Addressing Road Blocking Risks in Post-disaster Relief Supplies Distribution Using Failure Mode and Effect Analysis Technique

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Abstract

In humanitarian relief operations, the management of existing risks can be a crucial factor in making these operations more efficient. One of the risks involved in relief operations is encountering blocked roads while giving service to the affected people. Usually, researches investigating the issue of vehicle routing problem for relief commodities transportation or relief supplies allocations, have shown that the possibility of getting blocked of the existing routes can have a profound impact on the pre-planned programmes of these operations. Therefore, this paper, for the first time, has attempted to use the technique of Failure Mode and Effect Analysis (FMEA) as a way of overcoming these risks. In other words, the possibility of roads' being blocked has been estimated using this technique and in order to infuse these possibilities in relief operations planning, one mixed integer programming model will be introduced. In general, to implement the obtained data from FMEA technique into similar programming, similar models are required. Since these sorts of models are NP-hard, one Heuristic method having a suitable solution time and result based on the Graph Theory will be presented.

Keywords: Risk management, FMEA technique, Heuristic algorithm, Graph theory, Humanitarian relief operations

1. Introduction

The main objective of the humanitarian relief chain is to provide individuals affected by natural disasters with services to minimize the death toll and also the rate of injuries for the peoples around. Right time and right amount are two crucial factors regarding relief preparations. Balcik et al. (2010), remark that preparation aids are transferred through a four-stage supply chain including; suppliers (global or local); Central Distribution Centers (CDCs); Local Distribution Centers (LDCs); and Beneficiaries. Normally, CDCs are warehouses saving some aids beforehand. The amount of the saved preparations is to a level that can satisfy the needs of the affected people before their being provided with aid preparation of suppliers. (Rawls and Turnquist, 2012) CDCs are located outside the cities and far away from the disaster area and as the disaster occurs they start to distribute the supplies. LDCs can also include fixed places like school and hotel or they may be set up in camp forms in the affected area after occurring the disaster. The injured people will be transferred to the shelters which are temporary and located near the affected area. Therefore, it can be concluded that LDCs and shelters are located in the busy places of affected areas much likely to be blocked and a great planning for an overlain transferring of the facilities is required. Generally, lack of funding, shortage of transport capacity, and the possibility of roads being blocked are the main factors making troubles while transferring facilities to the LDC and shelters. Balcik et al. (2008) point out that this part of supply chain is known as Last Mile. Operational decisions relating to this section include: vehicle routing; vehicle delivering scheduling; and relief supply allocation.

Failure mode effect analysis (FMEA) is a systematic technique for failure analysis. It was introduced by reliability engineers in the 1950s. They applied this technique to study problems that might arise from malfunctions of military systems. A FMEA is mainly a qualitative analysis (Rausand and Hoylan (2004)). It is a combination of likelihood and consequences of failure. It is used to assess likelihood of failure of structures and processes and their effects on the whole the system. This type of process is usually used by environmentalists to conduct environmental risk assessments and by engineers to assess the risk of engineered systems.

Applying a FMEA technique, in this article, we are going to consider the possibility of blocked roads for Last Mile distribution. In other words, the relevant terms to this technique such as failure, failure mode, effect
etc. for blocking of the roads will be defined and we will find the best routes (those having the least possibility of getting blocked) applying the obtained risk level.

To the best of our knowledge, in the relevant literature, this is the first work presenting the methods of facing the risk of blocked roads when transferring facilities.

To apply the FMEA technique first a worksheet, similar to the one existing in industry, should be prepared. Then, a mixed integer programming model will be presented to apply the risk level obtained from the worksheet in the relief operation planning. It should be noted that this model does not take into consideration other aspects such as the cost of the goods not being received by the affected people, transportation cost of the facilities etc. and is merely presented to depict the way of creating a relation between FMEA technique and modeling for facility transportation programming. The presented model in this article, in spite of the simple hypotheses, is a mixed integer model having a complex solution. Moreover, having applied the FMEA technique in future studies and more authentic conditions, the presented model in this article will become more complicated, hence, a Heuristic method based on Graph Theory will be introduced which make the solution of such models much simpler.

2. Literature review

Several studies regarding vehicle routing problems and supply allocations in emergency conditions have been done. For example, having considered the food transportation from distribution centers to several centers, Knott (1988) has presented a mathematical model to determine travels to each shelter in a way that minimizes the transportation cost while maximizing the level the demand is satisfied. Operation research heuristics are combined with artificial intelligence technique to present a tool for supporting the decision relating to allocation and distribution. Ozdama et al. (2008) study the emergency logistic problem to distribute the goods from several suppliers to distribution centers. They assume that the distribution centers are located near the affected area and present a multi-period, multi-commodity network model. This model having the purpose of minimizing the unmet demand in mind determines suitable routes, time and amount of delivery.

Resource allocation models consider resource assignments without determining flow quantities along arcs. Most of such models for relief distribution are proposed to allocate equipment and resources to clean up oil spills or amend other maritime disasters. Charnes et al. (1976, 1979) proposed multi-objective models having user-specific goals for assigning equipment to oil spill areas. Wilhelm and Srinivasa (1997) considered time-phased allocation of equipment components to minimize the response time to oil spills in a way that requirements will be met at critical time points. Srinivasa and Wilhelm (1997) proposed an optimization routine following their former models. Sheu et al. (2005) developed a model to allocate commodities in disasters other than oil spills and used a fuzzy clustering technique along with the group demand points. They performed path selection and minimized distance costs from relief centers as well. Sheu (2007), Tzeng et al. (2007), and Yan and Shih (2009) formulated models determining only commodity flows along arcs and the quantities to travel along distinctive links without assigning them to any resources such as transportation vehicles. Sheu (2007) deals with the problem of distributing relief supplies from DCs to demand nodes that have earlier been grouped using a fuzzy clustering technique.

Some researchers have implemented the risk of blocked roads in their programming in one way or another. For example, Rawls and Tumugust (2012) consider a binary parameter and having defined different risk scenarios, they attempt to consider blocking of roads connecting several relief warehouses and shelters. Ukkusuri and Yushimito (2008) have established a model in which pre-positioning of the goods are determined in a way to maximize the possibility of having access to all demand nodes from at least one distribution center. They assume that the links in transportation network may become useless.

3. Failure Mode and Effect Analysis Technique

In this section, the way of applying FMEA method to achieve the possibility of blocking of roads and also choosing the best route to transfer facilities to injured people will be explained. As mentioned earlier, the supply chain consists of four stages and, in this article, goods distribution from the last two stages being closer to the affected area are considered. These two stages include transporting commodities from CDCs to LDCs and
from there to demand nodes. To implement the FMEA technique into the plan of commodity transportation, first a mathematical model will be introduced. This model contains a TRPN parameter obtained by applying FMEA technique. This parameter demonstrates the risk of the link between demand note and LDC. There is one link connecting each potential LDC and demand node. There is also one link connecting potential CDC and potential LDC. However, in this article, the risk of blocking of the roads between shelters and LDCs has been the only focus of the study.

3.1. Mathematical model

In this section we consider a facility location-relief distribution problem for the last mile distribution. The relief supplies are distributed from CDCs to LDCs and then to shelters. The number and location of shelters are known and there are some potential locations for both CDCs and LDCs. The capacity of every CDC is limited and each shelter is assumed to have a deterministic demand. In such problems, we have to deal with several relief commodities. However, we assume that the composition of goods is homogeneous, i.e., the relation of food to clothes to tents and other items is approximately constant for the demand nodes and that there are no large items to cause divisibility problems. Therefore, we can treat our problem as a single commodity problem. Also, it is assumed that there is a limited budget for some expenses such as transportation costs, fixed cost of opening DCs and material handling cost. The mixed integer mathematical model is as follows:

**Notations**

**Parameters**
- $N_k$: The number of demand nodes (shelters)
- $N_j$: The number of potential LDCs
- $N_i$: The number of potential CDCs
- $s_i$: Maximum capacity of CDC $i$
- $c_{ai}$: Fixed cost of opening CDC $i$
- $ct_{ij}$: Unit transportation cost from CDC $i$ to LDC $j$
- $q_j$: Fixed cost of opening LDC $j$
- $B_1$: Assigned budget to first phase of supply chain
- $B_2$: Assigned budget to second phase of supply chain
- $tc_{jk}$: Unit transportation cost from LDC $j$ to shelter $k$
- $TRPN_{jk}$: Blocking risk level of the best path between DC $j$ and shelter $k$ ($0 \leq TRPN \leq 1$)
- $D_k$: Demand of shelter $k$
- $DC_j$: Maximum capacity of LDC $j$
- $l_j$: Material handling cost per unit of commodity at LDC $j$

**Decision variables**
- $z_{pi}$: 1 if a central distribution center opened at location $i$; 0 otherwise
- $z_j$: 1 if a local distribution center opened at location $j$; 0 otherwise
- $x_{ij}$: The amount of commodities shipped from CDC $i$ to LDC $j$
- $y_{jk}$: The amount of commodities distributed from LDC $j$ to shelter $k$

**Model**

Max $\sum_{j=1}^{N_j} \sum_{k=1}^{N_k} y_{jk} (1 - TRPN_{jk})$

S.t.\[\sum_{i=1}^{N_i} x_{ij} = \sum_{k=1}^{N_k} y_{jk} \quad \forall j\] (1)
\[\sum_{j=1}^{N_j} x_{ij} \leq z_{pi}s_{i} \quad \forall i\] (2)
\[\sum_{k=1}^{N_k} y_{jk} \leq z_{j}DC_{j} \quad \forall j\] (3)
The objective function is to maximize the met demands with respect to the risk level of road blocking. Equation (1) ensures the flow balance at CDCs. Equations (2) and (3) indicate capacity constraints in CDCs and LDCs respectively. Two separate budgets B1, B2 are assigned to the first and second stage of the supply chain respectively. The budget B1 includes the fixed cost of opening facility, and transportation cost between CDCs and LDCs. The budget B2 includes material handling cost and transportation cost between opened local distribution centers and shelters. Equations (4) and (5) represent the limitations related to the mentioned budgets. Constraint (6) ensures not to deliver more than required amount of relief supplies in shelters. Constraint (7) is related to the non-negativity and binary restrictions on the decision variables.

3.2. FMEA Approach

TRPN parameter in the presented model determines the possibility of a link being useless due to blocking of the route. There are some special routes to pass from one certain potential LDC to one certain shelter. Each one of these routes (to be called 'main routes' from now on) contains some smaller routes (to be called 'subsidiary route' from now on) such as streets, bridges, intersections etc. Each of these subsidiary routes may be blocked leading to difficulties in transporting the commodities. Blocking of the roads after the disaster can be due to several factors. For example, bridge collapse, landslide, flood, heavy traffics as a result of people's sudden influx to some streets and highways can be regarded as some of these factors. Here, the purpose is to choose the best CDCs and LDCs among potential CDCs and potential LDCs and also to find the best main route from among each pair of shelter-LDC. The main route is referred to the one whose composing subsidiary routes involve the least risk level of roads' blocking. The best route chosen between each pair of shelter-LDC is finally considered as the link connecting that pair whose blocking risk is considered as a TRPN parameter. To achieve this goal, first we should calculate the risk level of each subsidiary route applying FMEA technique. For this purpose, one worksheet is prepared. The worksheet contains sections such as: detection, severity, probability of occurrence, potential causes, potential failure mode. For further information regarding these terms see Long Ford (1995). Definitions of these sections differ for different disasters and area and require an expert’s opinion. Table (1) to (4) show a few samples of these worksheets which is quite suitable for planning how to face earthquake in Tehran. The author of this article has changed this table into form of a worksheet; however, the content is taken from experts’ ideas and TDMMO website.
Table 1 Calculation of parameters S-O-D (Infusion of bridges)

<table>
<thead>
<tr>
<th>Potential cause</th>
<th>Potential effects</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse of surrounding buildings</td>
<td>Interruption or impairment of motion</td>
<td>Calculated according to $s=2*(h/b)$ factor, where $h$ is equal to the average height of structures, in the surrounding rout and $b$ is equal to the average width of the rout. $S$ is calculated in scale of a number (0-10).</td>
<td>Factor of $O$ is a number in (0-10) scale. So that the urban fabric is divided to 3 types, rusty (over 30 years old), old (age of 10 to 30 years), new (Less than 10 years old), Likelihood of falling structures surrounding rout, is directly related to the age of structure and distance to active fault, Which is proportional to a number between 0 and 1, so that in this way, is allocated $O=10$ to structures with over 30 years old and close to fault, and proportionally structures with lower longevity get less amount of $O$.</td>
<td>$D$ parameter is selected according to transportation equipment used for opening the way. Whenever equipment is weaker, $D$ will be closer to 10.</td>
</tr>
</tbody>
</table>

Table 2 Calculation of parameters S-O-D (Blocked due to traffic jams)

<table>
<thead>
<tr>
<th>Potential cause</th>
<th>Potential effects</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocked due to traffic jam exit in the rout in chaos</td>
<td>Interruption or impairment of motion</td>
<td>Determined with respect to the average traffic through the considered rout</td>
<td>Factor of $O$ is determined with respect to being local or non local route, the average height of structures around the rout, the type of rout exit and being close to the fault. $O$ is selected between (0-10)</td>
<td>$D$ parameter is selected according to transportation equipment used for opening the way. Whenever equipment is weaker, $D$ will be closer to 10.</td>
</tr>
</tbody>
</table>

Table 3 Calculation of parameters S-O-D (Rout failure by fault)

<table>
<thead>
<tr>
<th>Potential cause</th>
<th>Potential effects</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route failure by fault</td>
<td>Interruption or impairment of motion</td>
<td>Determined according to the type of infrastructure, the foundation and the type of soil</td>
<td>Factor of $O$ is determined according to the confluence of the considered rout with active faults. $O$ is selected in between (0-10)</td>
<td>$D$ parameter is selected according to transportation equipment used for opening the way. Whenever equipment is weaker, $D$ will be closer to 10.</td>
</tr>
</tbody>
</table>
Applying these worksheets helps us find the possibility of a route being blocked. Having prepared these worksheets, we calculate the risk level for each subsidiary route. This level is obtained from multiplying three factors of severity, detection, and occurrence. The obtained figure for the risk level regarding the presented information in Tables 1 to 4 is from 0 to 1000. In this article, the risk level is shown by RPN which equals:
\[ \text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection} \]

### 3.3. The Risk Level of the Main Route

Having calculated RPN for each subsidiary route, we consider the map of routes as a graph in a way that the arcs of the graph show the subsidiary route while its nodes represent places such as intersections, squares, etc. connecting the main routes together. Figure (1) shows a simple form of this kind of graph.

![Figure 1. Illustration of extracting a graph from a map](image)

To find the best main route between each pair of shelter-LDC we should obtain the algorithm of Dijkstra on the present graph. This algorithm was introduced by Dijkstra in 1956 whose main goal is to find the shortest route between one single node and the other nodes.

**Dijkstra algorithm**

Input: a digraph \( G \), weights \( c \) and a vertex \( m \in V(G) \).

Output: the shortest path from \( m \) to all \( v \in V(G) \). In other words, \( l(v) \) and \( r(v) \) are displayed as outputs. \( l(v) \) is the length of the shortest \( m-v \)-path, which consists of a shortest \( m-r(v) \)-path together with the edge \((r(v),v)\). If \( v \) is not reachable from \( m \), then \( l(v) = \infty \) and \( r(v) \) is undefined.

1. Set \( l(m) = 0 \). Set \( l(v) = 1 \) for all \( v \in V(G) \setminus \{m\} \).
2. Set \( R = \emptyset \).
3. Find a vertex \( v \in V(G) \setminus R \) such that \( l(v) = \min \{l(w) | w \in V(G) \setminus R\} \).
4. For all \( w \in V(G) \setminus R \) such that \((v,w) \in E(G)\) do:
   - If \( l(w) > l(v) + c((v,w)) \) then
     - set \( l(w) = l(v) + c((v,w)) \) and \( r(w) = v \).
5. If \( R \neq V(G) \) then go to 2.

In this paper, digraph \( G \) is the graph obtained with respect to the map of the considered area. Weight \( C \) is related to the RPN. \( E(G) \), \( V(G) \) is related to the set of arcs and vertices respectively. Also, in this algorithm \( m \) can be any vertices but in our problem \( m \) is a vertex chosen from LDCs’ nodes.
Having performed this algorithm for each LDC node, we are able to find the best route connecting each pair of shelter-LDC. The risk level of this main road equals the total possibility of blocking of each of its single composing subsidiary routes. We consider the risk level of this main route as TPRN parameter for the presented mathematical model. Therefore, we will be able to include the risk level of route blocking of one area calculated by FMEA technique in the mathematical model. As mentioned earlier, the objective function of this model is only to represent the way of applying FMEA technique and several other costs involved in transportation of facilities can be added to it.

4. Solution methodology

The presented model in this section is a mixed integer programming one. Generally, to apply the presented method in this article which is used to include the risk of routes’ blocking in the plans for transportation operations, is somehow similar to the model of this article which is likely to become more complex to solve after adding more authentic hypotheses. Therefore, a heuristic method for the given model using the Graph theory will be presented which can be used for similar models making small changes in it.

4.1. Graph theoretic view

In this section a graph theoretic approach is used to study the structure of mentioned problem.

Definition 1 A graph \( G = (V, E) \) is called \( r \)-partite \((r \geq 2)\) graph if \( V \) admits a partition into \( r \) classes such that every edge has its end in different classes, i.e., vertices in the same partition class must not be adjacent.

Definition 2 A complete tripartite graph is a tripartite graph in which any two vertices of each disjoint set of vertices are adjacent.

According to the definitions 1 and 2 we consider our problem as a complete tripartite graph in which potential CDCs, potential LDCs and shelters are associated with the three disjoint set of vertices (see figure 2). In this graph view we define two kinds of weights \( w_{ij} \) and \( w_{jk} \) as follows:

\[
\begin{align*}
(1) \quad w_{ij} &= \frac{c_{ai}}{s_i} + c_{tij} + \frac{q_j}{DC_j} \\
(2) \quad w_{jk} &= l_j + t_{ckj}
\end{align*}
\]

The notations are the same as those of the mathematical model section.

![Graph theoretic view](image)
4.2. Heuristic Algorithm

As mentioned before, we have studied the structure of above-mentioned problem in a tripartite view. Based on this structure, a heuristic algorithm is being proposed to escape from the complexity of mixed integer mathematical programming model. This algorithm is made up of three subsections. Subsections (algorithms) 1, 2 find a feasible solution for the first and second set of vertices respectively. That is, algorithm 1 finds a feasible solution as I*J matrix to find how much of supplies will be shipped from CDC i to LDC j and which potential CDCs and LDCs must be chosen. Algorithm 2 finds a feasible solution as a J*K matrix to show how much of the supplies will be distributed from LDCs to the shelters (demand nodes). Algorithm 3 uses these two algorithms and changes the feasible solutions to direct them toward optimal solution as much as possible.

Algorithm 1

**Inputs:**
- $\alpha$: set of suppliers opened
- $\beta$: set of DCs opened
- I: set of potential suppliers
- J: set of potential DCs
- $w_{ij}$: weight of arc (i, j)
- Plus other parameters mentioned in programming model.

**Outputs:**
- $m_{ij}$: amount of shipment from supplier i to DC j
- $z_p_i$: binary variable shows that NGO has contracted supplier i
- $z_j$: binary variable shows opened DCj

**Step 0**
- $m_{ij} = 0$, $\alpha = \emptyset$ and $\beta = \emptyset$  $\forall j \in J, \forall i \in I$

While $B1 > 0$, $\sum_{i=1}^{J} s_i > 0$

**Step 1**
- Select a node from the distribution center nodes which have nonzero capacities.
- $j=select$ random $\{j|DC_j \neq 0\}$  $\forall j \in J$
- If $j \notin \beta$
  - then $B1= B1- q_j$, $\beta = \beta + \{j\}$

**Step 2**
- $i^* = \arg \min \{weight \ w_{ij} | S_i \neq 0\}$
- If $i^* \notin \alpha$
  - then $B1= B1- Ca_i$, $\alpha = \alpha + \{i^*\}$

**Step 3**
- $m_{i^*j} = \min (S_{i^*}, \ DC_j)$

**Step 4**
- $DC_j = DC_j - m_{i^*j}$, $S_{i^*} = S_{i^*} - m_{i^*j}$

**Step 5**
- $B1 = B1 - m_{i^*j} * c_{tij}$

End while

**Step 6**
- For 1 to $J$
  - If $\sum_i m_{ij} > 0$, then $z_j = 1$
- For 1 to $I$
  - If $\sum_j m_{ij} > 0$, then $z_p_i = 1$

End

Algorithm 2

**Inputs:**
- K: set of demand nodes
- J: set of potential DCs
\( w_{jk} \): weight of arc \((j, k)\)
\( d_j \): a matrix which shows the amount of shipped supplies to each distribution centers.

**Outputs:**
\( m_{jk} \): amount of shipment from DC \( j \) to shelter \( k \)

**Step 0**
\[ m_{jk} = 0 \quad \forall j \in J, \forall k \in K \]

**While** \( B2 > 0, \sum_{j=1}^{J} d_j > 0 \)

**Step 1**
select a node from the demand nodes which have nonzero capacities.
\( k = \text{select random} \ {k} \ | \ d_k \neq 0 \)

**Step 2**
\[ j^* = \arg \min \{ \text{weight} \ w_{jk} \ | \ d_j \neq 0 \} \]

**Step 3**
\[ m_{j^*k} = \min (d_{j^*}, D_k) \]

**Step 4**
\[ d_{j^*} = d_{j^*} - m_{j^*k} \]
\[ D_k = D_k - m_{j^*k} \]

**Step 5**
\[ B2 = B2 - m_{j^*k} \ast (t_{cjk} + l_j) \]

**End**

Algorithm 3

**Step 1**
form an initial solution \( X \) using algorithm 1, then algorithm 2.
\( X^* = X_{\text{initial}}, Z(X^*) = Z(X_{\text{initial}}) \)

**Step 2**
For \( i = 1 \) to iteration 1
form a solution \( X_m \) using algorithm 1, then algorithm 2.

For \( j = 1 \) to iteration 2
Use algorithm 2 on \( X_m \), find a new solution \( X_{\text{new}} \)
If \( Z(X_{\text{new}}) > Z(X_m) \), then \( X_{\text{new}} = X_m \), \( Z(X_m) = Z(X_{\text{new}}) \)
End
If \( Z(X_m) > Z(X^*) \), then \( X^* = X_m \)
End

**Step 3**
Return the final solution \( X^* \).

**End**

The function \( Z \) is similar to the objective function and is computed as follows:
\[
Z = \sum_{j=1}^{N_j} \sum_{k=1}^{N_k} m_{jk} TRP_{jk}
\]

5. Classic genetic algorithm for solving the proposed problem

Although Genetic Algorithm (GA) is a classical metaheuristic algorithm, it has been used a lot in the literature related to the relief facilities location-allocation problems. (Zamarripa et al. (2012)). Therefore, GA can be a suitable measure to compare the proposed heuristic algorithm. To apply the classic GA, the following steps must be implemented:

5.1. Solution coding (chromosome structure)

In order to make a chromosome structure for the problem, according to the figure 4, we consider two matrices \( X, Y \) in which \( X_{ij} \) indicates the shipped amount from CDC \( i \) to LDC \( j \), and \( Y_{jk} \) indicates the distributed amount from distribution center \( j \) to shelter \( k \). To produce an initial solution, first, matrix \( X \) is produced randomly, and then matrix \( Y \) is produced corresponding to the matrix \( X \). To constitute more feasible solution, matrix \( \hat{X}, \hat{Y} \) are
produced earlier in which \( 0 \leq \hat{X}_{ij} \leq 1 \) and \( 0 \leq \hat{Y}_{jk} \leq 1 \). Then, the members of matrices \( X, Y \) are produced as follows:

\[
X_{ij} = s_i \times \frac{\hat{X}_{ij}}{\sum_j \hat{X}_{ij}} \quad (8)
\]

\[
y_{jk} = s_j \times \frac{\hat{Y}_{jk}}{\sum_i \hat{Y}_{jk}} \quad (9)
\]

This producing method of solutions causes them to satisfy the constraints (1), (2) of the programming model. About constraints (3), (4), (5), (6) a penalty is considered for their violation.

\[
X = \begin{bmatrix}
14 & \cdots & 67 \\
\vdots & \ddots & \vdots \\
35 & \cdots & 29
\end{bmatrix}
\]

\( X \) = Supplier

\[
Y = \begin{bmatrix}
44 & \cdots & 23 \\
\vdots & \ddots & \vdots \\
51 & \cdots & 26
\end{bmatrix}
\]

\( Y \) = DC

\( Y \) = Shelter

\( Y \) = DC

**Figure 5** a schematic illustration of chromosome structures

**5.2. Initial population**

The first step to start the algorithm is producing the initial population. The number of produced solutions (\( N_i \)) depends on the problem size and in this paper after analyzing the variety of sizes, we have concluded the suitable values. These values is introduced in advance.

**5.3. Fitness value**

In order to assess the quality measurement of a solution or chromosome, fitness value is used as a criterion. In this paper the fitness value is the same as the objective function presented in programming model.

**5.4. GA Operators**

The three well-known genetic algorithm operators are Inversion operator, Crossover operator and Mutation operator. In this paper Crossover and Inversion operators are considered to be used. Consequently, as the first step, we use Rolette wheel selection (Talbi, 2009) to select the parents to do the operations. We have assumed that the Crossover operator will be assigned to 80% of initial population and to the rest of this population Inversion operator will be applied.

**5.4.1. Crossover operation:**

One of the best methods to implement crossover operation is the Arithmetic crossover (Talbi, 2009). In this method two offsprings are produced by parent’s linear combinations. These linear combinations are:

\[
p_1 = \alpha x_1 + (1 - \alpha)x_2 \quad (10)
\]

\[
p_2 = \alpha x_2 + (1 - \alpha)x_1 \quad (11)
\]

If \( 0 \leq \alpha \leq 1 \), the value of \( p_1, p_2 \) are between their parents’s value. Because of this factor \( \alpha \)=uniform distribution (-\( \gamma \), 1+\( \gamma \)) has been assumed where \( \gamma \) can have any value and we have considered \( \gamma =10 \). The
operator is applied on all members of matrices $\tilde{X}$, $\tilde{Y}$ and then, after checking the members to be between 0 and 1, the equations 8, 9 are used to produce new offsprings. As mentioned above, this operation is applied to 80% of the population.

5.4.2. Inversion operator:
This operator is used to search more space in Genetic algorithm. In this operation, two rows of matrix $\tilde{X}$ are chosen randomly. And the members of these rows are replaced with each other; this method can be applied to matrix $\tilde{Y}$ as well. Then by using the equations 8, 9 new offspring will be produced.

5.4.3. Stopping criteria:
The new population produced by Crossover and Inversion operators, has more individuals than the considered number in the population number. Thus, the next step is to choose the best $N_f$ individuals and consider them as new generation. In this paper, the number of generations $N_g$ is considered as a stopping criterion. This number varies depending on the problem size which will be discussed more in experimental result section.

6. Experimental results
To evaluate the proposed heuristic algorithm performance, 23 random instances have been solved. These problems are generated randomly using uniform distributions according to Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>~uniform [3500  20000]</td>
</tr>
<tr>
<td>$DC_{mean}$</td>
<td>$\bar{\Sigma}^l_{i=1} s_i$</td>
</tr>
<tr>
<td>$DC$</td>
<td>~uniform [DC_{mean} DC_{mean} * 1.25]</td>
</tr>
<tr>
<td>$D_{mean}$</td>
<td>$\bar{\Sigma}^l_{i=1} DC_{i}$</td>
</tr>
<tr>
<td>$D$</td>
<td>~uniform [$D_{mean}$ $D_{mean} * 1.25$]</td>
</tr>
<tr>
<td>$Ca$</td>
<td>~uniform [10  50]</td>
</tr>
<tr>
<td>$Ct$</td>
<td>~uniform [50  500]</td>
</tr>
<tr>
<td>$q$</td>
<td>~uniform [10  50]</td>
</tr>
<tr>
<td>$tc$</td>
<td>~uniform [200  600]</td>
</tr>
<tr>
<td>$l$</td>
<td>~uniform [10  50]</td>
</tr>
<tr>
<td>$B1$</td>
<td>~uniform [1000,000  1200,000]</td>
</tr>
<tr>
<td>$B2$</td>
<td>~uniform [1000,000  1500,000]</td>
</tr>
</tbody>
</table>

Since LINGO 8.0 software is a valid optimization software and solves the problems by Branch and Bound (B&B) algorithm, we compare the results of heuristic algorithm to the solutions obtained by LINGO 8.0 for small/medium-sized problems. Also, as mentioned before, one of the most well-known algorithms used to solve supply chain problems, is Genetic Algorithm (GA). Thus, we compare the proposed heuristic algorithm results to the ones obtained by GA as well. Table 6 shows the comparison between heuristic algorithm and B&B for small/medium-sized problems. Table 7 contains the solutions obtained by GA and these results are compared to B&B and Table 8 shows the results of the heuristic algorithm and GA for large-sized problems. It should be noted that all the examples are coded in MATLAB 7.0 on an Intel_Celeron_Mobile 2.5 GHz (Core 2 Duo) personal computer with 3 GB RAM.
Table 5: Comparison between B&B and heuristic algorithm runs for small and medium-sized problems

<table>
<thead>
<tr>
<th>No.</th>
<th>Problem size</th>
<th>(I\times J\times K)</th>
<th>(z^{\text{mean}})</th>
<th>(z^{\text{best}})</th>
<th>(N_i)</th>
<th>(N_g)</th>
<th>Objective value</th>
<th>time(s)</th>
<th>(\text{Gap}^{\text{mean}})</th>
<th>(\text{Gap}^{\text{best}})</th>
<th>(\text{Gap}^{\text{best}} - \text{Gap}^{\text{mean}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2<em>10</em>5</td>
<td>19998</td>
<td>19998</td>
<td>200</td>
<td>150</td>
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<td></td>
<td></td>
<td>3.1</td>
<td></td>
<td></td>
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<td>6<em>10</em>8</td>
<td>44377</td>
<td>44607</td>
<td>200</td>
<td>150</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>8<em>12</em>8</td>
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<td>44999</td>
<td>200</td>
<td>150</td>
<td>17</td>
<td></td>
<td></td>
<td>19998</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8<em>15</em>10</td>
<td>72244</td>
<td>72876</td>
<td>200</td>
<td>150</td>
<td>42</td>
<td></td>
<td></td>
<td>45987</td>
<td>58</td>
<td></td>
</tr>
<tr>
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<td>9998</td>
<td>19998</td>
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<td>150</td>
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<td>94771</td>
<td>94818</td>
<td>320</td>
<td>200</td>
<td>195</td>
<td></td>
<td></td>
<td>94936</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10<em>17</em>20</td>
<td>119223</td>
<td>119934</td>
<td>320</td>
<td>200</td>
<td>218</td>
<td></td>
<td></td>
<td>94818</td>
<td>&gt;</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>15<em>20</em>20</td>
<td>114144</td>
<td>114640</td>
<td>320</td>
<td>200</td>
<td>298</td>
<td></td>
<td></td>
<td>115216</td>
<td>&gt;</td>
<td>-60</td>
</tr>
<tr>
<td>9</td>
<td>18<em>22</em>25</td>
<td>126268</td>
<td>126750</td>
<td>320</td>
<td>200</td>
<td>316</td>
<td></td>
<td></td>
<td>130415</td>
<td>&gt;</td>
<td>3.18</td>
</tr>
<tr>
<td>10</td>
<td>20<em>25</em>30</td>
<td>128890</td>
<td>129236</td>
<td>320</td>
<td>200</td>
<td>390</td>
<td></td>
<td></td>
<td>133000</td>
<td>&gt;</td>
<td>1.55</td>
</tr>
<tr>
<td>11</td>
<td>25<em>32</em>35</td>
<td>129666</td>
<td>131976</td>
<td>320</td>
<td>200</td>
<td>417</td>
<td></td>
<td></td>
<td>135918</td>
<td>&gt;</td>
<td>.05</td>
</tr>
<tr>
<td>12</td>
<td>28<em>35</em>40</td>
<td>142863</td>
<td>144604</td>
<td>320</td>
<td>200</td>
<td>458</td>
<td></td>
<td></td>
<td>145112</td>
<td>&gt;</td>
<td>-1.20</td>
</tr>
<tr>
<td>13</td>
<td>30<em>40</em>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>509</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\text{Ave.}=232.777\)

\(\text{Ave.}=2.004\)  \(\text{Ave.}=1.494\)  \(\text{Ave.}=0.475\)
In Tables 6, 7, regarding literature, the first six numbers are small-sized problems and the others are medium-sized problems. One of the most important parameters in the heuristic algorithm which affects the CPU time and quality of solutions is the number of iterations \( I_1, I_2 \). The same parameters in GA are the number of initial population (\( N_i \)) and the number of generations (\( N_g \)). With the aid of the test problems, the mentioned parameters have been tuned by testing different values and then comparing the results. As Tables 1, 2 show, we have concluded that the best number of iteration 1 for solving the small-sized problems and medium-sized problems is 120, 250 respectively. The number of iteration 2 has the same value as that of the iteration 1 in the small/medium-sized problems. These values in the case of large-sized problems are 550 for iteration 1 and 600 for iteration 2. Also, the best value for the number of initial population and generations in small-sized problems is 200 and 150 respectively. These values have been changed in medium-sized problems to 320 and 200 and in large-sized problems to 600 and 450. For each test problem the heuristic algorithm runs four times and the best \( z \) value (value of objective function (\( z_{\text{best}} \))) and the average of the corresponding \( z \) values (\( z_{\text{mean}} \)) are included in Tables 6, 7, 8. \( z_{\text{best}} \) and \( z_{\text{mean}} \) are used to calculate the gap percentage which is the percentage of error between optimal value obtained by LINGO software and the objective value of GA or heuristic. The considered maximum runtime for LINGO software is 5400 seconds and as it is obvious in Tables 6 and 7 the CPU time for both GA and heuristic algorithm is significantly lower than LINGO runtimes, especially in medium-sized problems. Consequently, applying the classic GA and the heuristic algorithm is acceptable in the case of medium/large-sized problems.

### Table 6-

<table>
<thead>
<tr>
<th>N. o.</th>
<th>Problem size ( I^*J^*K )</th>
<th>Heuristic algorithm</th>
<th>B&amp;B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( z_{\text{mean}} )</td>
<td>( z_{\text{best}} )</td>
<td>Objective value</td>
</tr>
<tr>
<td></td>
<td>iteration 1</td>
<td>iteration 2</td>
<td>time (s)</td>
</tr>
<tr>
<td>1</td>
<td>19802</td>
<td>19998</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>44594</td>
<td>44617</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>44971</td>
<td>45112</td>
<td>120</td>
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<td>4</td>
<td>72590</td>
<td>72861</td>
<td>120</td>
</tr>
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<td>5</td>
<td>96975</td>
<td>96985</td>
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<td>6</td>
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<td>100024</td>
<td>100160</td>
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<td>95270</td>
<td>2500</td>
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<td>9</td>
<td>120918</td>
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<td>250</td>
</tr>
<tr>
<td>11</td>
<td>124338</td>
<td>125459</td>
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</tr>
<tr>
<td>12</td>
<td>145112</td>
<td>147289</td>
<td>250</td>
</tr>
</tbody>
</table>

**Ave.=206.454**
6.1. Comparison of the classic GA and the heuristic algorithm

According to the Tables 6 and 7 the average of $\text{Gap}^{\text{mean}}$, $\text{Gap}^{\text{best}}$ and $|\text{Gap}^{\text{mean}} - \text{Gap}^{\text{best}}|$ have been improved in heuristic algorithm in comparison to the classical GA. Also, the average of CPU time has been improved when using the heuristic algorithm. In order to evaluate the performance of the heuristic algorithm in the case of large size ones, ten large-sized test problems produced with respect to Table 5, have been solved by both GA and the heuristic algorithm. In Table 8 it is shown that the average of optimal value (Ave. $z^{\text{best}}$) obtained by the heuristic algorithm is better than Ave. $z^{\text{best}}$ obtained by GA. Also, the CPU time has been improved in comparison with GA. To sum up, with respect to the mentioned measures the proposed heuristic algorithm dominates the classical GA in solving the proposed problem.

### Table 7 Comparison between heuristic algorithm and GA for large-sized problems

<table>
<thead>
<tr>
<th>No.</th>
<th>Problem size</th>
<th>Heuristic algorithm</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I<em>J</em>K</td>
<td>$z^{\text{mean}}, z^{\text{best}}$ iteration1 iteration2</td>
<td>$z^{\text{mean}}, z^{\text{best}}$ N$_i$ N$_g$ average time (s)</td>
</tr>
<tr>
<td>1</td>
<td>30<em>45</em>50</td>
<td>153220 156718 550 600</td>
<td>147410 0717 600 450</td>
</tr>
<tr>
<td>2</td>
<td>32<em>48</em>55</td>
<td>150812 152091 550 600</td>
<td>136000 8009 600 450</td>
</tr>
<tr>
<td>3</td>
<td>35<em>50</em>62</td>
<td>161012 165912 550 600</td>
<td>159710 162216 600 450</td>
</tr>
<tr>
<td>4</td>
<td>35<em>54</em>68</td>
<td>180451 182915 550 600</td>
<td>170915 173215 600 450</td>
</tr>
<tr>
<td>5</td>
<td>38<em>57</em>72</td>
<td>178413 183248 550 600</td>
<td>178216 176409 600 450</td>
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<td>6</td>
<td>40<em>60</em>75</td>
<td>178413 183248 550 600</td>
<td>174812 178591 600 450</td>
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<tr>
<td>7</td>
<td>43<em>65</em>78</td>
<td>193505 199126 550 600</td>
<td>189611 195225 600 450</td>
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<tr>
<td>8</td>
<td>45<em>70</em>85</td>
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<td>195673 204013 600 450</td>
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<tr>
<td>9</td>
<td>45<em>75</em>90</td>
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<td>202812 206850 600 450</td>
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<tr>
<td>10</td>
<td>50<em>75</em>10</td>
<td>212451 219299 550 600</td>
<td>205401 210053 600 450</td>
</tr>
</tbody>
</table>

Ave. = 186149.2 Ave. = 839.1 Ave. = 180529.8 Ave. = 912.3

7. Conclusions and future research directions

One of the main problems involved in humanitarian relief operations is the presence of several uncertainties while planning for these operations. One of these uncertainties can be named to be the blocked roads while giving services to the injured people. In this paper, for the first time indeed, we , applying the FMEA technique, calculated the risk of roads' getting blocked and then include it in our planning for relief supplies allocation. To do this, we prepared some worksheets special for FMEA technique and for several subsidiary routes such as streets, bridges etc., and then calculate the risk level of each subsidiary route using the obtained results from these worksheets. Then considering the map of that area as a Graph, we perform on it the Dijkstra algorithm used to find the shortest route connecting one node and other nodes of the graph. We find the best route (the one having the least risk of getting blocked) connecting each pair of shelter-LDC using this algorithm. We consider the possibility of these routes getting blocked as a parameter and then apply it in the given mathematical model. Since this model requires mathematical models similar to the one presented in this paper and because these models carry a complexity with themselves to be solved, one heuristic method based on the Graph Theory for
these sorts of models is presented. To prove the accuracy of the solutions, the presented model is solved for small problems using Lingo 8.0 software (a valid software), and is compared with the heuristic results. Finally, to prove the superiority of this heuristic for problems larger in size we compare it with Genetic Algorithm. The results show that both the GA and heuristic algorithm have good results in comparison to LINGO solutions, but the heuristic algorithm dominates the GA with respect to measures of average $\text{Gap}^{\text{mean}}$, average $\text{Gap}^{\text{best}}$, average $|\text{Gap}^{\text{mean}} - \text{Gap}^{\text{best}}|$ and CPU time.

For future research, one of the best topics would be to use the risk management framework for other stages of the humanitarian relief supply chain such as recycle and extermination stages. Also, many of the paths can be recovered temporarily after the incident. Therefore, considering a new model which would be able to trade off between recovering the planned path and using a longer path could be a suggestion for future research.

References

Talbi, E.G., Metaheuristic from design to implementation. 2009 ( John Wiley & Sons Publisher: United States of America).


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