrices in the problems, the actual locations of the above hospitals were taken into account and the actual distances between these locations and the injuries were added to the path matrix. In addition, it was assumed that the number of hospitals in the problems varied between 1 and 3, thus it was aimed to determine the dynamic response of the problem to the increase in the number of hospitals.

**Hospital capacity:** While determining the total hospital capacity, it was considered to be more than the total number of injured and the values were given randomly. The total hospital capacity is shared among the relevant hospitals at different rates. For example, in the related problem, if it is assumed that there are 2 hospitals and the total hospital capacity is determined to be 30, the capacity of one hospital may be 10 and the other 20. Or the capacity of both could be 15. The number of hospitals used under 16 trial studies and their total capacities are shown in table 4 while the distribution of the total capacity to the hospitals is shown in table 5.

Number of ambulances: Within the scope of the study, the number of ambulances varied between 2 and 10, thus the effect of the increase in the number of ambulances on the solution of the problem was tried to be determined. Ambulance starting points are assumed to be at the respective hospitals. The number of ambulances allocated to each hospital within the related problem was determined randomly.

Ambulance capacity: During the research, it was noted that ambulances with capacity of four are available and being actively used. Based on this information, it is assumed that the ambulance capacity varies between 1 and 4. In addition, it is assumed that all ambulances have equal capacities.

Number of trips: The following formulation was used to determine the number of trips.

Number of trips = (Total number of injured) / (Number of ambulances × Ambulance capacity)

The distribution of the number of ambulances, their capacities, the number of injuries and trips among 16 trial runs are shown in table 6.

The model that was developed along with all these data sets and the assumptions was solved using the GAMS software and the obtained results are provided in the next section.

## 4. Conclusion and recommendations

In the light of the information given in Section 4, the model that was developed in Section 3 was tested and ambulance routing for Erzincan province was examined for small-scale samples. 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 given in table 7.

The findings obtained as a result of the experiments are as follows. After the first trial, the program gave a solution very quickly, and the result was the optimum solution. However, in

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 |

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 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.

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 | - | - | - | - |

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