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Last Mile Humanitarian Aid Delivery Model with Electric Vehicles to Disaster Areas

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Abstract

Natural disasters that cause loss of life and property in Türkiye occur frequently. It is also very important to quickly deliver the necessary materials and equipment to people affected by these disasters. Therefore, in this study, Last Mile Humanitarian Aid Distribution with Electric Vehicles 0-1 Mixed Integer Mathematical Model is proposed due to the fuel problems that will be experienced during the disaster process. The proposed model calculates routes that minimize the total distance traveled by electric vehicles, while also considering their charging needs and energy consumption. Given the likelihood of power outages post-earthquake, the model prioritizes the use of solar-powered electric vehicle charging stations. 7 earthquakes with magnitudes between 4 and 5 occurred in Kayseri in 2023. In this study, an application was carried out for a possible earthquake close to the magnitude of the earthquakes that occurred in Kayseri in recent years. The application of this proposed model was demonstrated in an example of post-earthquake aid distribution using electric vehicles in Kayseri province. Distance data and consumed energy amounts for the Kayseri province example were entered into the model and solved in the CPLEX program. As a result, 3 identical electric vehicles met the demands and the total distance traveled by Vehicle 1 is 414.3 km, Vehicle 2 is 18 km and Vehicle 3 is 10.8 km. Additionally, the effectiveness of the use of energy-efficient electric vehicles in disaster management was evaluated in the article.

1. Introduction

Disasters are natural and human-induced events that can cause loss of life and property, affect the flow of life, and cause serious social and economic damage to society. Every year, millions of people in the world lose their lives due to disasters. For this reason, it is very important to take precautions against disasters and to provide timely aid to disaster victims in case of disasters.

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Factors such as our country's geographical location and landforms lead to natural disasters. The Gölcük earthquake (1999), Van earthquake (2011), Izmir earthquake (2020), Elazığ earthquake (2020) and many such devastating earthquakes with high loss of life that occurred in the past years can be given as examples. It is the earthquake that occurred recently on February 6, 2023, in the Pazarcık and Elbistan districts of Kahramanmaraş, with a magnitude of 7.8 and 7.7, respectively, and affected 11 provinces. According to the Disaster and Emergency Management Presidency (AFAD), according to the latest data due to earthquakes, more than 50,000 people lost their lives, more than 108,000 people were injured, and more than 430,000 people had to leave their homes and the province they lived in and were resettled to other provinces.

Humanitarian aid logistics is the implementation of a planned and controlled approach from the starting node to the destination node, to reach the victims in an effectively planned manner in case of disaster and emergency, and to meet their needs at the right time and in the right place. Humanitarian aid logistics because of natural disasters is important to reduce the damage caused by the disaster as quickly as possible. In addition, this humanitarian aid logistics must be done quickly and at a low cost. Taking this into consideration, choosing the vehicles that provide logistics in this study as electric vehicles is very important in terms of cost savings and faster delivery, as well as preventing fuel problems that may occur since they can be supported by renewable energy. Another reason for choosing an electric vehicle in this study is prevent the use of harmful fossil fuels due to CO_2 release and greenhouse gases and emissions into the air.

Green logistics are logistics activities aimed at increasing economic efficiency by reducing transportation costs, reducing dependence on gasoline vehicles, and increasing environmental benefits. Countries are trying to integrate this understanding into society by enacting laws. For example, in Belgium, financial support is provided to people who want to buy an electric vehicle, and electric vehicles in the Flanders region are exempt from registration tax and ownership tax [1]. This kind of laws are very important for the adoption of the concept of green logistics.

It is extremely important to correctly route the electric vehicles we use in our study, which aims to ensure that the humanitarian aid distribution model is carried out at the lowest cost and in the shortest distance, considering the concept of green logistics. For this reason, in our study, a last-mile humanitarian aid distribution model was created to ensure optimal routing. The term 'last mile' is used because it represents the final direct transportation leg from the airport to the hospital.

A study was conducted on Kayseri, which we discussed in the context of the problem because it is situated near significant earthquake fault lines and is classified as a third-degree earthquake zone [2]. A mixed integer (0-1) mathematical model was created for last-mile humanitarian aid distribution with electric vehicles from Erkilet Airport to selected hospitals in Kayseri province. Solar charging stations in certain regions have been selected to meet the battery charging needs of electric vehicles. The model was solved in the CPLEX program and aid routes to hospitals were created in the shortest distance. In addition, the battery tracking of the vehicles is also monitored.

In Section 2, the literature on disasters and vehicle routing problems is presented. Section 3 provides an explanation of the methods employed. In Section 4, the proposed mathematical model for last-mile humanitarian aid delivery, utilizing 0-1 mixed-integer electric vehicles, is presented and elucidated. The developed model was applied to Kayseri province, and the results are detailed in Section 5. Section 6 covers scenario analysis, encompassing a broad spectrum of potential fluctuations and increases in patient demands, with subsequent presentation of results and discussion. Section 7 includes the results and recommendations.

2. Literature Review

Disaster is called a natural, technological, and human-origin event that causes material and moral damage to people and human-made artifacts and affects societies in the form of stopping or interrupting everyday life and human activities [3-6]. The disasters that have occurred all over the world have caused great destruction and brought with them the necessary precautions and responsibilities as a result.

There is a lot of research conducted on disasters. For example, in Akin and Ordu [7] study on the COVID-19 pandemic, which recently occurred on Earth and caused the death of many people, a new simulation based on two-stage optimization has been developed to determine the shifts and numbers of nurses working for the Covid19 service in a Turkish Public Hospital. This study was performed in three stages. In the first stage, a simulation model was developed to determine the number of nurses required per week and scenarios based on increased patient activity. In the second stage, the first mathematical model was applied to determine the number of weekly shifts. In the third stage, fair nurse shift planning has been prepared for the pandemic service. With the model created as a result of the study, it has been observed that well-balanced planning was achieved among the nurses working in the COVID-19 service. This study is significant, as it will enable health managers to plan for personal needs during the next surges of the COVID-19 pandemic.

In another study about COVID-19, a Data Envelopment Analysis (DEA)-based model has been developed to evaluate the effectiveness of regions against a pandemic outbreak to better manage the fight against the epidemic by the relevant authorities and implement emergency action plans [8]. The DEA method has been used to measure the productivity scores of countries. DEA is an extremely popular technique that is applied to a wide range of sectors, including healthcare, education, agricultural culture, finance, and manufacturing services. It is a method that provides meaningful results for comparative performance. This method was utilized in the study to improve both reliable rankings of countries and health services. In the study, 16 countries have been selected that after the confirmed hundredth cases, undergo at least five weeks of continuous pandemic process. 16 DEA models have been developed for each week. The percentage of fertile countries decreased significantly from 43.75% in the first week to 25% in the fifth week. Unlike most European countries, China and South Korea have increased their effectiveness by implementing all the necessary measures after the first week. This study sheds light on the effectiveness of the policies adopted by the countries and the management strategies in the fight against the COVID-19 pandemic for the better by standing.

Another study conducted on the disaster in Turkey is on the emergency service network for the possible earthquake disaster in Istanbul [9]. The hybrid study includes artificial neural networks (ANN) to estimate the number of casualties and discrete event simulation to analyze the impact of the increase in patient requests in the emergency department after the earthquake. In the study, the five emergency service region networks that are estimated to have the highest injury rate after an earthquake in Istanbul were selected. The study consists of three stages. In the first stage, the earthquake casualty model is run for the next stage with ANN. In the second stage, the Earthquake Time Emergency Department Network Simulation Model creates the performance outputs of simulated emergency departments with the ANN outputs of the first stage. In the last stage, the simulation results are evaluated and produce some practical results for planning. The model has been run more than once because the region studied is large and there are stochastic variables. For each of the 432 scenarios, five repetitions were made with random numbers cause five repetitions are enough to make inferences. To compare the simulation scenarios, variance analysis (ANOVA) was performed with the Minitab program with a significance level of 5%. This study is important in terms of the lack of a study on emergency service simulation in earthquake disasters.

Disaster logistics is very important for emergency response to people in case of disaster and providing the materials they need. There are quite important studies on this topic in the literature. The selection of the ideal disaster warehouse location for disaster logistics made by Ergun et al (2020) is one of these studies [10]. In the study, the selection of the ideal disaster warehouse location in Giresun for disaster logistics was selected. The reason why the disaster storage place of the study was established in Giresun is that floods and landslides occur frequently in the city. In addition, the fact that the districts in the inner parts of Giresun are close to the fault lines is one of the reasons for being chosen. The AHS method was used to determine the alternatives in the selection of the warehouse location. Later, the selection of the ideal disaster storage location was carried out by AHS-based MAUT and SAW methods. AHS is a mathematical approach used in decision making and measurement. The MAUT method is the method of finding the most useful alternative with quantitative and qualitative criteria. In the SAW method, the highest performing alternative is selected by sorting the alternatives first after matrix normalization. In the study, infrastructure was determined as the most important criterion for choosing the ideal disaster storage location for sustainable disaster logistics. Location is the main criterion, while you are the least important. It is an exemplary study because there is no such study in the literature reviews.

Another valuable study in disaster logistics is Tezcan et al (2021) [11]. In the study, temporary storage location selection and a multi-vehicle vehicle routing application were made after the disaster. The study was applied in Kırıkkale province. The reason why Kırıkkale was chosen is that it is the intersection of 43 provinces, the fact that there are large industrial enterprises located between Ankara and Kırıkkale increases the importance of the temporary warehouse to be established in the city in case of a possible earthquake other than Kırıkkale. The problem has been addressed in three stages. In the first stage, the alternative four districts and in the second stage, the alternative six locations were decided using the multi-criteria decision-making method. After the location of the temporary warehouse was determined, the route of food distribution was determined in the third stage. The methods used, AHP, FAHP, TOPSIS, PROMETHEE and VIKOR methods were used. In the first stage, when the districts were sorted, it was determined that the best location was Yahşihan district. In the second stage, it has been determined that the best alternative from six locations in Yahşihan district is the southern parking area. In the third stage, it is determined by which route the food will reach the disaster victims. The study provides convenience in post-disaster planning.

In their study, Küçük and Çavdur (2019) modeled and solved the distribution problem of post-disaster relief materials as a Time-Window Divided-Distributed Vehicle Routing Problem (ZPBD-ARP) [12]. Moreover, Cavdur et al (2016) [13], using the results of the model developed by the initial distribution problem is divided into smaller dimensional transport problems, which are solved as ZPBD-ARP. In the model developed by Cavdur et al (2016) [13], the locations of temporary facilities, the quantity, and the number of relief materials to be distributed to disaster victims are determined. The determined optimal amounts of relief material distribution, the amounts to be transported from the facilities to the disaster victims were taken as inputs to the model. In the study, the solution of the distribution problem after the disaster was provided by considering the data of the earthquake sample event in Bursa province. The ZPBD-ARP model was coded in Mathematical Programming Language (MPL) environment and decoded by Gurobi program. In the study, the route was designed to meet the potential maximum demand, considering the worst-case earthquake scenario.

The implementation of humanitarian aid logistics in a planned and controlled manner from the starting point to the destination to meet the needs of the victims of disasters and emergencies in an effectively planned manner and the right place to meet their needs at the right time and in the right place is called humanitarian aid logistics. Humanitarian aid logistics as a result of natural disasters is important to reduce the damage caused by disasters in the fastest way possible. In the study, electric vehicles were considered because fossil-fueled vehicles are expendable, high-cost, and quite harmful to the environment.

There are many studies in the literature on models that will enable vehicles to be rotated in the fastest way. When looking at electric vehicle routing problems (EARP), Çimen and Belbağ (2022) [14], one of the first studies to take into account the use of electric vehicles, contributes in terms of presenting a mixed integer linear programming-based solution approach for solving the sustainable dynamic vehicle routing problem, in which electric vehicles are taken into account and demonstrating the applicability and value of the proposed method with the help of numerical analysis. This study, unlike other studies, wanted to draw attention to the issues of dynamic traffic density, electric vehicles, and social and environmental sustainability. In the results obtained with static and dynamic assumptions, it was seen that there is a faster delivery in the static case, and in future studies, it aimed to integrate issues such as time window or load capacity for dynamic parameters into the model, to enrich the literature on addressing different dynamic parameters such as changing or canceling demand points.

In another study conducted on EARP, a mixed integer linear programming model was proposed for a multi-use and time-window vehicle routing problem [15]. In the study, the relationship between the time window and vehicle capacity was questioned by constructing the model of 2 types of test classes. In each test class, the customers in type R problems are completely random, and in type C problems, the customers are concentrated in certain regions and placed. As a result of the study, it has been seen that the solution to the problem becomes easier as the restrictions on route times decrease. It has been found that RC-type problems have a higher Percentage Deviation Value compared to R and C-type problems.

The heterogeneous fleet method, which includes 8 different electric vehicles with different technical characteristics, was examined with EARP, which was considered by Desaulniers et al (2016) [16]. While the fuel capacities of vehicles are not included in the normal ARP, the charging capacities of vehicles, the amount of charge consumed at a unit distance, charging time, and battery capacity have been added as restrictions in EARP. Desaulniers et al (2016) [16] the studies carried out by Solomon also used the data set derived by Solomon for time-window vehicle routing. To test the validity of the first developed model, the model was run and developed the model. It has been observed that it has a shorter processing time compared to the model.

3. Methodology

3.1. Electric Vehicles

The rising population exacerbates energy and fuel-related challenges. Examining fossil fuel reserves reveals a limited 50-year supply [17]. Simultaneously, the detrimental impact of fossil fuels on the environment, including the release of greenhouse gases into the air, constitutes a significant drawback to their utilization. Another negative aspect of fossil fuel use is that fuel prices may increase depending on the dollar exchange rate in our country. As is widely known, vehicles, being crucial providers of transportation and logistics, rely on fuel or a propulsion system. Modern drive systems can be supplied by either electric vehicles with internal combustion engines or electric motors. Although it initially appeared more logical for the propelling force behind vehicle movement to be electric, the limited battery capacity and the absence of widespread charging stations necessary for electric vehicle charging made internal combustion engine vehicles more popular from the late 1800s to the early 2000s. In the early 2000s, with the spread of lithium batteries and the decrease in costs, electric vehicles entered our lives widely again. In this way, the damage caused by fossil fuels to the environment has been reduced over the years and vehicles have been moved efficiently with more efficient drive systems. The number of electric vehicles and stations in our country is increasing day by day. While this number was 1342 in the first three months of 2022, it became 4870 in the same period of 2023 (TUIK). The number of electric vehicles charging stations is 4498 according to the Electricity Market Regulatory Board. The number of electric vehicles in the world has exceeded 10 million (TURKSTAT). When looked at in this context, it is very important to make disaster, emergency, and other plans according to these systems that have become widespread in our country.

3.2. Renewable Energy Supported Charging Stations

Renewable energy: generally, covers the energy obtained from solar, wind, biomass, geothermal, and hydraulic energy sources. Since Kayseri province was considered as the subject of this study and Kayseri has a very high potential when sunshine hours were examined, a model was developed by considering solar charging stations [18].

3.2.1 Solar Charging Stations

Solar energy is the energy released because of the fusion process in the core of the sun. Solar energy has an important place among renewable energy resources. Because it is known that the amount of energy is equal to 50 times the coal reserves and 800 times the oil reserves. We can produce more solar energy than Germany, which ranks first among the countries producing energy from the sun in the world. Electrical energy production by the photovoltaic method, which has an important place among solar energy production systems, is used more since it is cheaper than collector structures that provide production by thermal means. Photovoltaic solar cells consist of semiconductor materials and convert solar energy into electrical energy. The cells are connected, and a photovoltaic energy production system is created with solar panels, accumulators, converters, and various circuit elements. Solar charging stations also work in integration with these photovoltaic systems, appearing as an environmentally friendly method that reduces fuel costs [19].

3.3. Vehicle Routing Problem

Traveling Salesman Problem (TSP) is an optimization problem that returns to where it started after visiting all n nodes with known distances between each other at least once, and whose aim is to obtain the shortest route (minimum cost). TSP is classified as an NP-complete problem. Although TSP has many advantages, as the number of nodes increases, the probability of the resulting solution being optimal decreases. For this reason, various heuristic methods have been developed for a better solution. Some of these heuristics can be listed as: Ant Colony Optimization, Artificial Bee Colony Optimization, Genetic Algorithms, Particle Swarm Optimization, Tabu search, Differential Evolution, and Scatter Search algorithms. The traveling salesman problem method, which is used in many fields, especially logistics, still has a very important place today [20].

The vehicle routing problem is to ship products or services according to customers' needs in the logistics system. The vehicle routing problem consists of warehouses and customers. Products or services are sent from warehouses in the quantities requested by customers. While warehouses may be single, sometimes there may be more than one. In vehicle routing problems, when meeting the needs of customers, some targets are taken into consideration and the order in which distribution is more advantageous to the customers is preferred. Vehicle Routing Problem was first introduced to the literature by Dantzig et al (1959) [21]. This study focused on distributing gasoline to gas stations. In the study, the problem was solved with the aim of minimum transportation cost and minimum distance of the vehicle leaving a certain warehouse with certain constraints. After the studies of Dantzig and Ramser, studies were carried out on types of vehicle routing problems. (e.g., Cordeau et al., 2005 [22]). In the literature, the vehicle routing problem is known as an improved version of the traveling salesman problem.

4. Proposed Mathematical Model of Last Mile Humanitarian Aid Distribution with 0-1 Mixed Integer Electric Vehicles

In this study, a last-mile humanitarian aid distribution model with electric vehicles was proposed to meet the medical aid needs that may arise after the earthquake disaster in Kayseri. The assumptions of the proposed model are as follows:

- Hospitals will not be damaged after the earthquake occurs.
- In the event of an earthquake, power outages may occur. Therefore, if gas stations are unable to provide service, electric vehicles can be charged using solar charging stations.
- No other disaster will occur after the earthquake occurs.
- Electric vehicles will be available to receive medical aid from airports after the earthquake occurs.
- The roads that electric vehicles will use to deliver aid to hospitals will remain undamaged.

Indices

n: Airport and hospitals index
k: Hospitals index
l: Charging stations index
h: Airport index

t: All points index

Parameters
B: Vehicle battery capacity
vehicle_number: Number of vehicles
Cap: Vehicle material capacity

Clusters
C: Hospital cluster
DAC: All nodes cluster
CDD: Set of all nodes
Vehicle: Vehicle cluster
Charging: Set of charging stations
C1: Airport and hospitals cluster
$\boldsymbol{q_i}$**:** i. hospital's request
$\boldsymbol{RM_{ij}}$**:** Fuel consumption from node i to node j (kWh)
$\boldsymbol{M_{ij}}$**:** Distance matrix of node i to node j (KM)

Decision Variables
$\boldsymbol{u_i}$**:** Sub-route decision variable
$\boldsymbol{remaining\_fuel_{ijk}}$**:** Decision variable showing the remaining fuel of vehicle k when it goes from node i to node j
$\boldsymbol{x_{ijk}}$**:** k vehicle route decision variable $\begin{cases} 1,: \ 1, if \ vehicle \ k \ departs \ node \ i \ toward \ node \ j \\ 0, otherwise \end{cases}$
$\boldsymbol{y_{ik}}$**:** $\begin{cases} 1, If \ vehicle \ k \ arrives \ at \ point \ i \\ 0, otherwise \end{cases}$
$\boldsymbol{z_k}$**:** $\begin{cases} 1, if \ vehicle \ k \ is \ moving \\ 0, otherwise \end{cases}$
$\boldsymbol{current\_fuel_{ik}}$**:** Current fuel value of vehicle k at node i

Min Z= $\sum_{i \in DAC} \sum_{\substack{j \in CDD \\ i \neq j}} \sum_{k \in arac} M_{ij} \times x_{ijk}$ (1)

Subject to

$\sum_{i \in DAC} \sum_{k \in vehicle} x_{ijk} = 1 \quad \forall_j \in C1, j \neq 1$ (2)

$\sum_{i \in DAC} \sum_{k \in vehicle} x_{jik} = 1 \quad \forall_j \in C1, j \neq 1$ (3)

$\sum_{\substack{j \in DAC \\ j \neq 1}} x_{1jk} \leq 1 \quad \forall_k \in vehicle$ (4)

$\sum_{\substack{j \in DAC \\ j \neq i}} x_{ijk} = \sum_{\substack{j \in DAC \\ j \neq i}} x_{ijk} \quad \forall_i \in DAC, \forall_k \in vehicle$ (5)

$u_j - u_i \geq 1 - M \times (1 - x_{ijk}) \quad \forall_{i,j} \in DAC \ \ i \neq j, i \neq 1, j \neq 1, \forall_k \in vehicle$ (6)

$\sum_{\substack{i \in DAC \\ i \neq 1}} x_{i1k} \leq 1 \quad \forall_k \in vehicle$ (7)

$\sum_{i \in DAC} \sum_{j \in DAC} x_{ijk} \leq t \times z_k \quad \forall_k \in vehicle$ (8)

$\sum_{i \in DAC} \sum_{j \in DAC} x_{ijk} \geq z_k \quad \forall_k \in vehicle$ (9)

$\sum_{j \in DAC} x_{ijk} + \sum_{j \in DAC} x_{jik} = 2 \times y_{ik} \quad \forall_i \in DAC, \forall_k \in vehicle$ (10)

$\sum_{\substack{i \in DAC \\ i \neq 1}} \sum_{\substack{j \in DAC \\ j \neq 1 \\ i < j}} x_{ijk} \leq \sum_{\substack{i \in DAC \\ i \neq 1}} y_{ik} - y_{zk} \quad \forall_z \in DAC, z \neq 1, \forall_k \in vehicle$ (11)

$\sum_{i \in DAC} \sum_{k \in vechicle} x_{iik} = 0$ (12)

$\sum_{i \in DAC} \sum_{j \in C} q_j \times x_{ijk} \leq Cap \quad \forall_k \in vehicle$ (13)

$x_{ijk} \geq 1 => current\_fuel_{jk} = B \times x_{ijk} \quad \forall_i \in DAC, \forall_j \in charging,, \forall_k \in vehicle$ (14)

$x_{ijk} \geq 1 => remaining\_fuel_{ijk} = B \times x_{ijk} \quad \forall_i \in DAC, \forall_j \in charging, \forall_k \in vehicle$ (15)

$remaining\_fuel_{ijk} = B - x_{ijk} \times RM_{ij} \quad \forall_i \in DAC, i = 1, \forall_j \in C, \forall_k \in vehicle$ (16)

$x_{ijk} \geq 1 => current\_fuel_{jk} = remaining\_fuel_{ijk} \quad \forall_i \in DAC, \forall_j \in C1, \forall_k \in vehicle$ (17)

$remaining\_fuel_{ijk} = current\_fuel_{jk} - x_{ijk} \times RM_{ij} \quad \forall_i \in DAC, i \neq 1, \forall_j \in DAC, j \notin charging, \forall_k \in vehicle$ (18)

$remaining\_fuel_{ijk} \leq RM_{jz} => x_{izk} = 1 \quad \forall_i \in DAC, \forall_j \in C, i \neq j, \forall_k \in vehicle, \forall_z \in Charging$ (19)

$current\_fuel_{ik} \geq \min(s \in charging) \ RM_{is} \quad \forall_i \in DAC, \forall_j \in DAC, \forall_k \in vehicle$ (20)

$current\_fuel_{ik} \leq B \quad \forall_i \in DAC, \forall_j \in DAC, \forall_k \in vehicle$ (21)

$remaining\_fuel_{ijk} \geq min(s \in charging) \ RM_{js} \quad \forall_i \in DAC, \forall_j \in DAC, \forall_k \in vehicle$ (22)

$remaining\_fuel_{ijk} \leq B \quad \forall_i \in DAC, \forall_j \in DAC, \forall_k \in vehicle$ (23)

$x_{ijk} \in (0,1) \quad \forall_i \in DAC, \ \forall_j \in DAC, \ \forall_k \in vehicle$ (24)

$z_k \in (0,1) \quad \forall_k \in vehicle$ (25)

$y_{ik} \in (0,1) \quad \forall_i \in DAC, \ \forall_k \in vehicle$ (26)

$u_i \in Z^+ \quad \forall_i \in DAC$ (27)

$remaining\_fuel_{ijk} \in R \quad \forall_i \in DAC, \forall_j \in DAC, \forall_k \in vehicle$ (28)

$$current\_fuel_{ik} \in \quad R \qquad \forall_i \in DAC, \forall_k \in vehicle \tag{29}$$

In the mathematical model, the objective function shown in equation (1) minimizes the total distance traveled. These are the constraints that ensure that (2) it must visit every node, while (3) it ensures that it leaves after visiting the nodes. (4) is the constraint that indicates that not all the tools in the tool set have to be used. Constraint (5) ensures that the vehicles entering a node and the vehicles leaving it are equal. (6) is the sub-round elimination constraint. Constraint (7) ensures the return to the warehouse. (8) limits the number of nodes it visits based on the number of exiting vehicles. Constraint (9) determines the lower limit based on the number of vehicles. Constraint (10) makes the sum of the number of vehicles entering and exiting the node equal to the number of vehicles. Constraints (11) and (12) ensure that the same node is not visited. Constraint (13) ensures that the vehicle does not exceed its cargo capacity. (14) is the constraint that makes the current charge value at the point equal to the battery capacity of the vehicle if the vehicle visits the charging point. Constraint (15) tracks the charge of the vehicle and shows the current charge value. Constraint (16) determines the remaining capacity of the battery as a result of the first step. (Such a constraint was added because a special situation occurred when the battery was at full capacity when leaving the warehouse in the first step.) Constraint (17) is the constraint that synchronizes the remaining charge of the vehicle with the current charge at the node. Constraint (18) determines the remainder as a result of the next step by taking the value of the previous node of the current one when it leaves the node where the remaining fuel value is entered and goes to the next node. Constraint (19) prevents the vehicle from stranding on the road by controlling the remaining fuel value of the vehicle. Constraint (20) determines the nearest charging stations that the vehicle can go to, considering its current value at the node. Constraint (21) ensures that the vehicle does not exceed the current charging battery capacity at the node. Constraint (22) ensures that the remaining charge of the vehicle is at least enough to get to the charging point. Constraint (23) ensures that the remaining fuel capacity is not exceeded. Constraints numbered (24-26) x, y and z can only take values 1 and 0. Constraints numbered (27-29) show the set elements.

5. Kayseri Province Application

In the problem under consideration, it is planned that the electric transit vehicle will provide the logistics. The capacity of this vehicle was determined as 600 units and distribution was made according to the demands of nine hospitals. Five solar charging stations were determined to meet the charging needs of electric vehicles. Information about the vehicle and charging station used in the application is included in Table 1.

Table 1. Electric vehicle and charging station power values used [23]

Vehicle Battery Capacity	68kWh
Solar Energy Supported Charger Power (Tomma Tech Commercial 120kW)	120 kW (DC)
Vehicle Charging Time 20%-80%	34 min

As shown in Table 1, Tomma Tech brand charging stations, capable of working in conjunction with solar energy, can charge the Ford E-Transit vehicle, with a battery capacity of 68kWh, to 80% in just 34 minutes. The data used in the study were obtained through the Google Maps program. A distance matrix was created on the map, indicating the distances from the airport, charging stations, and between hospitals in Kayseri province. The created distance matrix is given in Table 2. The fuel consumption matrix obtained by using the distance matrix is given in Table 3 below. The value in each cell is multiplied by 0.3 to calculate fuel burned by distance.

Table 2. Distance matrix

DISTANCES (KM)	Airport	Akkışla	Bunyan	Develi	Felahiye	Hacılar	İncesu	Kayseri State	Kayseri City	Talas	i1	i2	i3	i4	i5
Airport	0	85.9	44.3	50.6	50.6	17.5	36.4	5.4	9	13	5.9	5.6	11.5	29	21.4
Akkışla	85.9	0	52.9	121	70.1	92.4	116	80.3	85.6	83.6	81	77.6	88	104	69.9
Bunyan	44.3	52.9	0	90.5	55.9	55.5	79.1	43.4	48.6	46.5	44	40.7	51.1	67.1	33
Develi	50.6	121	90.5	0	93.1	33.9	54.4	44.4	52.3	39	41.2	43.6	51.8	20	55.5
Felahiye	50.6	70.1	55.9	93.1	0	66	87.5	53.9	57	57.1	52.6	49.6	59.4	75.7	48.9
Hacılar	17.5	92.4	55.5	33.9	66	0	33.7	11.9	19.3	15.5	13	15.3	16.6	16.7	26.4
İncesu	36.4	116	79.1	54.4	87.5	33.7	0	33.7	34.1	44.1	37	37.8	26.1	51.3	51
Kayseri State	5.4	80.3	43.4	44.4	53.9	11.9	33.7	0	9	11.1	2.1	4.9	8.3	25.2	15.3
Kayseri City	9	85.6	48.6	52.3	57	19.3	34.1	9	0	19.5	12.4	14.6	3,4	35.2	20.6
Talas	13	83.6	46.5	39	57.1	15.5	44.1	11.1	19.5	0	8.4	8.3	18.7	21.9	16.8
i1	5.9	81	44	41.2	52.6	13	37	2.1	12.4	8.4	0	2.8	11.3	24.4	14.5
i2	5.6	77.6	40.7	43.6	49.6	15.3	37.8	4.9	14.6	8.3	2.8	0	12.3	27.1	12.4
i3	11.5	88	51.1	51.8	59.4	16.6	26.1	8.3	3,4	18.7	11.3	12.3	0	32.4	24.1
i4	29	104	67.1	20	75.7	16.7	51.3	25.2	35.2	21.9	24.4	27.1	32.4	0	38.3
i5	21.4	69.9	33	55.5	48.9	26.4	51	15.3	20.6	16.8	14.5	12.4	24.1	38.3	0

Table 3. Fuel Consumption Matrix

FUEL CONSUMPTION	Airport	Akkışla	Bunyan	Develi	Felahiye	Hacılar	İncesu	Kayseri State	Kayseri City	Talas	i1	i2	i3	i4	i5
Airport	0	25.77	13.29	15,18	15,18	5.25	10.92	1.62	2.7	3.9	1.77	1.68	3.45	8.7	6.42
Akkışla	25.77	0	15.87	36.3	21.03	27.72	34.8	24.09	25.68	25.08	24.3	23,28	26.4	31.2	20.97
Bunyan	13.29	15.87	0	27.15	16.77	16.65	23.73	13.02	14.58	13.95	13.2	12,21	15.33	20,13	9.9
Develi	15,18	36.3	27.15	0	27.93	10,17	16.32	13.32	15.69	11.7	12.36	13.08	15.54	6	16.65
Felahiye	15,18	21.03	16.77	27.93	0	19.8	26.25	16,17	17.1	17,13	15.78	14.88	17.82	22.71	14.67
Hacılar	5.25	27.72	16.65	10,17	19.8	0	10,11	3.57	5.79	4.65	3.9	4.59	4.98	5.01	7.92
İncesu	10.92	34.8	23.73	16.32	26.25	10,11	0	10,11	10.23	13.23	11.1	11.34	7.83	15.39	15.3
Kayseri State	1.62	24.09	13.02	13.32	16,17	3.57	10,11	0	2.7	3.33	0.63	1.47	2.49	7.56	4.59
Kayseri City	2.7	25.68	14.58	15.69	17.1	5.79	10.23	2.7	0	5.85	3.72	4.38	1.02	10.56	6.18
Talas	3.9	25.08	13.95	11.7	17,13	4.65	13.23	3.33	5.85	0	2.52	2.49	5.61	6.57	5.04
i1	1.77	24.3	13.2	12.36	15.78	3.9	11.1	0.63	3.72	2.52	0	0.84	3.39	7.32	4.35
i2	1.68	23,28	12,21	13.08	14.88	4.59	11.34	1.47	4.38	2.49	0.84	0	3.69	8.13	3.72
i3	3.45	26.4	15.33	15.54	17.82	4.98	7.83	2.49	1.02	5.61	3.39	3.69	0	9.72	7.23
i4	8.7	31.2	20,13	6	22.71	5.01	15.39	7.56	10.56	6.57	7.32	8.13	9.72	0	11.49
i5	6.42	20.97	9.9	16.65	14.67	7.92	15.3	4.59	6.18	5.04	4.35	3.72	7.23	11.49	0

Table 4. Hospital Demands

Akkışla District State Hospital	5
Bünyan State Hospital	29
Develi State Hospital	66
Felahiye Integrated District Hospital	5
Hacilar Community Health Center	12
İncesu State Hospital	29
Kayseri State Hospital	410
Kayseri City Hospital	582
Talas Community Health Center	169

According to the AFAD, in 2023, Kayseri experienced a series of seven earthquakes ranging in magnitudes between 4 and 5. In response to the seismic activity, a study was conducted to develop a model for predicting potential earthquakes with magnitudes similar to those observed in recent years in Kayseri. The practical application of this proposed model was demonstrated through an example involving the distribution of post-earthquake aid using electric vehicles in the Kayseri province. Demands of hospitals are shown in Table 4. A commodity, such as a tent, needed by one in every thousand people affected by the disaster is taken as basis.

Therefore, the number of materials to be sent was determined by dividing the total population by thousand. The total demand for hospitals was determined as 1307, in direct proportion to the population of the districts considered. For example, while the population of Akkışla district was 5563, the hospital demand was set at 5, following the same method for other districts. In the application, the distance data of the hospitals to each other, the airport, and the charging stations in Table 2 were used. In addition, the amount of fuel consumed by electric vehicles per 1 km to reach hospitals is determined in Table 3. At the same time, the demands of the hospitals and the capacity of the electric vehicle were specified in Table 4, ensuring that the materials were delivered by traveling the shortest distance.

The proposed Last Mile Humanitarian Aid Distribution Mathematical Model with 0-1 Mixed Integer Electric Vehicles was solved in the ILOG Cplex program for the Kayseri province application and the results were obtained. In practice, the total demand for 3 identical electric vehicles with a capacity of 600 and hospitals is 1307. In this case, the routes obtained by the model for 3 vehicles are given below.

Route of Vehicle 1: 1-7-4-14-6-10-12-3-2-15-5-1 and the total distance traveled by Vehicle 1: 414.3 km

Route of Vehicle 2: 1-9-1 and total distance traveled by Vehicle 2: 18 km

Route of Vehicle 3: 1-8-1 and total distance traveled by Vehicle 3: 10.8 km

Table 5. Routes obtained with the model for all vehicles.

Vehicle	Node i	Node j
1	1	7
1	7	4
1	4	14
1	14	6
1	6	10
1	10	12
1	12	3
1	3	2
1	2	15
1	15	5
1	5	1
2	1	9
2	9	1
3	1	8
3	8	1

The routes obtained as a result of the model are in Table 5, the current charge values at the nodes are in Table 6, and the route formed on the map is in Figure 1.

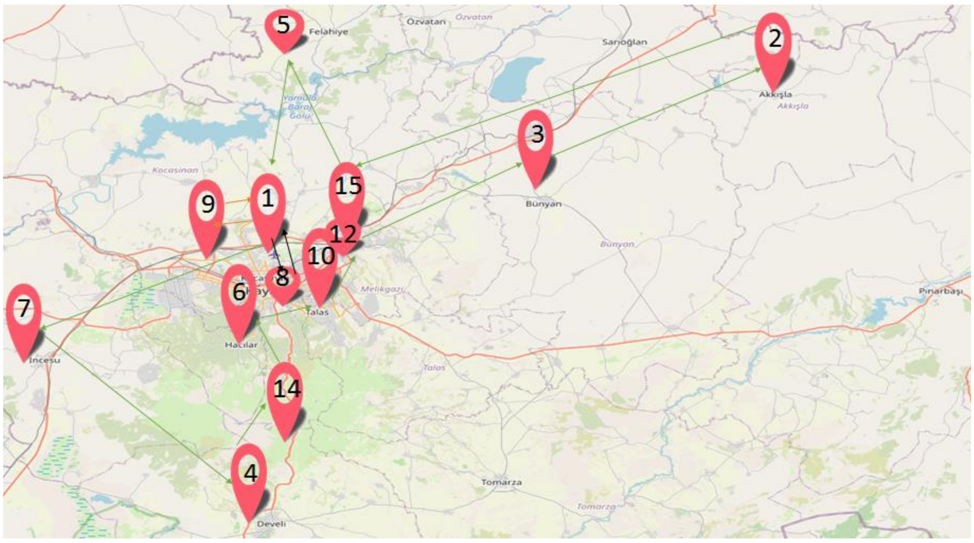

Figure 1. Representation of the route on the map

Table 6. Current Charge Values at the Point

All Nodes Cluster (DAC)	Vehicle (Size 3)		
	1	2	3
1	30.15	54.6	56.76
2	31.92	22,711	22,711
3	47.79	31,201	31,201
4	32.76	60	60
5	45.33	31,201	31,201
6	54.99	60	31,201
7	49.08	31,201	31,201
8	31,201	60	58.38
9	31,201	57.3	60
10	50.34	60	31,201
11	60	60	31,201
12	60	31,201	31,201
13	60	60	60
14	60	31,201	31,201
15	60	31,201	31,201

6. Results and Discussion

The objective of this research is to establish a Last Mile Humanitarian Aid Delivery Model utilizing electric vehicles for disaster areas. The significance of this research lies in addressing the critical aspect of last-mile humanitarian aid delivery, a phase often challenging to navigate due to its proximity to disaster-stricken areas. The utilization of electric vehicles introduces an eco-friendly and efficient approach to aid distribution, considering the potential benefits of reduced environmental impact and operational costs. The justification for employing electric vehicles in aid distribution will be explored, taking into account their potential for agility, reduced emissions, and lower operating costs compared to traditional vehicles.

In the literature, Kilic (2020) [24] optimized and compared the routing costs of electric and gasoline vehicles. Kabadurmus and Erdogan (2022) [25] addressed a dual-purpose time window green vehicle routing problem in their study, aiming to minimize carbon emissions.

The rationale behind the choice of Kayseri province as a case study is grounded in the recent seismic activity experienced in the region. The occurrence of multiple earthquakes with magnitudes between 4 and 5 underscores the importance of implementing an effective aid delivery system that can swiftly respond to the needs of affected communities. Furthermore, the study assesed the feasibility and practicality of the proposed model by considering real-life factors such as infrastructure, technology, and community engagement. By doing so, the study aims to provide insights into how the Last Mile Humanitarian Aid Delivery Model with Electric Vehicles can be implemented effectively in Kayseri and potentially serve as a benchmark for similar regions facing comparable challenges. This research endeavors to not only propose a Last Mile Humanitarian Aid Delivery Model tailored for Kayseri but also to establish a comprehensive justification for its adoption.

Finally, a sensitivity analysis was performed to assess the system's response to the broader spectrum of increased demand.

6.1. Sensitivity Analysis

In this section, a thorough scenario analysis was conducted, encompassing a wide range of potential fluctuations and increases in patient demands. Scenario analysis involves considering different possible situations or scenarios that could impact the system or process under investigation. In healthcare, scenarios could include changes in patient demographics, new disease outbreaks, changes in healthcare policies, or other factors that might influence patient demand. Fluctuations and increases in patient demand analysis likely involves exploring how the system responds to variations in the number of patients seeking healthcare services. This could be due to seasonal changes, unexpected events, or other factors that might lead to fluctuations or increases in patient demands. Sensitivity analysis is a technique used to understand how changes in one variable (in this case, patient demand) affect the outcomes of interest. It helps identify which factors have the most significant impact on the system and which are less influential. The specific focus on the increase in patient demand suggests that the analysis is particularly interested in understanding how the system copes with higher-than-usual patient loads. This could involve assessing the capacity of healthcare facilities, the availability of resources, and the ability to adapt to sudden spikes in demand.

Different scenarios were defined a range of possible situations that could affect patient demand, considering both fluctuations and sustained increases. The demands of Kayseri State Hospital and Kayseri City Hospital were 410 and 582. In the scenario analysis, the demands of these hospitals were taken as constant so that they would not exceed the vehicle capacity of 600. In our mathematical model, constraint (13) ensures that the vehicle does not exceed its cargo capacity. Scenarios have been determined based on an increase in the demands of other hospitals from 5% to 50%. And these scenarios are listed in Table 7.

Each scenarios results were obtained from Proposed Last Mile Humanitarian Aid Distribution with Electric Vehicles 0-1 Mixed Integer Mathematical Model and results were given in Table 8.

Table 7. Scenarios of Kayseri Province Application

# Scenario	1	2	3	4	5	6
Demand	100%	105%	110%	115%	120%	150%
Akkışla	5	5.00	6.00	6.00	6.00	8.00
Bunyan	29	30.00	32.00	33.00	35.00	44.00
Develi	66	69.00	73.00	76.00	79.00	99.00
Felahiye	5	5.00	6.00	6.00	6.00	8.00
Hacılar	12	13.00	13.00	14.00	14.00	18.00
İncesu	29	30.00	32.00	33.00	35.00	44.00
Kayseri State	410	410	410	410	410	410
Kayseri City	582	582	582	582	582	582
Talas	169	177.00	186.00	194.00	202.00	254.00
objective function value (total distance)	443.1	443.1	443.1	443.1	443.1	443.1

Table 8. Routes obtained with the model for all vehicles and all scenarios.

# Scenario	Routes produced by the model for vehicles																**objective function value (total distance)**
1	Vehicle	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	443.1
	Node i	1	7	4	14	6	10	12	3	2	15	5	1	9	1	8	
	Node j	7	4	14	6	10	12	3	2	15	5	1	9	1	8	1	
2	Vehicle	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	443.1
	Node i	1	7	4	14	6	10	12	3	2	15	5	1	9	1	8	
	Node j	7	4	14	6	10	12	3	2	15	5	1	9	1	8	1	
3	Vehicle	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	443.1
	Node i	1	5	15	3	2	12	10	6	14	4	7	1	9	1	8	
	Node j	5	15	3	2	12	10	0	14	4	7	1	9	1	8	1	
4	Vehicle	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	443.1
	Node i	1	7	4	14	6	10	12	3	2	15	5	1	9	1	8	
	Node j	7	4	14	6	10	12	3	2	15	5	1	9	1	8	1	
5	Vehicle	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	443.1
	Node i	1	7	4	14	6	10	12	3	2	15	5	1	9	1	8	
	Node j	7	4	14	6	10	12	3	2	15	5	1	9	1	8	1	
6	Vehicle	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	443.1
	Node i	1	5	15	3	2	12	10	6	14	4	7	1	9	1	8	
	Node j	5	15	3	2	12	10	0	14	4	7	1	9	1	8	1	

According to the results, the model identifies different routes but maintains the same distance for all scenarios. These findings demonstrate the model's robustness in handling possible fluctuations and increases in patient demands. Scenario 1 presents the results based on the initial demand amounts without a demand increase. Other scenarios showcase the model's outcomes with demand increases of 5%, 10%, 15%, and, finally, 50%, respectively.

In Scenarios 2, 4, and 5, both the routes and distances are the same as in Scenario 1. In Scenario 3 and 6, the routes are identical, and their distances are the same as in Scenario 1.

7. Conclusion and Recommendations

Within the scope of this study, the issue of last-mile aid distribution after disaster was addressed with energy-efficient electric vehicles. Considering the problems encountered after the February 6 earthquake in our country, a 0-1 mixed integer last-mile humanitarian aid distribution model was developed. In the developed model, electric vehicles that can be charged at solar-powered stations were used, considering the power outages experienced after the disaster. The application of the proposed model was carried out with the example of Kayseri province. The model has 9 hospitals and 5 solar charging stations. The total demand for hospitals is assumed to be 1307. Erkilet Airport was chosen as the warehouse. Electric vehicles: 3 E-Transit vehicles with a battery capacity of 68 kWh and a material capacity of 600 units were preferred. Distance data and consumed energy amounts were entered into the model and solved in the CPLEX program. The model calculated the route for each vehicle that minimized the total distance. In the future, this study could provide support for our country to determine the most suitable routes for every natural disaster in every province and to provide immediate intervention and assistance without waiting in the event of a disaster. In the future, with meta-heuristic algorithms and artificial intelligence techniques, appropriate routes could be created for all provinces in case of natural disasters such as fire, flood, and landslide, and all kinds of humanitarian and medical aid will be provided to disaster victims in minimum time. In addition, these models could be expanded in our country and could set an example for other countries and the whole world could be prepared for possible disasters.

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We commemorate with mercy those who lost their lives in the earthquake of February 6, 2023.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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