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Designing a cross docking-based humanitarian supply chain network using a meta-heuristic algorithm

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Abstract

In present study, a mathematical model for designing a humanitarian supply chain network and vehicle routing problem considering cross-dock is proposed where a Non-dominated Sorting Genetic Algorithm (NSGAIII) is used for implementing the proposed model in a large-scale problem. Since the model was implemented in a large-scale case, various sensitivity analyses were performed to extract the results. Hence, the results showed that the costs have more effect on the first objective function (patients compared to total injuries) and the second one (shortage), respectively. Compared to the other two objective functions, the impact on the cost function is negligible. The effect of transportation cost of relief goods/supplies from the supplier to the warehouse on the first objective function is higher than the others; however, the effect of this cost is further than that of the cost from the supplier to the distributor, accordingly, in comparison to the previous cost, the output reacted more to this cost. The transportation cost from the distributor to the warehouse (cross-docking) has less effect on the cost function unlike the transportation cost from the supplier to the warehouse. Nevertheless, the result shows that an increase in the cost can lead to a considerable increase in the ratio of patients to total injuries as well as shortage. In other words, the objective functions would deteriorate when this parameter tends to be increased.

Keywords: Supply chain network, humanitarian relief, vehicle routing problem, cross-docking, NSGA (III)

1- Introduction

Today, in spite of existing technological advances, sufferings caused by natural disasters (e.g. earthquakes, floods, storms, lightning, avalanches, tornadoes, fires and volcanoes) and unnatural ones (i.e. wars, terrorist incidents, road crashes, industrial accidents, political unrest and migration of refugees) are the main barriers to the sustainable development of countries (Uitto & Shaw, 2016; Pourghader Chobar et al. 2021). Hence, not being prepared and dealing with them appropriately cause heavy casualties and damages to nations and their assets, which sometimes cannot be compensated. Relying on a coherent and scientific crisis management system in the country, crises can be prevented by predicting and identifying them, and in the event of a crisis, this system can prioritize, plan, organize, direct, lead and control necessary activities.

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If these measures are done successfully to intervene, guide and control the crisis and to heal after the crisis, we can hope that many crises will be predicted and contained before they occur, or in the event of a crisis, the consequences of them are reduced to the minimum possible (Anikina, Fefelov & Malanina, 2019; Jahangiri et al. 2021; Bayanati et al. 2022). Therefore, due to the increase of unexpected accidents and land, ocean and atmospheric disasters in recent years, planning to better respond to these accidents seems necessary. One of the most important disasters mentioned is the earthquake, which can cause a lot of loss of life and money. Earthquakes account for the largest number of natural events, the effects of strong earthquakes can be devastating, even though thousands of seismograph stations are networked and connected around the world and the collected data is continuously analyzed. We are still not able to predict the exact time and place of earthquakes. This is while a megacity like Tehran has a population of thirteen million people and an earthquake can kill more than one million people (Kamranzad, Memarian & Zare, 2020).

Meanwhile, supply chain in the event of an earthquake are of great importance. Productivity is an important success factor in supply chain networks. It is necessary to ensure the proper flow of goods and services in humanitarian supply chains in response to a disaster. Natural disasters have always been a part of our lives, despite scientific and technological developments, humans are unable to prevent these events. For this reason, one of the priority goals of local authorities and relief organizations is to establish a humanitarian relief network to prepare the city. In humanitarian preparations, the initial measures must be taken within the first 72 hours after the earthquake. The first 12 hours after the disaster is very important and is known as the standard relief time, any kind of delay in taking necessary measures can lead to more deaths. Public and non-governmental organizations must immediately assess the situation and start sending relief products from local warehouses to the affected areas. In addition, time constraints must be considered, as well (Salehi, Mahootchi & Husseini, 2019; Pourghader Chobar et al. 2022).

One of the most important strategies to improve the performance and reduce the delay and damage caused by the earthquake is to establish relief distribution centers and care centers in the right place. In addition, determining the optimal plans for the appropriate response to the distribution of relief equipment and the evacuation of the casualties in disaster conditions can significantly reduce the loss of life and money (Zhang, Wang & Ren, 2019; Eshghali et al. 2023). In general, the logistics plan in the disaster response phase has two objectives. The first is to transport the injured people from the affected areas to shelters, hospitals and other emergency medical centers, and the second is to send relief equipment from predetermined warehouses or suppliers to the affected areas. Evacuation is done at the beginning of the response phase and takes the injured people out of the affected area. Effective planning of logistic activities during the response phase can significantly reduce the number of deaths. Moreover, in this situation, the available resources, goods and vehicles are usually insufficient. Therefore, the proper location of temporary care centers and temporary accommodation centers and their optimal allocation can reduce financial and human losses (Maharjan & Hanaoka, 2018; Chobar et al. 2022; Hosseini et al. 2022).

Another important issue in the aid supply chain is the planning for blood collection, production, inventory control and distribution. The blood supply chain is a challenge due to the increased blood demand, especially because of disasters. Blood supply chains include several processes such as collecting, producing and distributing blood and its derivatives from donors to recipients (Asadpour, Olsen & Boyer, 2022; Rezaei Kallaj et al. 2021). An efficient and humane logistics system should minimize human casualties by sending and delivering aid. Meanwhile, cross-docking is one of the most effective solutions in logistics systems, which leads to the reduction of inventory costs and generally timely delivery of goods. Cross-dock activities include three general classes: loading, sorting, and unloading (Kiani Mavi et al., 2020; Babaeinesami et al. 2022).

Besides, supply chain management is the evolutionary result of warehousing management and is an important infrastructural foundation of business implementation, in many of which it is a basic effort to shorten the time between the customer's order and the actual delivery of the goods. Cross-dock is one of the most important options to reduce time in the supply chain. Its general idea is to transfer cargo from incoming to outgoing trucks without any storage and usually with less than 24 hours in cross-docks and sometimes less than one hour. Accordingly, it is necessary to create a model that can provide the best locations for the central warehouses among the designated areas and to determine the capacity of the central warehouses (Benrqya, 2019; Zandbiglari et al. 2023). At the same time, it makes sense to consider the best policy of relief operations by routing the vehicles and the program of prioritizing relief goods and reducing its costs through the transit temporary warehouse (cross-dock) for the conditions before and after the disaster. In many studies, only the flow of relief resources or only the flow of casualties is considered. Failure to pay attention to these two at the same time creates a gap between the problem and the real world. In many studies, the type of casualties in the evacuation operation is not considered. Paying attention to the type of relief goods and their priority to optimize the distribution, including blood, food, water, blankets and tents have not been studied in any study, and the use of cross-docking to implement this strategy is one of the undone tasks of previous studies. Furthermore, injured people are among the tasks that have not been considered in most studies (Barsing et al., 2018). In the meantime, routing between different levels is very important, so that on one hand, it imposes lower costs on the system and on the other hand, accelerates the evacuation and distribution, taking into account the possibility of spoilage of blood, food, etc. (Faghih-Mohammadi, Nasiri & Konur, 2022).

In addition, according to the type of injury, the casualties are transferred from the node of the affected area to the temporary care centers and hospitals, taking into account the location of the nodes and the routing of connections (Alinaghian et al., 2021). Also at this stage, decisions are made about how to allocate the nodes of the affected area to hospital nodes and the number of vehicles used between them and in the case of establishing a temporary care center, how to allocate temporary care centers in the affected areas (Miç, Koyuncu & Hallak, 2019). The desired goals of the proposed model in this study are as follows: 1- Minimizing the dissatisfaction of injured people with relief and treatment services, by minimizing the maximum weight ratio of the number of untreated injured people in different time periods to the total number of injured people in any affected area. 2- Minimizing people's dissatisfaction with the distribution of relief items by minimizing the maximum weight ratio of the lack of goods at different times of the period to the total demand of the affected areas. 3- Minimizing the total cost of preparation before the disaster, this cost includes the expenses of creating distribution centers, warehousing, and transportation, and the costs of creating temporary warehouses (cross-docks), temporary medical centers, and transportation costs in disaster conditions.

In general, today's decisions affect tomorrow's. Therefore, there is a need for a comprehensive model, which considers simultaneous decisions. Our proposed model considers both before and after the disaster, as an integrated model can eliminate the delay in relief operations and have an optimal allocation. This system is scenario-oriented and is planned based on different demand scenarios. It is planned in multiple periods and includes several types of relief products, including blood with a limited lifespan, as well as several types of vehicles suitable for transporting goods, blood and people. As a result, in a nutshell, it should be said that in this network, relief resources are transferred from the nodes of the suppliers to the nodes of the distribution centers and reach the temporary warehouse node (cross-dock) in the post-disaster stage by different vehicles and according to the relief goods. In this stage, decisions about unloading, sorting, prioritizing, loading and shipping operations are made. Hence, the current research aims at designing a humanitarian aid supply chain network and vehicle routing based on cross-docking.

This study is presented in five sections in such a way that in the first and second sections, the introduction and statement of the main challenge of the study are explained, and by reviewing the recent studies conducted in the field of the subject raised in the present study, the research gap of this study is presented. Next, in the third section, the proposed model is presented and after stating the hypotheses of the model, indices and parameters, the objective functions are presented and finally the limitations of the model will be mentioned. In the fourth section, the numerical results obtained from solving the model using Non-dominated Sorting Genetic Algorithm III (NSGAIII) are presented, and finally, in the fifth section, the conclusion is provided.

2- Literature review

Ghasemi[a] et al. (2021) presented a multi-stage mixed mathematical and random integer programming model for logistics distribution and evacuation planning during an earthquake. In this model, cost related issues are considered in the proposed models through three objective functions. Several constraints have also been taken into consideration in their proposed model to make the model more flexible. Finally, the above model was solved using NSGA-II algorithm.

Rahbari et al. (2019) provided a mixed linear integer programming model with two objectives for the cross-dock vehicle routing and scheduling problem for perishable products. In their model, it is shown that attention to a purpose and sacrificing the other create a suitable relationship by the L1 metric method. Moreover, a robust model is created when the travel time of suburban vehicles and the freshness of products are uncertain. Their results show that the effect of the apparent uncertainty in the travel time on the worsening of the objectives is greater than that of the freshness of the products, and by using the proposed model, the freshness of the delivered products increases by 74.14% on average without increasing the distribution cost, thus reducing the waste.

Tavana et al., (2018) proposed a multi-level humanitarian logistics network that considers the location of central warehouses, inventory management of perishable products in the pre-disaster phase, and routing the relief vehicles in the post-disaster phase. For this purpose, they proposed a multi-level humanitarian logistics that considers the location of central warehouses, inventory management of perishable products in the pre-disaster phases and routing the relief vehicles in the post-disaster phase. Accordingly, they proposed a non-dominated sorting genetic algorithm (NSGA-II) to solve the mixed integer linear programming problem.

Ghasemi[b] et al. (2019) presented a mixed integer programming model for locating in the response phase. Their proposed model has five levels with the titles of affected areas, distribution centers, hospitals, temporary accommodation centers and temporary care centers. In addition, in their model, the objective of the two functions is to minimize the total cost of locating the facilities and minimizing the lack of relief resources and demand restrictions, the circulation of relief goods, the capacity of the center, transportation of the casualties, the total capacity of transporting the goods and the casualties in different time periods.

Oksuz and Satoglu (2019) provided a two-stage stochastic model for planning the location of temporary medical centers to respond the natural disasters. Their proposed model finds an optimal locating solution and minimizing the total system commissioning cost and the expected total transportation cost by considering the types of injuries, demand, the possibility of damage to roads and hospitals, and the distance between disaster areas and medical centers.

Hashemi Petrudi et al. (2020) investigated the chain challenges facing the Iranian Red Crescent population. To identify these challenges, fuzzy Delphi method and fuzzy interpretive structural modeling were used and the cause and effect relationships between these challenges were examined.

In the study of Timperio et al. (2020), it is tried to propose a solution by integrating multi-criteria decision-making, network optimization and discrete event simulation to address inventory default, improving the efficiency, effectiveness and agility of relief chains.

The study of Aghajani et al. (2020) develops a two-stage scenario-based stochastic probabilistic hybrid programming model to deal with various uncertainties. First-stage decisions include supplier selection and capacity reservation level per supplier/period and inventory level. In the second stage, the decisions related to the time and volume are made. The applicability of the model was confirmed through a real case study. In addition, a case study was presented to demonstrate the performance and application of the proposed models in practice. Furthermore, numerical experiments and several sensitivity analyzes were performed to understand the effects of agreement conditions and some key parameters on the final decisions.

García-Alvez et al. (2021) discussed a road network reconstruction planning and relief distribution under heterogeneous road disturbances. In this regard, a mathematical model for the timing and routing of relief vehicles and machines was presented. This approach follows a reconstruction plan dedicated to providing support to relief operations. This requires the prioritization of road reconstruction, taking into account their impact on the efficiency of relief operations. In addition, a heuristic algorithm was presented to solve large instances of the problem. This approach is applied to a realistic case study based on a flood that occurred in the Mojana region of northern Colombia in 2010-2011.

Kyriakakis et al. (2022) solved the humanitarian problem of vehicle routing with time windows relying on a new approach with a predetermined number of available vehicles and a hybrid search meta-heuristic algorithm. This study presented a metaheuristic Hybrid Tabu Search - Variable Neighborhood Descent (HTS-VND) algorithm for the Cumulative Capacitated Vehicle Routing Problem Time Windows (CCVRPTW). This algorithm was also used to solve the unconstrained Cumulative Capacity Vehicle Routing Problem (CCVRP).

Therefore, the research gap that this study aims to fill is to consider decisions about location, routing, distribution, allocation (before and after the disaster) simultaneously for equipment, goods and casualties as a comprehensive mathematical model for relief network against natural disasters. In other words, we aim at designing the humanitarian relief supply chain structure considering the transit temporary warehouse (cross dock) that can eliminate the delay in distribution and have an optimal allocation by sorting the relief goods according to demand. In our proposed model, expanding the use of transit temporary warehouse (cross-dock) for the distribution of relief products as well as cost and humanitarian goals are considered at the same time. In the suggested model, the flow of casualties and the flow of relief resources are considered simultaneously, the flow of relief resources is between suppliers, distribution centers, transit temporary warehouses (cross-docks) and affected areas and hospitals, and the flow of casualties is between care centers, the affected areas and hospitals. In our proposed model, two types of severe and moderate injuries are considered for people. Considering having relief goods at three levels: first (essentials: blood, medicine, water, food, powdered milk), second (moderate: tents, blankets), third (less essential: clothes, etc.), the methods presented were used in a real-world case study.

3- Proposed model

In this study, a humanitarian supply chain model considering transit warehouse (cross-dock) as well as vehicle routing is presented. First, the description of the model is presented in full, and then the hypotheses and indices, parameters and decision variables, as well as the objective functions and its constraints are presented. In addition, the scenario that includes Malloy et al.'s robust model is also described at the end. Considering the importance of the problem of crisis management in today's world, in this study, a mixed mathematical programming model and an integer multi-purpose routing locating model for multiple goods and multiple vehicles are proposed. A six-level relief supply chain including suppliers, distribution centers, cross-docks, affected areas or demand points, temporary care centers and hospitals is considered before and after the disaster. Decisions related to the forecasting phase are related to the location of permanent aid distribution centers and their number. The decisions of the second stage are to determine the optimal location for the establishment of cross-docks and temporary care centers to increase the speed of treatment of casualties and distribution of goods in the affected areas. This process includes a three-level supply chain between cross-docks, distribution centers and demand points, as well as the supply chain for demand points, temporary treatment centers and hospitals. In the following, the decisions related to the cross-dock are as follows: the entry and exit area decisions. 1) In the cross-dock entry area: the time of arrival of incoming vehicles, the assignment of incoming vehicles to the entrance doors and the sequence of incoming vehicles to each entrance door. 2) The exit area: allocation of relief goods to cross-border vehicles, travel time of outgoing vehicles, allocation of outgoing vehicles to the exit door, exit time of outgoing vehicles and routing the outgoing vehicles in the delivery process.

In the meantime, routing between different levels is very important because it imposes lower costs on the system and accelerates evacuation and distribution, taking into account the possibility of blood and food spoilage, etc. Routing for such a system is comprehensive and is made between different levels, including cross-dock transit warehouse routing. In this system, there are three types of priorities for relief goods, which include essential, moderate, and less essential, and two types of severe and moderate injuries are considered for casualties, which are those with severe injuries in the hospital and outpatients, respectively, who are transferred to temporary care centers. Sorting and prioritization of relief goods, including blood, medicine, water, food, powdered milk, tents, blankets, clothes, etc., is done in the cross-dock. The flow of casualties and the flow of relief resources are considered simultaneously. The flow of relief resources between suppliers of distribution centers, temporary warehouses and affected areas is considered, and the flow of injured people is between care centers, affected areas and hospitals. Considering the importance of maximum demand coverage, which demand should be covered by which center has been considered.

As a result, in a nutshell, it should be said that in this network, the relief resources are transferred from the nodes of the suppliers to the nodes of the distribution centers, and by different vehicles and according to the relief goods, they reach the cross-dock node in the post-disaster stage. At this stage, the decisions are made on such operations as unloading, sorting, prioritizing, uploading and sending. In addition, according to the type of injury, the injured people are transferred from the node of the affected area to temporary care centers and hospitals, taking into account the location of the nodes and routing of communications. In this stage, the decisions are made on how to allocate the nodes of the affected area to the nodes of hospital and the number of vehicles used between them and on the establishment of a temporary care center and how to allocate temporary care centers in the affected areas. The objectives of the proposed model are as follows: 1) Minimizing the dissatisfaction of casualties with relief and treatment services by minimizing the maximum weight ratio of the number of untreated injured people in different time periods to the total number of casualties in each affected area. 2) Minimizing people's dissatisfaction with the distribution of relief items by minimizing the maximum weight ratio of the lack of goods at different time-periods to the total demand of the affected areas. 3) Minimizing the total cost of preparation and procurement before a disaster occurs. This cost includes the expenses of creating distribution centers, warehousing and transportation, the costs of creating temporary warehouses, temporary medical centers, and transportation costs in disaster conditions.

For this study, the model hypotheses are as follows:

H1) Six levels including suppliers, distribution centers, cross-docks, affected areas, temporary care centers and hospitals are considered as before and after the disaster.

H2) Demand points, suppliers, existing care centers and the amount of demand are known.

H3) All the distance between the facilities in the planning periods is fixed and known.

H4) It is possible to establish aid distribution centers for cross-docks in any candidate location.

H5) The distribution centers have the ability to distribute blood.

H6) Blood products have a limited shelf life and their vulnerability is considered from the time of their production.

H7) A set of vehicles including various types of transport vehicles such as refrigerator-equipped vehicles for blood transfusion with different capacities has been considered for the transportation of relief goods and the casualties.

H8) Vehicles are considered different for the collection and delivery process in the cross-dock.

H9) In the entrance area of the cross-dock, loading and moving operations of an incoming vehicle cannot be done at the same time. In other words, a moving operation can only start after the incoming vehicle is fully loaded.

H10) In the area outside the cross-dock, the loading operation of a cross-border vehicle begins only after receiving all orders assigned to that vehicle and transferring it to the area outside the warehouse.

H11) Each of the delivery routes starts and ends in the cross-dock.

H12) Customer's entire order must be delivered by one cross-border vehicle only.

H13) Health and care personnel classify patients in safety zones after the disaster.

H14) The existing medical centers have the ability to treat both types of injuries, while the temporary care centers only have the ability to treat the casualties with moderate severity.

H15) Each affected area can send injured people to one or more care centers, and each care center can receive injured people from one or more affected areas.

H16) Each vehicle can only be moved from one point to another in each mission.

H17) The ability and capacity of different vehicles to carry different types of relief goods and injured people with different injuries have been determined in advance, in other words, each vehicle cannot carry all types of relief goods and injured people with all kinds of injuries.

3-1- Indices, parameters and decision variables

The indices and parameters used in the objective functions are defined in tables 1 and 2.

Table 1. Indices of objective functions

Index	Definition
i	Supplier
j	Distribution centers
k	Transit temporary warehouses (cross-docks)
l	Demand points
m	Temporary care centers
n	Hospitals
p	Relief goods
q	Priority of relief goods
o	Type of injury of casualties
v	Vehicle
w	Potential location
a	Cross-border vehicle
d	Entrance door
dd	Exit door
r	Route

Table 2. Parameters of objective functions

Parameter	Definition
$HDEM_{lrt}$	The amount of total demand of injured people with the type of injury r in the demand area l in the time period t
$HDEM_{pqlt}$	The amount of demand for relief goods p with priority q in demand area l in period t
$TCIJ_{ijpq}$	The cost of transporting relief goods p with priority q from supplier i to distributor j
$TCKI_{ikpq}$	The cost of transporting relief goods p with priority q from supplier i to transit warehouse k
$TCKJ_{jkpq}$	The cost of transporting relief goods p with priority q from distributor j to transit warehouse k
$TCLJ_{jlpq}$	The cost of transporting relief goods p with priority q from distributor j to demand points l
$TCKL_{klpq}$	The cost of transporting relief goods p with priority q from transit warehouse k to demand point l
$TCRVLN_{rvln}$	The cost of transporting casualties with type r injuries by vehicle v from demand point l to hospital n
$TCRVLM_{rvlm}$	The cost of transporting casualties with type r injuries by vehicle v from demand point l to temporary care center m
$FCmw_{mw}$	The cost of constructing a temporary care center m at a potential location w
$FCkw_{kw}$	The cost of constructing a transit warehouse k at a potential location w
$FCjw_{jw}$	The cost of constructing a distribution center j at a potential location w
$Capij_{pqij}$	The capacity of distributor j to store product p of type q from supplier i
$Capjk_{pqjk}$	The capacity of transit warehouse k to store goods p of type q from distributor j
$Capik_{pqik}$	The capacity of transit warehouse k to store goods p of type q from supplier i
$PETEV_{vk}$	Processing time of vehicle v in transit warehouse k
$Capm_m$	The capacity of the temporary care center m to receive the casualties
$Capn_n$	The capacity of the temporary care center n to receive the casualties
$Capv_v$	The capacity of vehicle v

The decision variables are presented in table 3.

Table 3. Decision variables

Variable	Definition
$ETEV_{vk}$	Arrival time of incoming vehicles v to transit warehouse k
$EVRD_{vkd}$	1: If the incoming vehicle v is assigned to the receiving door d of transit warehouse k; 0: otherwise
$EVED_{vv'k}$	1: If the vehicle v overtakes the vehicle v' to any entrance door d of transit warehouse k; 0: otherwise
$HCBV_{pa}$	1: If relief goods p are assigned to cross-border vehicle a; 0: otherwise
EVT_{v}	The travelling time of vehicle v
EVD_{vdk}	1: If exiting vehicle v is assigned to exit door *dd* of transit warehouse k; 0: otherwise
$EEVT_{v}$	The exit time of vehicle v
ER_{vr}	1: If route r is selected for outgoing vehicle v; 0: otherwise
LN_{ln}	1: If demand node l is assigned to hospital node n; 0: otherwise
mw_{mw}	1: If temporary care center m is built at potential location w; 0: otherwise
LNV_{ln}	The number of vehicles to transport the casualties from the demand point l to the hospital n
jw_{jw}	1: If distribution center j is built in location w; 0: otherwise
kw_{kw}	1: If cross-dock k is built in location w; 0: otherwise
$Xvlm_{vlmt}$	Number of casualties transported from demand node l to temporary treatment center m by vehicle v in period t
$Xvln_{vlnt}$	Number of casualties transported from demand node l to hospital n by vehicle v in period t
$Ypqij_{pqij}$	Transferred goods p of type q from supplier i to distributor j
$Ypqjk_{pqjk}$	Transferred goods p of type q from distributor j to transit warehouse k
$Ypqik_{pqik}$	Transferred goods p of type q from supplier i to transit warehouse k
$Ypqjl_{pqjl}$	Transferred goods p of type q from distributor j to demand point l
X	Total number of untreated casualties
Y	Shortage of goods

The first objective function seeks to minimize the weight ratio of the untreated patients to the total number of wounded and injured people.

$$\min z1 = X.\frac{1}{\sum_{l} \sum_{r} \sum_{t} HDEM_{lrt}} \tag{1}$$

The second objective function seeks to minimize the shortage of relief goods.

$$\min z2 = Y.\frac{1}{\sum_{l} \sum_{p} \sum_{t} \sum_{q} HDEM_{lptq}} \tag{2}$$

The third objective function seeks to minimize the cost of the entire system, this cost includes the expenses of transportation as well as the construction of temporary storage centers and temporary treatment centers.

$$\min z3 = \sum_i \sum_j \sum_p \sum_q TCIJ_{ijpq} . Ypqij_{pqij} + \sum_j \sum_k \sum_p \sum_q TCKj_{jkpq} . Ypqjk_{pqjk}$$
$$+ \sum_i \sum_k \sum_p \sum_q TCKI_{ikpq} . Ypqik_{pqik} + \sum_l \sum_j \sum_p \sum_q TClj_{ljpq} . Ypqjl_{pqjl}$$
$$+ \sum_k \sum_l \sum_p \sum_q TCkl_{klpq} . Ypqkl_{pqkl} + \sum_m \sum_w FCmw_{mw} . mw_{mw}$$
$$+ \sum_k \sum_w FCkw_{kw} . kw_{kw} + \sum_j \sum_w FCjw_{jw} . jw_{jw} \tag{3}$$

3-2- Constraints

$$Ypqij_{pqij} \leq Capij_{pqij} \tag{4}$$

Constraint 4 indicates the storage capacity of relief goods by distribution centers.

$$Ypqjk_{pqjk} + Ypqik_{pqik} \leq Capjk_{pqjk} \tag{5}$$

Constraint 5 indicates the limitation of storage capacity for transit warehouses or cross-docks.

$$Ypqkl_{pqkl} \geq HDEM_{pqlt} \tag{6}$$

Constraint 6 states that the amount of transferred goods from transit warehouse k should fulfill the demand of transferred goods from the affected area.

$$Ypqkl_{pqkl} \leq Capjk_{pqjk} \tag{7}$$

Constraint 7 states that the amount of goods transferred from transit warehouse k cannot exceed the capacity of the transit warehouse in accepting goods from distributor j.

$$Ypqkl_{pqkl} \leq Capik_{pqik} \tag{8}$$

Constraint 8 indicates that the amount of goods transferred from transit warehouse k cannot exceed the capacity of the transit warehouse in receiving goods from supplier *i*.

$$ETEV_{vk} = ETEV_{v-1k} + PETEV_{vk} \tag{9}$$

Constraint 9 indicates the time of entry of vehicles into transit warehouse.

$$EEVT_v = ETEV_{vk} + PETEV_{vk} \tag{10}$$

Constraint 10 indicates the time when the vehicles leave the transit warehouse.

$$EEVT_v + EVT_v \leq T_{pq} \tag{11}$$

Constraint 11 represents the threshold limit of perishable goods.

$$\sum_k EVRD_{vkd} = 1 \tag{12}$$

Constraint 12 indicates that each vehicle is assigned to only one transit warehouse.

$$\sum_d EVRD_{vkd} = 1 \tag{13}$$

Constraint 13 indicates that each vehicle is assigned to one entrance door.

$$\sum_v EVED_{vv'tk} = 1 \tag{14}$$

Constraint 14 indicates the sequence between vehicles.

$$\sum_p HCBV_{pa} = 1 \tag{15}$$

$$\sum_k EVD_{vkdd} = 1 \tag{16}$$

Constraint 16 indicates that each vehicle is assigned to a transit warehouse.

$$\sum_{dd} EVD_{vkdd} = 1 \tag{17}$$

Constraint 17 indicates that each vehicle is assigned to a transit warehouse's exit door.

$$\sum_r ER_{vr} = 1 \tag{18}$$

Constraint 18 indicates that each vehicle is assigned to at most one route.

$$\sum_n LN_{ln} \leq N \tag{19}$$

Constraint 19 indicates the total number of available hospitals.

$$\sum_w mw_{mw} \leq 1 \tag{20}$$

Constraint 20 states that each temporary treatment center is assigned at most one potential location.

$$LNV_{ln} \leq \frac{HDEM_{lrt}}{Capv_v} \tag{21}$$

Constraint 21 indicates the total number of vehicles.

$$\sum_w jw_{jw} \leq 1 \tag{22}$$

Constraint 22 indicates that each distribution center is built in at most one place.

$$\sum_w kw_{kw} \leq 1 \tag{23}$$

Constraint 23 states that each transit warehouse is constructed in at most one potential location.

$$\sum_v \; Xvlm_{vlmt} \leq Capm_m \tag{24}$$

Constraint 24 indicates the limitation of the capacity of temporary medical centers.

$$\sum_v \; Xvlm_{vlnt} \leq Capn_n \tag{25}$$

Constraint 25 indicates the limitation of the capacity of hospitals.

$$EVRD_{vkd} \in \{0,1\} \tag{26}$$

$$EVED_{vv\prime k} \in \{0,1\} \tag{27}$$

$$HCBV_{pa} \in \{0,1\} \tag{28}$$

$$EVD_{vdk} \in \{0,1\} \tag{29}$$

$$LN_{ln} \in \{0,1\} \tag{30}$$

$$mw_{mw} \in \{0,1\} \tag{32}$$

$$jw_{jw} \in \{0,1\} \tag{33}$$

$$kw_{kw} \in \{0,1\} \tag{34}$$

Constraints 26 to 34 indicate the limitations of the binary variables of the problem.

$$EEVT_v \geq 0 \tag{35}$$

$$ETEV_{vk} \geq 0 \tag{36}$$

$$LNV_{ln} \geq 0 \tag{37}$$

$$Xvlm_{vlmt} \geq 0 \tag{38}$$

$$Xvln_{vlnt} \geq 0 \tag{39}$$

$$Ypqij_{pqij} \geq 0 \tag{40}$$

$$Ypqjk_{pqjk} \geq 0 \tag{41}$$

$$Ypqik_{pqik} \geq 0 \tag{42}$$

$$Ypqjl_{pqjl} \geq 0 \tag{43}$$

$$Ypqkl_{pqkl} \geq 0 \tag{44}$$

Constraints 35 to 43 indicate the limitations of the integer variables of the problem.

4- Findings

4-1- Solving the model with meta-heuristic algorithm

In this section, the model was solved using meta-heuristic NSGAIII algorithm. Pareto points were obtained by solving the algorithm, which indicates the performance of the algorithm in implementing the model and solving it. The results of solving the algorithm based on Pareto points are as follows. The problem is represented in a large scale as described in table 4.

Table 4. Representation of the problem in a large scale

Problem	Supplier	Distribution centers	Cross-docks	Demand points	Temp care centers	Hospitals	Relief goods	Priority of relief goods	Injury type	Vehicles	Potential location	Time periods	Cross-border vehicle	Entrance door	Exit door	Route
1	10	15	4	20	15	12	5	3	3	30	30	5	5	5	5	20
2	11	15	4	20	15	13	5	3	3	30	30	5	5	5	5	20
3	12	16	4	21	15	14	5	3	3	32	32	5	5	5	5	21
4	12	16	4	21	16	14	5	3	3	32	32	5	5	5	5	22
5	13	16	4	22	16	14	5	3	3	33	33	5	5	5	5	23
6	13	17	4	23	16	14	5	3	3	34	34	5	5	5	5	23
7	14	18	4	23	17	14	5	3	3	35	35	5	5	5	5	23
8	14	18	4	24	18	15	5	3	3	35	35	5	5	5	5	24
9	15	19	4	24	18	16	5	3	3	36	36	5	5	5	5	24
10	15	19	4	24	19	16	5	3	3	36	36	5	5	5	5	25

By representing the problem in a large scale, the model can now be implemented, the result of which is the Pareto points produced by the NSGAIII algorithm. The results of solving the model are presented in figure 1.

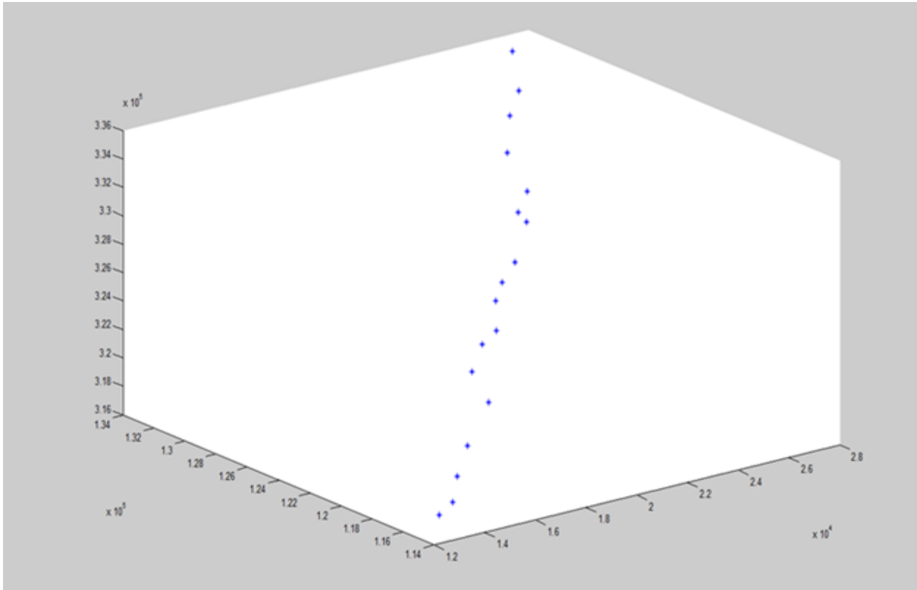

Fig 1. Pareto chart of NSGAIII algorithm

Using the NSGAIII algorithm, it can be seen that according to the presentation of Pareto points, the NSGAIII algorithm succeeded in solving the designed model.

4-2- Analysis of the sensitivity of the problem in a large scale

Considering that the problem was solved in large scale, we took advantage of the sensitivity analysis of the problem using more parameters. The results of the sensitivity analysis are presented in table 5.

Table 5. Sensitivity analysis of the transporting relief goods cost from the supplier to the distributor

The cost of transporting relief goods from the supplier to the distributor	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20465989	32244310	9712842981216	0.00582030	0.00414325	0.00013916
20%	20617696	32347812	9714465132716	0.00741264	0.00320993	0.00016701
30%	20744509	32462246	9715688111816	0.00615069	0.00353761	0.00012589
40%	20919969	32585530	9716711252916	0.00845814	0.00379777	0.00010531
50%	21113096	32724885	9717890801016	0.00923171	0.00427659	0.00012139

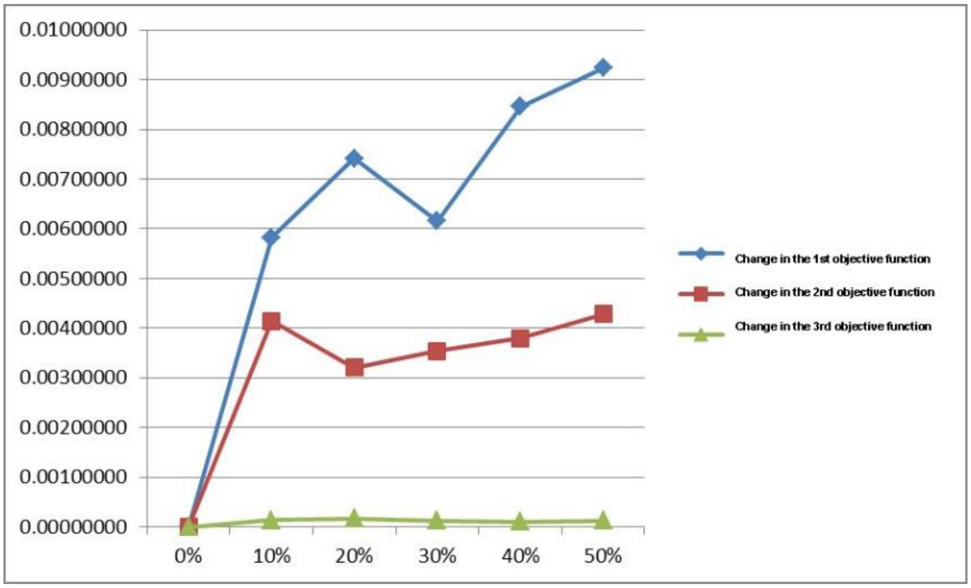

Fig 2. Sensitivity analysis of transporting relief goods cost from the supplier to the distributor

As it can be seen from the above diagram, this cost has the greatest effect on the first objective function, which is the ratio of patients to the total number of causalities, and then it has shown its effect on the second objective function, which is shortage. The influence on the cost function is apparently at the lowest level and shows less influence compared to the other two objectives.

Table 6. Sensitivity analysis of transporting relief goods cost from the supplier to the transit warehouse

The cost of transporting relief goods from the supplier to the cross-dock	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20364144	32130742	9713338007355	0.00081504	0.00060655	0.00019014
20%	20381192	32148033	9714590157462	0.00083716	0.00053815	0.00012891
30%	20398295	32162475	9716490597583	0.00083916	0.00044923	0.00019563
40%	20416908	32173451	9717627243992	0.00091248	0.00034127	0.00011698
50%	20436489	32191204	9719025225491	0.00095906	0.00055179	0.00014386

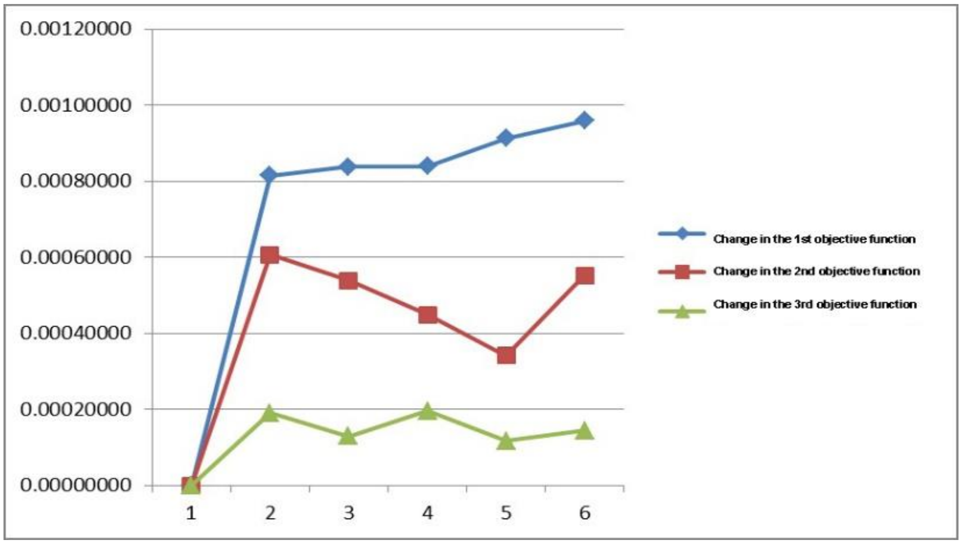

Fig 3. Sensitivity analysis of transporting relief goods cost from the supplier to the cross-dock

Regarding the effect of transporting relief goods cost from the supplier to the warehouse, it is also observed that the greatest effect is on the first objective function, but the next effect is still on the second objective function. However, the effect of the cost of transportation from the supplier to the cross-dock on the cost is more than that of transportation cost from the supplier to the distributor, and the response of the model to the cost is higher than the sensitivity analysis of the previous parameter.

Table 7. Sensitivity analysis of the cost of transporting relief goods from the distributor to the transit warehouse

The cost of transporting relief goods from distributer to cross-dock	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20544690	32263253	9712721224944	0.00968814	0.00473317	0.00012663
20%	20735472	32403296	9714108986642	0.00928620	0.00434063	0.00014288
30%	20900229	32584191	9715442530540	0.00794566	0.00558261	0.00013728
40%	21022431	32757420	9717064654720	0.00584692	0.00531635	0.00016696
50%	21182071	32863137	9718310764234	0.00759379	0.00322727	0.00012824

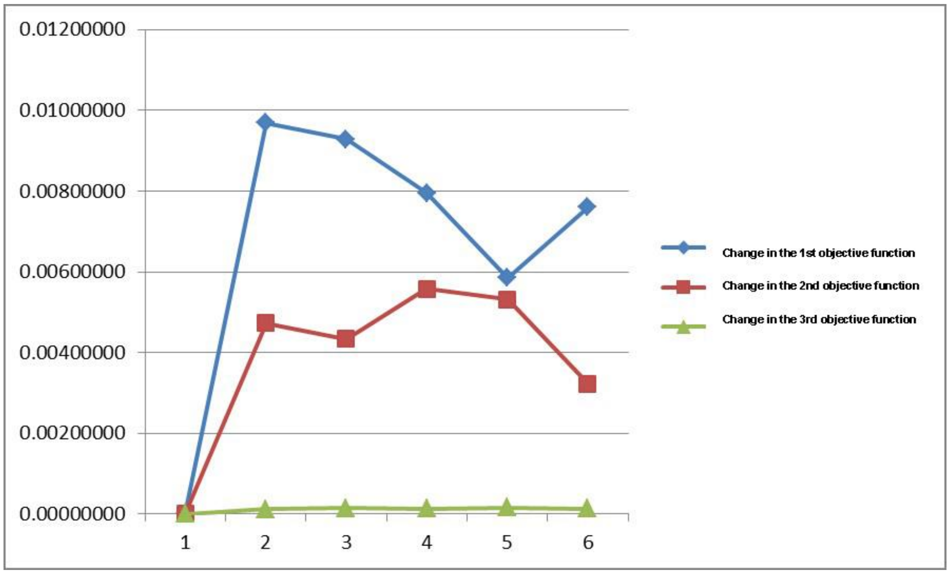

Fig 4. Sensitivity analysis of transporting relief goods cost from the distributor to the cross-dock

Regarding the cost of transportation from the distributor to the cross-dock, it can be seen that the effect on the cost is less compared to the transportation cost from the supplier to the cross-dock. However, it is still observed that such an increase can lead to a large increase in the ratio of patients to the total number of casualties. In other words, it leads to the deterioration of the solution and the model reacts negatively to the increase of this parameter.

Table 8. Sensitivity analysis of the cost of transporting the casualties by vehicle from demand points to the hospital

The cost of transporting relief goods from demand points to hospital	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20483377	32283851	9712695383731	0.00667485	0.00537462	0.00012396
20%	20620972	32474047	9714392493904	0.00671740	0.00589137	0.00017473
30%	20800175	32614972	9715682341817	0.00869033	0.00433962	0.00013278
40%	20941121	32782196	9717549942061	0.00677619	0.00512722	0.00019223
50%	21058083	32893995	9719386996330	0.00558528	0.00341036	0.00018905

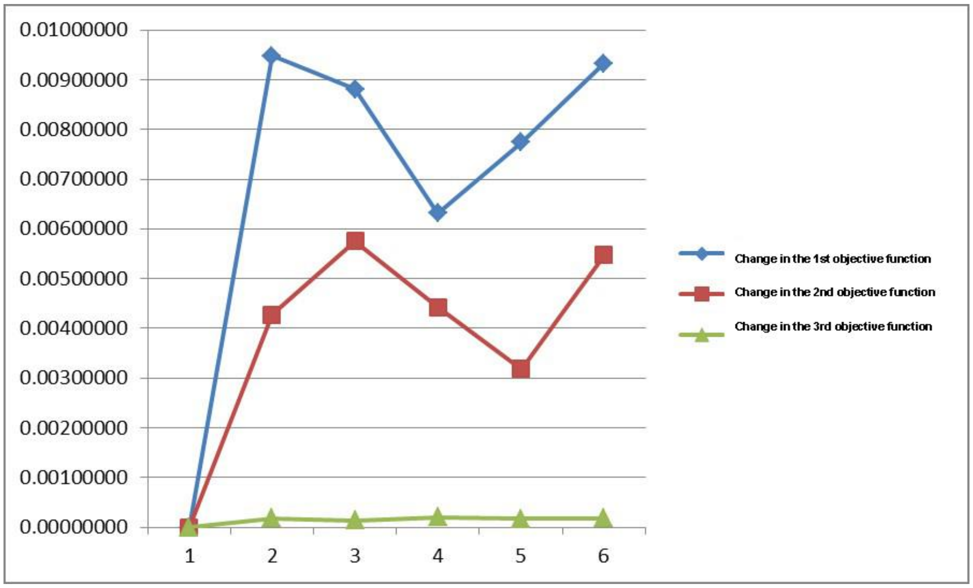

Fig 5. Sensitivity analysis of the cost of transporting the casualties by vehicle from the demand points to the hospital

In this section, followed by the transportation of goods, the transportation of the casualties by vehicle from the demand points to the hospital is discussed. Given the analysis result, the cost of transporting the casualties leads to an increase in the first and second objective functions and in fact to the deterioration of the solution, while it has a lower effect on the cost and the cost shows a poorer reaction to this increase.

Table 9. Sensitivity analysis of the cost of transporting the casualties by vehicle from demand points to temporary care centers

The cost of transporting relief goods from demand points to temp care centers	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20496404	32237998	9713389175564	0.00731508	0.00394668	0.00019540
20%	20607645	32359625	9714470835026	0.00542734	0.00377278	0.00011136
30%	20769280	32472870	9716301404774	0.00784345	0.00349958	0.00018844
40%	20964572	32591148	9717450000855	0.00940293	0.00364236	0.00011821
50%	21099845	32758549	9718702044596	0.00645246	0.00513639	0.00012884

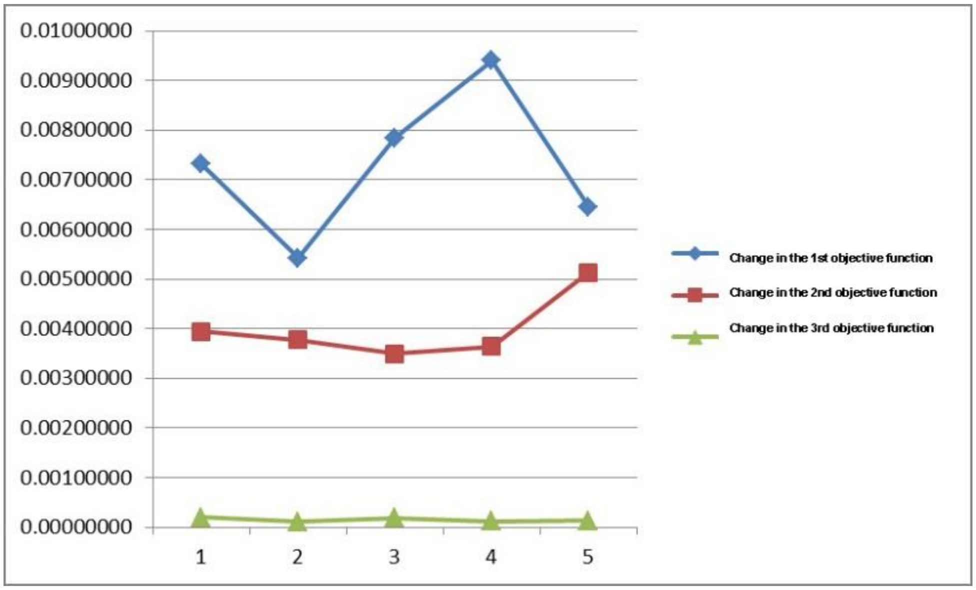

Fig 6. Sensitivity analysis of the cost of transporting the casualties by vehicle from demand points to temporary care centers

The results of the analyzing the cost of transporting the casualties by vehicle from the demand points show that if this cost increases, the proportion of patients can increase significantly and also there will be a shortage of goods. In other words, the increase in the cost of transporting the casualties can lead to a shortage, but the total cost will be less affected.

Table 10. Sensitivity analysis of the cost of constructing a temporary care center in a potential location

Cost of transporting relief goods from constructing a temp care center in a potential location	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20521493	32234191	9728718285237	0.00854810	0.00382813	0.00177386
20%	20666812	32420007	9743096062772	0.00708131	0.00576456	0.00147787
30%	20826311	32552477	9754825045470	0.00771764	0.00408606	0.00120383
40%	21019577	32663153	9770867885908	0.00927990	0.00339993	0.00164461
50%	21191543	32786706	9787293875353	0.00818123	0.00378264	0.00168112

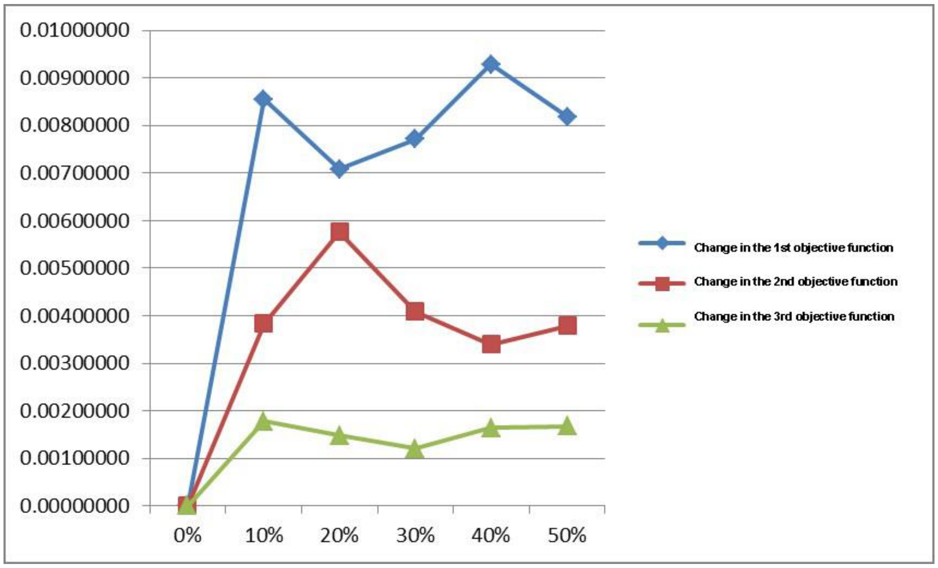

Fig 7. Sensitivity analysis of the cost of constructing a temporary care center in a potential location

In this section, the costs of building centers are considered. It can still be seen that the increase in the cost of constructing temporary centers can increase the number of patients who have not been treated, while this also leads to a shortage. However, apparently the effect of the shortage is decreasing. The total cost is also more affected compared to the shipping costs.

Table 11. Sensitivity analysis of the cost of constructing a cross-dock in a potential location

The cost of constructing a cross-dock in a potential location	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20469267	32251629	9729727088474	0.00598141	0.00437118	0.00187773
20%	20593788	32441044	9742016949458	0.00608332	0.00587304	0.00126312
30%	20762613	32548014	9758588771662	0.00819786	0.00329737	0.00170107
40%	20920419	32728113	9778429174141	0.00760049	0.00553333	0.00203312
50%	21039199	32830582	9792926035091	0.00567771	0.00313092	0.00148253

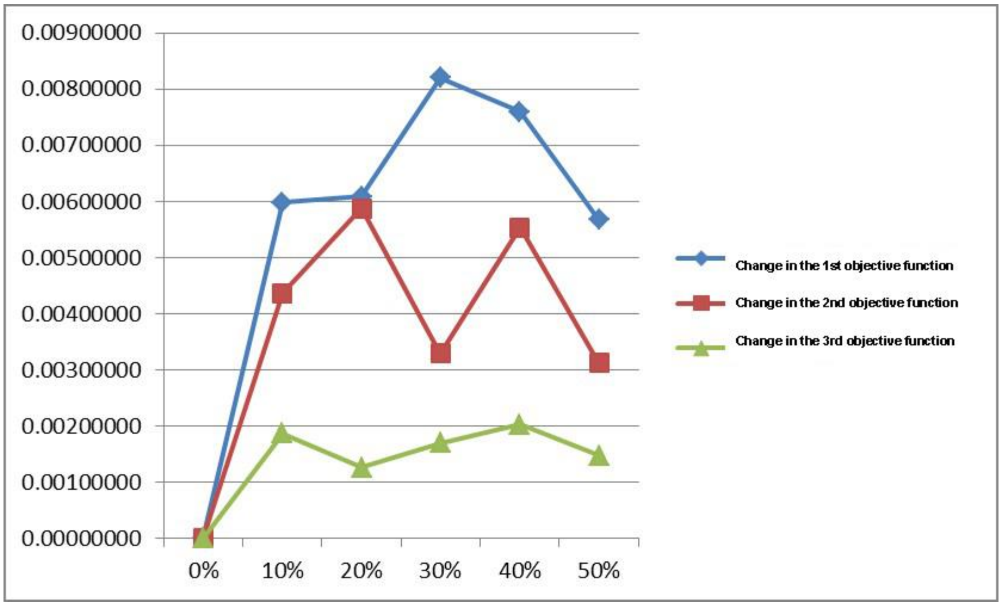

Fig 8. Sensitivity analysis of the cost of constructing a cross-dock in a potential location

If the cost of construction of cross-dock increases, we will see that it has an effect on the three objective functions and the values of the objective functions will increase significantly, however, this effect is greater on the first, second and third objective functions, respectively.

Table 12. Sensitivity analysis of the cost of building a distribution center in a potential location

The cost of constructing a cross-dock in a potential location	Minimizing the weight ratio of patients	Minimizing the shortage	Minimizing the cost	Change in 1st objective function	Change in 2nd objective function	Change in 3rd objective function
0%	20347560	32111265	9711491502816	0.00000000	0.00000000	0.00000000
10%	20457326	32226220	9730639719580	0.00539455	0.00357990	0.00197171
20%	20581847	32415635	9746040920169	0.00608687	0.00587767	0.00158275
30%	20750672	32522605	9758797141146	0.00820262	0.00329995	0.00130886
40%	20908478	32702704	9775546396347	0.00760486	0.00553766	0.00171632
50%	21027258	32805173	9794281797101	0.00568095	0.00313335	0.00191656

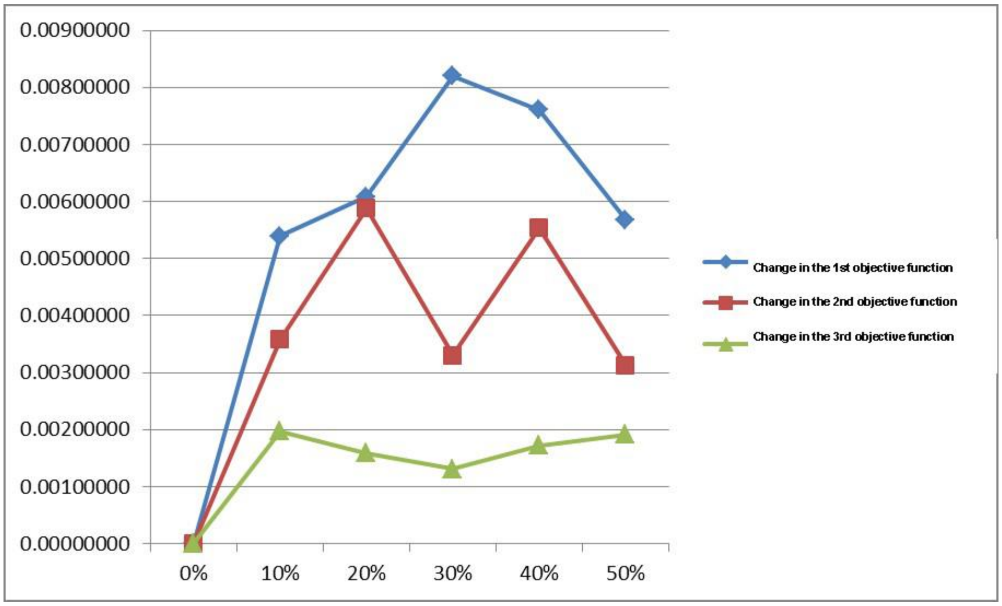

Fig 9. Sensitivity analysis of the cost of building a distribution center in a potential location

Regarding the cost of construction of distribution centers, if it increases, no significant difference will be observed, and the same amount of influence that was observed regarding other parameters can also be considered regarding this parameter.

4-3- Determining the most effective cost

In this section, it is examined which goal is more affected by which type of cost. The results are presented in the form of tables and graphs below.

Table 13. Comparison of the effect of different parameters of transportation cost on the first objective function

Minimizing the weight ratio of patients	Cost of transporting relief goods from the supplier to the distributor	Cost of transporting relief goods from the supplier to the cross-dock	Cost of transporting relief goods from the distributor to the cross-dock
0%	20347560	20347560	20347560
10%	20465989	20364144	20544690
20%	20617696	20381192	20735472
30%	20744509	20398295	20900229
40%	20919969	20416908	21022431
50%	21113096	20436489	21182071

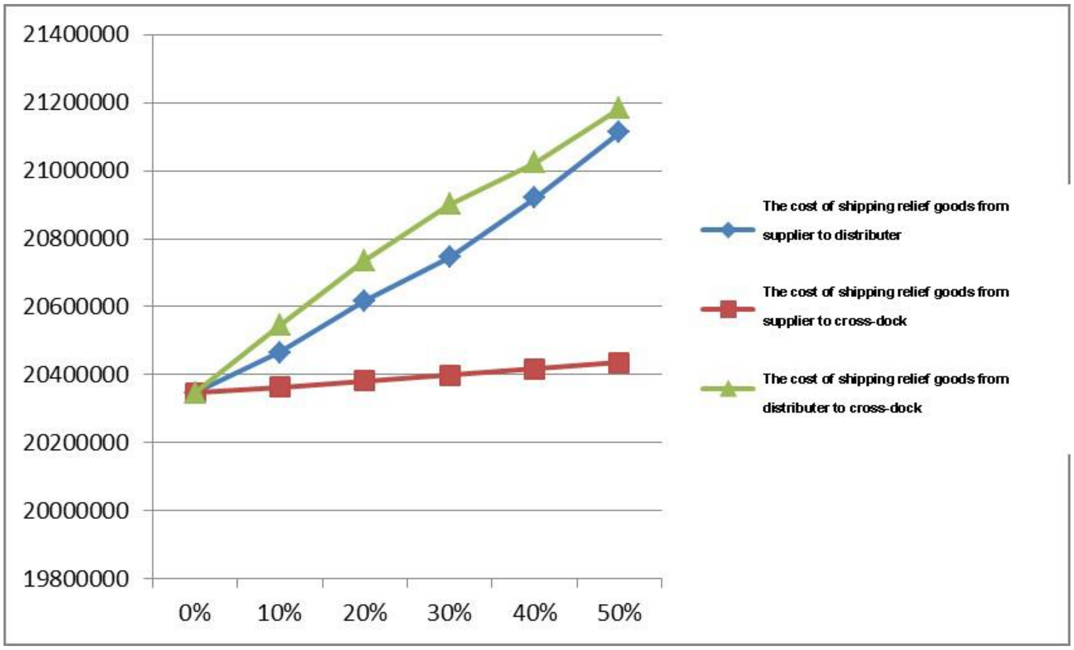

Fig 10. Comparison of the effect of different transportation cost parameters on the first objective function

As it can be seen in the above diagram, the cost of transporting relief goods from the supplier to the cross-dock has a much lower effect than the other two parameters of transportation cost and has a gentle slope. However, the cost of transporting relief goods from the distributor to the cross-dock is the most effective, followed by the cost of transporting relief goods from the supplier to the distributor.

Table 14. Comparison of the effect of different parameters of transportation cost on minimizing the shortage

Minimizing the shortage	Cost of transporting relief goods from the supplier to the distributor	Cost of transporting relief goods from the supplier to the cross-dock	Cost of transporting relief goods from the distributor to the cross-dock
0%	32111265	32111265	32111265
10%	32244310	32130742	32263253
20%	32347812	32148033	32403296
30%	32462246	32162475	32584191
40%	32585530	32173451	32757420
50%	32724885	32191204	32863137

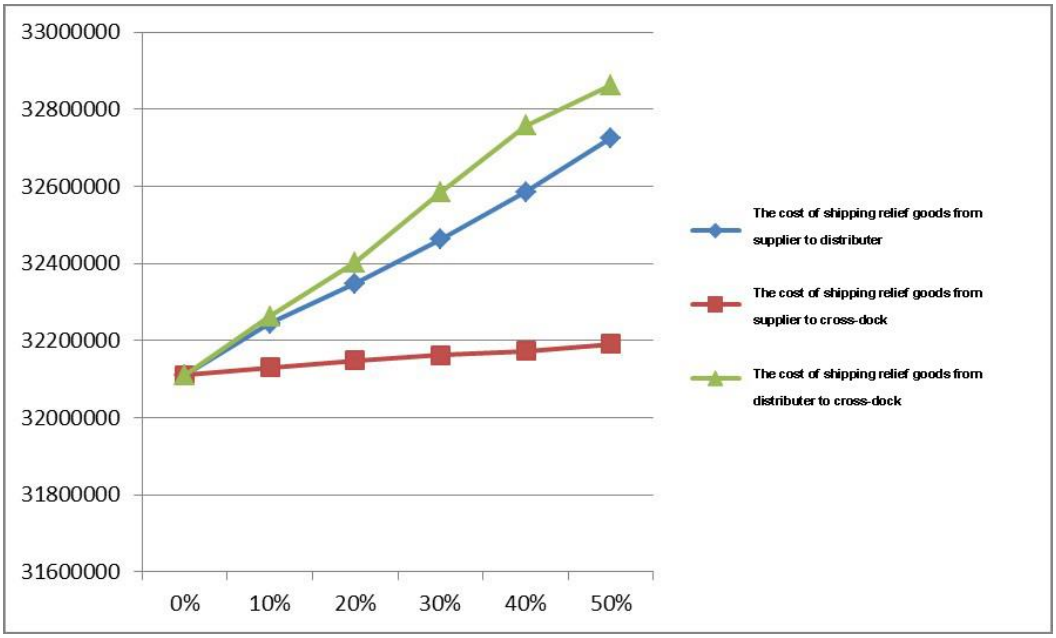

Fig 11. Comparison of the effect of different parameters of transportation cost on minimization of shortage

As it can be seen, the three transport parameters still lead to an increase in the shortage, but the effect of the cost of the relief goods from the supplier to the cross-dock is less than the other two parameters. However, the cost of transporting the relief goods from the distributor to the cross-dock has the highest slope and effect.

Table 15. Comparison of the effect of different parameters of transportation cost on cost minimization

Cost minimization	Cost of transporting relief goods from the supplier to the distributor	Cost of transporting relief goods from the supplier to the cross-dock	Cost of transporting relief goods from the distributor to the cross-dock
0%	9.71E+12	9.71E+12	9.71E+12
10%	9.71E+12	9.71E+12	9.71E+12
20%	9.71E+12	9.71E+12	9.71E+12
30%	9.72E+12	9.72E+12	9.72E+12
40%	9.72E+12	9.72E+12	9.72E+12
50%	9.72E+12	9.72E+12	9.72E+12

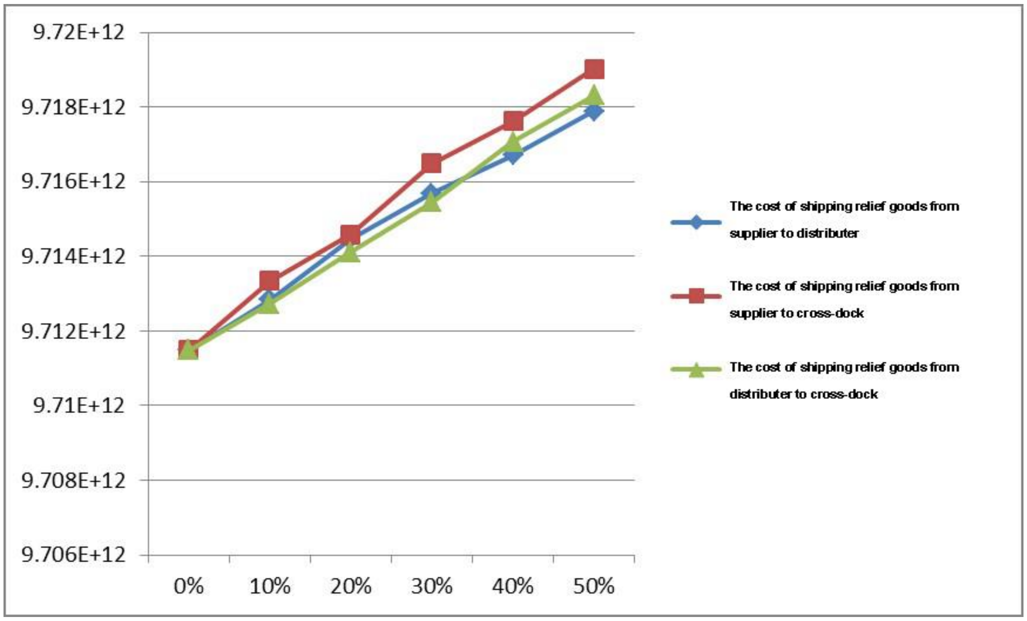

Fig 12. Comparison of the effect of different parameters of transportation cost on cost minimization

Based on the above graph, it can be seen that the effect of different parameters of transportation cost on minimizing the cost is almost similar, but the cost of transporting relief goods from the supplier to the cross-dock is more compared to the other two parameters.

Table 16. Comparison of the costs of transporting the casualties and construction costs and their effect on the weight ratio of patients

Minimizing the weight ratio of patients	Cost of transporting the casualties by vehicle from demand points to the hospital	Cost of transporting the casualties by vehicle from demand points to temporary care centers	Cost of constructing a temporary care center at a potential location	Cost of constructing a cross-dock at a potential location	Cost of constructing a distribution center at a potential location
0%	20347560	20347560	20347560	20347560	20347560
10%	20540468	20496404	20521493	20469267	20457326
20%	20721471	20607645	20666812	20593788	20581847
30%	20852357	20769280	20826311	20762613	20750672
40%	21013671	20964572	21019577	20920419	20908478
50%	21209656	21099845	21191543	21039199	21027258

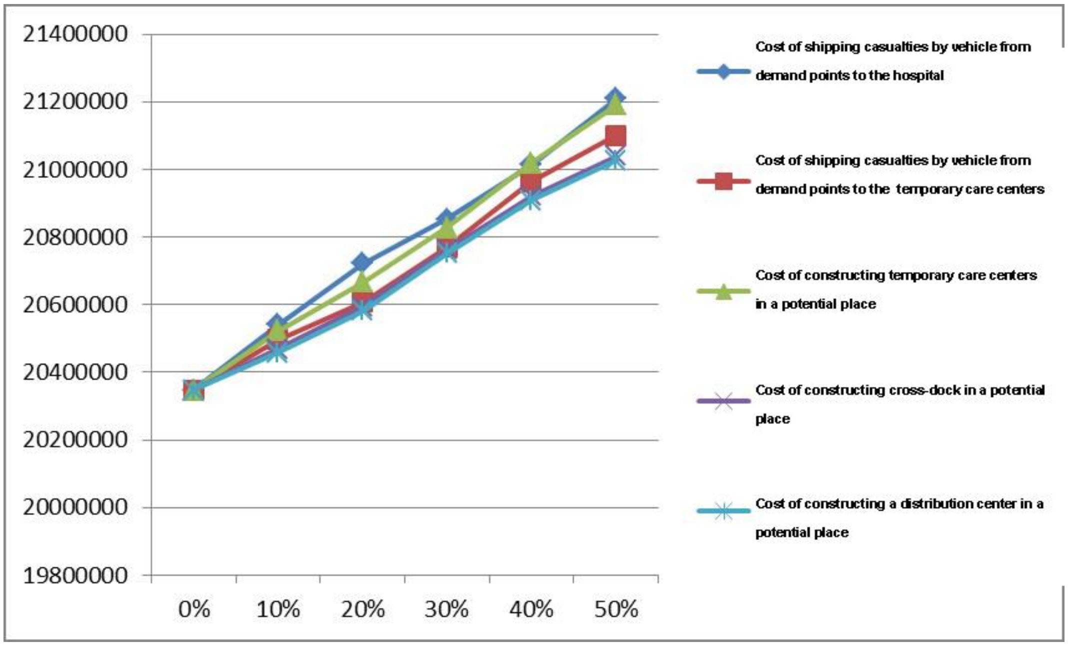

Fig 13. Comparison of the costs of transporting the casualties and construction costs and their effect on the weight ratio of patients

Based on the above graph, it can be seen that the cost of constructing a temporary care center and the cost of constructing a distribution center in a potential location has the greatest effect on increasing the weight ratio of patients and worsening the first objective function. However, this effect regarding the cost of transporting the casualties by vehicles from the demand points to hospitals is at the lowest level, so it can be said that two parameters are in the middle.

5- Conclusion

In this study, in order to design a humanitarian relief supply chain network, vehicle routing with cross connection, a model was presented, which was solved using meta-heuristic NSGAIII algorithm in a large scale. Considering that the problem was solved in a large scale, we looked for the sensitivity analysis of the problem using more parameters. The cost has the greatest effect on the first objective function, which is the ratio of patients to the total number of casualties, and then it has shown its effect on the second objective function, which is shortage. The influence on the cost function is apparently at the lowest level and shows less influence compared to the other two objectives.

Regarding the effect of the cost of transporting relief goods from the supplier to the warehouse, the greatest effect was observed on the first objective function. However, the next effect is still on the second objective function. This is while the effect of the cost of transportation from the supplier to the cross-dock on the cost is more than that of transportation cost from the supplier to the distributor. Meanwhile, the response of the model to the cost is greater compared to the sensitivity analysis of the previous parameter. Regarding the cost of transportation from the distributor to the cross-dock, it can be seen that the effect on the cost is less compared to the transportation cost from the supplier to the cross-dock. However, it is still observed that such an increase can lead to a large increase in the ratio of patients to the total number of casualties. In other words, it leads to the deterioration of the solution and the model reacts negatively to the increase of this parameter. Here, followed by the transportation of goods, the transportation of the casualties by vehicle from the demand points to the hospital was discussed. Given the analysis result, the cost of transporting the casualties leads to an increase in the first and second objective functions and in fact to the deterioration of the solution, while it has a lower effect on the cost and the cost shows a poorer reaction to this increase.

The results of the analyzing the cost of transporting the casualties by vehicle from the demand points show that if this cost increases, the proportion of patients can increase significantly and also there will be a shortage of goods. In other words, the increase in the cost of transporting the casualties can lead to a shortage, but the total cost will be less affected. Besides, the costs of constructing the centers were considered. The results showed that the increase in the cost of constructing temporary centers could increase the number of patients who have not been treated, while this also leads to a shortage. However, apparently the effect of the shortage is decreasing. The total cost is also more affected compared to the transportation costs. If the cost of construction of cross-dock increases, we will see that it has an effect on the three objective functions and the values of the objective functions will increase significantly, however, this effect is greater on the first, second and third objective functions, respectively. Regarding the cost of construction of distribution centers, if it increases, no significant difference will be observed, and the same amount of influence that was observed regarding other parameters can also be observed regarding this parameter. The cost of transporting relief goods from the supplier to the cross-dock has a much lower effect than the other two parameters of transportation cost and has a gentle slope. However, the cost of transporting relief goods from the distributor to the cross-dock is the most effective one, followed by the cost of transporting relief goods from the supplier to the distributor. Still, the three parameters of transportation lead to an increase in shortage, but the effect of the cost of the relief goods from the supplier to the cross-dock is less compared to the other two parameters, and the cost of transporting the relief goods from the distributor to the cross-dock has the highest slope and effect.

The results show that the effect of different transportation cost parameters on cost minimization is almost similar, but the cost of transporting relief goods from the supplier to the cross-dock is more compared to the other two parameters. Also, the results show that the cost of constructing a temporary care center and the cost of constructing a distribution center in a potential location has the greatest effect on increasing the weight ratio of patients and worsening the first objective function. However, this effect regarding the cost of transporting the casualties by vehicles from demand points to hospitals is in the lowest level and therefore it can be said that two parameters are in the middle state.

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