A multi-objective three-level hierarchical hub location-queue problem with congestion and reliability under uncertainty: A case study

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Abstract. This study investigates a three-level hierarchical hub problem considering numerous features, such as congestion and reliability. This relates to ground and air hubs as high layers in this hierarchical network. A four-objective model is presented; it lowers the number of routes, network-related costs, and hub queue waiting times while raising the network's route reliability. Due to the impact of service time on customer satisfaction in this issue, a time frame that a penalty is assigned for the amount of delay is considered. Both the airport and the ground are hub facilities in this regard. $M/M/C/K$ queue systems are those found in the airport and ground hubs. Due to the multi-objective nature of the problem, the LP-metric and goal attainment (GA) approaches are used to resolve it and verify multiple samples with varying weight values provided by the decision-maker. The results from the above-mentioned methods are ranked using a simple additive weighting (SAW) method. A few parameters are treated as fuzzy numbers to make the model more realistic, and the Jimenez's model and chance-constrained programming are used to present the findings. Considering numerous weights for each objective function and solving two methods, Pareto solutions are obtained.

KEYWORDS: Hierarchical hub problem; Reliability; Queue system; LP-metric; Goal attainment; Chance-constrained fuzzy programming.

1. Introduction

Due to the importance of facility programming discussion, including the design and location of facilities to achieve the best deployment plan in real systems and high direct communication costs between all routes, two-way communication in the network is impossible. Hence, a hub collects, sorts, and distributes flow in the network to benefit from economies of scale. This results in real-world systems achieving the best and highest efficiency and productivity.

In hierarchical problems and systems, decisions are made about the location of interacting facilities in a multi-layered configuration with different service levels and the

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allocation of routes from nodes to central or non-central hubs, which are transferred from the demand node to the destination demand node [1]. Cargo delivery, communication network planning, and air transportation are the most common uses of hub placement challenges. It seeks to determine hub nodes' location from non-hub nodes and establish a suitable route between the source-destination pair through these points. A hub (at least one hub node) occurs. Due to this problem, this research's main focus is on delivering cargo so that almost all goods and shipments can be sent and reach their destinations according to the predetermined time. Due to the nature of different types of communication systems and structures and considering the existing networks, several facilities at different levels can be seen to optimize the current communications and, consequently, the costs incurred. This feature of networks should also be considered. On the other hand, hierarchical location problems mainly go back to recent decades, especially back to the 1980s, when several studies were conducted but did not specify the exact dimensions of hierarchy.

In this research, due to the large flows in the routes and inputs to each hub, it will create a waiting time and queues in hubs, which, to get nearer to reality, the queuing system for hubs should be considered. When the problem is limited to the importance of delivery time, which may be goods, people, or information, there is no problem and causes congestion in the network's least state. On the other hand, due to the possibility of failure in the routes or the failure of one of the service centers, the network's route's reliability should be at its highest and optimal state. For this reason, assumptions have been used in the objective function to minimize the network's cost, queue time, and reliability to reach its optimal state. Furthermore, considering that capacity is a significant issue in practice. It affects most businesses; these restrictions are considered in both ground hubs and airport hubs to make the issue more plausible.

The rest of this paper consists of the following sections: In Section 2, there is a summary of the literature on hierarchical hub location challenges, the techniques utilized, and their findings. In Section 3, problem modeling is presented according to the assumptions considered in this research, and the fuzzy model is equivalent to the crisp model. In Section 4, problem-solving methods are explained. Section 5 presents the results obtained by the solution methods in this research. Finally, in Section 6, conclusions are drawn, and some recommendations for further study in this area.

2. Literature review

The beginning of studies and research in the hub location can be considered a result of Weber's research in 1900. Many scientists and researchers focused on investigating hub location problems in various fields and research in various areas [2-7]. Marianov and Serra [8], in the same vein in another study, examined hub models in airlines by considering congestion. In this research, the $M/D/C$ queue model has been used. The innovative method of forbidden search has been used to solve the model.

A hub location-routing problem with a queuing system was resolved by Pourmohammadi et al. [9] using a fuzzy meta-heuristic method. This paper develops a unique multi-objective mathematical model that considers the unpredictability of flows, costs, timeframes, and various job possibilities. The reduction of total transportation costs was the idea behind this innovation. It employed the $M/M/C/K$ queuing mechanism. To address this issue, a powerful evolutionary meta-heuristic strategy built on fuzzy invasive weed optimization, variable neighborhood search, and game theory was developed.

A hybrid of facility and hypercube queuing models for emergency medical systems was created by Ghobadi et al. [10]. By merging the location and hypercube queuing models, two new mathematical models were presented in this study to combine location and dispatching policy decisions. The offered models' location model constraints were derived from the hypercube queuing model's flow-balance equations. In the initial model, each server's status was either idle or busy, much like in the original hypercube queuing architecture. The second model assumes that on-scene time is unrelated to trip time, and it states that each server was either idle, busy, traveling, or busy serving a client at the incident location. The models were first successfully tested on a few small-scale cases. An optimization framework based on the evolutionary algorithm was subsequently created due to the models' difficulty in handling larger scales. Geramianfar et al. [11] used the simulated annealing (SA) algorithm to examine a multi-objective hub and identify congestion problems. To resolve a novel priority $M/M/C$ queue model for a hub covering location issues, Sedehzadeh et al. [12] used a multi-objective parallel SA algorithm. Production planning was examined in industrial sectors that were portrayed as hub location-allocation issues with manufacturing system congestion by Ghodratnama et al. [13]. A novel bi-objective hierarchical hub placement problem was addressed by Khodemani-Yazdi et al. [14] using an $M/M/C$ queuing framework. The $M/M/C$ queuing system examined the two-objective hierarchical hub problem. The cost of building a hub facility and transportation costs were both kept to a minimum. Two different queuing systems were investigated for the two types of facilitation in the issue, $M/M/C$, and $M/M/1$. The fuzzy game based on variable neighborhood invasive weed optimization (GVIWO), a non-dominated sorting genetic algorithm (NSGA-II), and a hybrid SA algorithm were all used in this study. A bi-objective hub location-allocation model that takes congestion into account was planned by Ghodratnama et al. [15].

The hub location research from 2010 to the present is summarized in Figure 1. According to these data, the hierarchical hub problem received less attention in recent years than in other hub location areas.

{Please insert Figure 1 about here.}

The research on hierarchical hub location that researchers have conducted is listed in Table 1, along with the differences between the current study and earlier research. Some research projects have been completed, though, regarding uncertainty [16-28]. Numerous research studies have been conducted on solution techniques to date [29-46].

{Please insert Table 1 about here.}

3. Hub location allocation mathematical model

The network structure used in the present study is generally shown in Figure 2. There is only one link between ground hubs and airport hubs, although there are several connections between demand points and ground hubs [47].

{Please insert Figure 2 about here.}

3.1. Assumptions

The following are the basic assumptions of the proposed model:

- It is known how many airports and ground hubs there are. Transport modes are designed for more flexibility and adaptability to reality in the hub network, including small trucks and large trucks and aircraft. Discount factors have been used in various communications.
- Each of these ground and airport hubs has a capacity constraint.
- Due to the importance of delivery time for carriers and customers, it is set for each route. Each pair of flows between the source and destination nodes must be transmitted at a predetermined time. In the case of failure, a penalty is assigned for the delay.
- Direct communication between two demand nodes is not allowed, and they must use a hub in their route. Also, not every ground hub can be connected to another ground hub, but airport hubs can be connected.
- Due to the limitation on the number of units allocated to the hub, the queue could happen. Then, we propose a separate queuing system in each hub, including airport and in-ground hubs, as $M/M/C/K$ system.
- If the system has a queue and creates congestion, each hub's input flow is more than its service rate.
- Hubs benefit from economies of scale (between the airport and ground hubs and airport hubs).
- The present paper is organized depending on allocation (flow-based). Each node is connected to several hubs, and ground hubs are distributed to airport hubs in a single allocation (multiple allocations).

3.2. Indices

$i, j \in \{1, 2, \ldots, IT\}$	Index for network nodes
$k, m \in \{k_1, k_2, \ldots, k_{GT}\}$	Index for a potential location for ground hubs
$l, n \in \{l_1, l_2, \ldots, l_{AT}\}$	Index for a potential location for airport hubs
$v \in \{1, 2, \ldots, VT\}$	Index for counter identifier in queue formula
$u \in \{1, 2, \ldots, UT\}$	Index for a potential considered route

3.3. Parameters

GN	Number of ground hub facilities
AN	Number of airport hub facilities
α	Discount factor for large truck vehicles compared to small vehicle trucks
β	Confidence factor between the airport and ground hubs
χ	Confidence factor between the airport hubs
δ	Confidence factor between the ground hubs
ϕ	Discount factor between the airport and ground hubs
φ	Discount factor between the airport hubs
RG_k	Reliability, the ability to facilitate ground hubs to provide service without delays and congestion
RA_l	Reliability, the ability to facilitate the airport hub to provide service without delays and congestion
$RR_{i,j}$	Reliability in routes *i* and *j*
FG_k	Fixed establishment cost for ground hub *k*
FA_l	Fixed establishment cost for airport hub *l*
$W_{i,j}$	Amount of flow unit between nodes *i* and *j*
μG_k	Ground hub service rate *k*
ΓG_k	Possible ground hub *k*'s capacity
ΓA_l	The possible airport hub *l*'s capacity
μA_l	Service rate of airport hub *l*
NG_k	Numbers of servers at ground hub *k*
NA_l	Numbers of servers at airport hub *l*
QCG_k	Queue capacity related to the ground hub *k* in $M/M/C/QC_k$ model
QCA_l	Queue capacity related to the airport hub *l* in $M/M/C/QC_l$ model
$C_{i,j}$	Cost per unit of travel between nodes *i* and *j*

$D_{i,j}$	Nodes *i* and *j*'s distances
RT	The time range during which the origin and destination node pairs must be finished
$CP_{i,j}$	Cost of the penalty unit when the delivery time of the relevant flow to the route exceeds the predetermined limit .
$TNG_{i,k}$	Travel time by small truck vehicle from node *i* to ground hub *k* and vice versa
$TGA_{k,l}$	Travel time by large truck from ground hub *k* to airport hub *l* and vice versa.
$TAA_{l,n}$	Traveling time from airport hub *l* to airport hub *n* and vice versa via a big truck
RO_i	Ready time from origin *i*
LA_l	Loading time in airport hub *l*
M	Big number

3.4. Variables

g_k	1 if a ground hub is formed at node *k*; 0, otherwise.
a_l	1 if a hub for an airport is built at node *l*; 0, otherwise.
$ga_{k,l}$	1 if there is a direct route (connection) between ground hub *k* and airport hub *l*; 0, otherwise.
$aa_{\mathrm{l,n}}$	1 if a direct path (link) exists between airport hubs *l* and *n*; 0, otherwise.
$s_{i,m}$	1 if a path (link) connects nodes *i* and ground hub *k*; 0, otherwise.
$nga_{i,k,l}$	1 if a path exists between nodes *i* and ground hub k, then airport hub *l*; 0, otherwise.
$anaa_{i,l,n}$	Amount of flow that leaves the starting node and travels via airport hubs *l* and *n*
$anga_{i,k,l}$	Flow volume begins at node *i* and flows via ground hub *k* to airport hub *l*.
λg_k	Rate of entry flow (goods) to the ground hub *k*
λa_l	Rate of entry flow (goods) to the airport hub *l*
pg_{0k}	Probability of being zero customers (goods) in-ground hub *k*
pg_{QC_k}	Probability of being QC_k customers (goods) in-ground hub *k*
lqg_k	Length of the queue formed in ground hub *k*
lqa_l	Length of the queue formed in airport hub *l*
wqg_k	Waiting time elapsed in-ground hub *k*
wqa_l	Waiting time elapsed in airport hub *l*
pg_{0l}	Probability of being zero customers (goods) in airport hub *l*

pg_{QC_l}	Probability of being QC_l customers (goods) in airport hub l
$dt_{i,j,u}$	Delivery time via u path (link) from origin i to destination j

3.5. Objective functions

Our suggested mathematical model considers four objective functions, as indicated below:

4.5.1. The first objective function

$$\min \sum_{l=1}^{l_{AT}} \sum_{n=1, n \neq l}^{l_{AT}} a_l . a_n \qquad (1)$$

Reduced route numbers between airport hubs are the first objective function.

3.5.2. The second objective function

$$\begin{aligned} &\min \sum_{k=1}^{k_{GT}} FG_k . g_k + \sum_{l=1}^{l_{AT}} FA_l . a_l \\ &+ \sum_{i=1}^{IT} \sum_{j=1, j \neq i}^{IT} (W_{i,j} + W_{j,i}) . \sum_{k=1}^{k_{GT}} C_{i,k} . D_{i,k} . \sum_{l=1}^{l_{AT}} nga_{i,k,l} + \sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \phi . C_{k,l} . D_{k,l} . anga_{i,k,l} \\ &+ \sum_{i=1}^{IT} \sum_{l=1}^{l_{AT}} \sum_{n=1, n \neq l}^{l_{AT}} \varphi . C_{l,n} . D_{l,n} . anaa_{l,n}^{i} + \sum_{i=1}^{IT} \sum_{j=1}^{IT} CP_{i,j} . \sum_{u=1}^{UT} \max \left\{ dt_{i,j,u} - RT, 0 \right\} \end{aligned} \qquad (2)$$

The second objective function is to reduce costs throughout the whole network. This job's first and second elements reduce the cost of constructing ground and airport hubs. The third expression involves minimizing transmission costs in the routes between nodes across the network, where the costs will be equal to time and distance. The fourth expression in this objective function means that the penalty unit is considered according to the delay in delivery of the consignment so that if it arrives at the destination earlier than the predetermined time, no penalty is considered. If there is a delay, the penalty amount will be considered according to the time difference with the predetermined amount.

3.5.3. The third objective function

The degree of success in establishing communication to deliver the cargo without congestion, or the amount lost between the source and destination node pairs, is considered reliability in the communication network. In fact, we are looking for this goal in this research so that the existing facilities can transfer the flow without failure. Reliability arises between two nodes when those two nodes are connected [48]. The reliability obtained in this study is according to the research carried out by Kim and O'Kelly [49] and is as follows. The route includes n communication so that:

In addition to this study, route reliability $(RR_{k,m}^{i,j})$ is described as the efficient transportation of flow through the hubs k and m from the origin i to the destination j $(i \rightarrow k \rightarrow m \rightarrow j)$. We multiply the reliabilities $RR_{i,k}$ $RR_{k,m}$ $RR_{m,j}$ into each other to get the route's reliability.

The discount factor is also introduced due to a hub's ability to transmit traffic without traffic and delay, like factor α $(0 \leq \alpha \leq 1)$, which is calculated as $(RR_{k,m})^{1-\alpha}$. Also, in a route with one hub $(i \rightarrow k \rightarrow j)$, reliability is calculated as $RR_{i,k}.(RR_{k,k})^{1-\alpha}.RR_{k,j}$.

The general method of calculating reliability in the hub model of this research is calculated according to the following conditions shown in Figure 3

{Please insert Figure 3 about here.}

The third objective function is specified by:

$$
\begin{aligned}
&\max \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} (RR_{l,n})^{1-\chi} \sum_{i=1}^{IT} anaa_{l,n}^{i}.a_l.a_n \\
&+\sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} W_{k,n}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.a_n \\
&+\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{m=1,m\neq k}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} (RR_{i,k}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.(R_{n,m})^{1-\chi}.(W_{i,m}.s_{i,m}.\sum_{j=1,j\neq i,j\neq k,j\neq l}^{IT} W_{ij}.nga_{i,k,l}) \\
&+\sum_{i=1}^{IT} \sum_{j=1,j\neq i}^{IT} \sum_{k=1}^{k_{GT}} \sum_{m=1,m\neq k}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} W_{i,j}(R_{i,k}.(R_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.(RR_{n,m})^{1-\beta}.RR_{m,j}).nga_{i,k,l}.nga_{j,n,m} \qquad (4) \\
&+\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{j=1,j\neq i,j\neq k,j\neq l}^{IT} (W_{i,j}+W_{j,i}).RR_{i,k}.(RG_k)^{1-\delta}.s_{i,k} + \\
&\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} RR_{i,k}.(RR_{k,l})^{1-\beta}.(RA_l)^{1-\chi}.anga_{k,l}^{i}.nga_{i,k,l} + \\
&\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} RR_{i,k}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.anaa_{l,n}^{i}.a_n
\end{aligned}
$$

The third objective seeks to maximize the route's reliability according to the network trends. Thus, each has its equations according to the network routes, based on considering all possible routes.

3.5.4. Fourth objective function

Before discussing the fourth objective function, let's look at the $M/M/C/K$ queuing system and the associated equations.

3.5.4.1. Queue systems

A queuing system consists of several service providers, each serving at its service rate and having an input rate to the system that is not necessarily human and will not be physical. The service in such systems is such that if the service provider and the customer are unemployed, the recipient of the service will be dealt with immediately, otherwise, if the service provider is not unemployed, the customer must wait in line, and this will cause queuing and congestion in the system. Therefore, the main condition for such systems' stability is that the input rate is always higher than the service rate. In the present study, due to the instability of the input rate to each hub, the following are the queue model's parameters:

λ_n	When there are n customers in the system, the customer entrance rate
μ_n	Customer service rate is when n customers are present in the system.
p_0	Probability of having no clients at all.
p_n	Probability that there will be n clients in the system.
L_q	Line's average length (number of customers in the queue).
W_q	Average length of time customers wait in line.

- Model of the $M/M/C/K$ queue

This model's queuing system consists of C servers, each of which has service rates similar to one another regardless of the system's condition (i.e., the number of users). System circumstances have no impact on the pace of consumer logins. This system has two alternatives depending on the limited number of customers. The customer exit rate equals n if there are fewer servers than consumers (n) in the system. On the other hand, the customer departure rate will be c if there are more customers than servers because of the duration between the two outputs, which follows an exponential distribution.

The average rate of input into the system should be smaller than the system's average potential service rate for no congestion or queue for a steady state to exist. These queues in the $M/M/C/K$ versions contain parallel channels and notches. In this paradigm, the maximum queue size or the number of users is equal to K, and the following results are as follows:

$$\lambda_n = \begin{cases} \lambda & 0 \le n < K \\ 0 & K \le n \end{cases} \tag{5}$$

$$\mu_n = \begin{cases} n\mu & 0 \le n < C \\ 0 & C \le n \le K \end{cases} \tag{6}$$

$$P_n = \prod_{i=1}^{n} \frac{\lambda_{i-1}}{\mu_i} P_0 = \begin{cases} \dfrac{\lambda^n}{n\mu.(n-1)\mu.....1\mu} P_0 & 0 \le n \le C \\ \dfrac{\lambda^n}{\underbrace{C\mu.C\mu.....C\mu}_{(n-c)\ \ Statements}.\underbrace{(C-1)\mu.(C-2)\mu.....1\mu}_{c\ \ Statements}} P_0 & C \le n \le K \end{cases} \tag{7}$$

$$P_n = \begin{cases} \dfrac{\lambda^n}{\mu^n.n!}.P_0 & 0 \le n \le C \\ \dfrac{\lambda^n}{C^{n-C}.\mu^n.C!} P_0 & C \le n \le K \end{cases} \tag{8}$$

$$\sum_{n=0}^{K} P_n = 1 \Rightarrow \sum_{n=0}^{C-1} \frac{1}{n!}.(\lambda/\mu)^n.P_0 + \sum_{n=C}^{K} \frac{1}{C^{n-C}.C!}.(\lambda/\mu)^n.P_0 = 1 \tag{9}$$

$$P_0 = \begin{cases} \left[\sum_{n=0}^{C-1} \dfrac{r^n}{n!} + \dfrac{r^n}{C!}.\dfrac{1-\rho^{K-C+1}}{1-\rho}\right]^{-1} & \text{if } \rho = \dfrac{\lambda}{\mu} \ne 1 \\ \left[\sum_{n=0}^{C-1} \dfrac{r^n}{n!} + \dfrac{r^n}{C!}(K-C+1)\right]^{-1} & \text{if } \rho = \dfrac{\lambda}{\mu} = 1 \end{cases} \tag{10}$$

$$L_q = \sum_{n=C}^{K} (n-C).P_n = \frac{P_0.(C.\rho)^C.\rho}{C!.(1-\rho)^2}.\left[1-\rho^{K-C+1}-(1-\rho).(K-C+1).\rho^{K-C}\right] \tag{11}$$

$$W_q = \frac{L_q}{\lambda.(1-P_k)} \tag{12}$$

The *M/M/C/K* model is changed into the *M/M/C* model when *K* gets sufficiently large. Shortle et al. [50] is an appropriate reference for more examination. The meaning of the queue in our mathematical model is the congestion of the flow and, for example, goods, which are created behind the ground and air hubs. In the ground hubs, only trucks, vans, and ground vehicles enter the ground hubs and unload the goods, and congestion is created. There are several servers in the ground hubs; after the trucks are loaded at the servers, they are sent to other ground hubs, air hubs, or end customers. In the air hubs, planes, trucks, vans, and ground vehicles enter the air hubs, the goods are unloaded, and congestion is created. In the service providers, goods are loaded in trucks, other land vehicles, and airplanes and sent to other land and air hubs.

The amount of incoming flow to the hubs is variable and depends on which nodes the Model solver hubs (i.e., ground or air) and single and multiple allocations. The number of servers, the capacity of each hub, both ground and air, and the service rate of the servers are predetermined, and mathematical equations and relationships (related to the Markov process) associated with the queue length and the subsequent waiting time are calculated. Figures 4 and 5 show the queue formation or congestion process, unloading and reloading at servers, both ground and air hubs.

As a consequence, the total average elapsed time is minimized by the fourth objective function

$$\min \sum_{k=1}^{k_{GT}} wqg^{k} + \sum_{l=1}^{l_{AT}} wqa_{l} \tag{13}$$

The first expression involves minimizing the total time spent on ground hubs. The second phase minimizes the average time spent on airport hubs and the type of system.

{Please insert Figure 4 about here.}
{Please insert Figure 5 about here.}

3.6. Proposed multi-objective hub location problem

$$\min \sum_{l=1}^{l_{AT}} \sum_{n=1, n\neq l}^{l_{AT}} a_l . a_n$$

$$\min \sum_{k=1}^{k_{GT}} FG_{k} . g_k + \sum_{l=1}^{l_{AT}} FA_l . a_l$$

$$+ \sum_{i=1}^{IT} \sum_{j=1, j\neq i}^{IT} (W_{i,j} + W_{j,i}) . \sum_{k=1}^{k_{GT}} C_{i,k} . D_{i,k} . \sum_{l=1}^{l_{AT}} nga_{i,k,l} + \sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \phi . C_{k,l} . D_{k,l} . anga_{i,k,l}$$

$$+ \sum_{i=1}^{IT} \sum_{l=1}^{l_{AT}} \sum_{n=1, n\neq l}^{l_{AT}} \varphi . C_{l,n} . D_{l,n} . anaa_{i,l,n} + \sum_{i=1}^{IT} \sum_{j=1}^{IT} CP_{i,j} . \sum_{u=1}^{UT} \max\left\{ dt_{i,j,u} - RT, 0 \right\}$$

$$\max \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} (RR_{l,n})^{1-\chi} . \sum_{i=1}^{IT} anaa_{i,l,n}.a_l.a_n$$

$$+\sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} W_{k,n}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.a_n$$

$$+\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{m=1,m\neq k}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} (RR_{i,k}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.(R_{nm})^{1-\chi}.(W_{i,m}.s_{i,m}. \sum_{j=1,j\neq i,j\neq k,j\neq l}^{IT} W_{ij}.nga_{i,k,l})$$

$$+\sum_{i=1}^{IT} \sum_{j=1,j\neq i}^{IT} \sum_{k=1}^{k_{GT}} \sum_{m=1,m\neq k}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} W_{i,j}(R_{i,k}.(R_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.(RR_{n,m})^{1-\beta}.RR_{m,j}).nga_{i,k,l}.nga_{j,n,m}$$

$$+\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{j=1,j\neq i,j\neq k,j\neq l}^{IT} (W_{i,j}+W_{j,i}).RR_{i,k}.(RG_k)^{1-\delta}.s_{i,k} +$$

$$\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} RR_{i,k}.(RR_{k,l})^{1-\beta}.(RA_l)^{1-\chi}.anga_{i,k,l}.nga_{i,k,l} +$$

$$\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1,n\neq l}^{l_{AT}} RR_{i,k}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.anaa_{i,l,n}.a_n$$

$$\min \sum_{k=1}^{k_{GT}} wqg_k + \sum_{l=1}^{l_{AT}} wqa_l$$

$$\sum_{k=1}^{k_{GT}} af_{i,k} = \sum_{j=1}^{IT} W_{i,j} \qquad \forall i \qquad (14)$$

$$af_{i,k} \leq \sum_{j=1}^{IT} W_{i,j}.g_k \qquad \forall i,k \qquad (15)$$

$$\sum_{k=1}^{k_{GT}} g_k = GN \qquad (16)$$

$$\sum_{l=1}^{l_{AH}} a_l = AN \qquad (17)$$

$$\sum_{n=1}^{l_{AT}} aa_{l,n} = a_l \qquad \forall l \qquad (18)$$

$$\sum_{l=1}^{l_{AT}} aa_{l,n} = a_n \qquad \forall n \qquad (19)$$

$$\sum_{k=1}^{k_{GT}} s_{i,k} = 1 \qquad \forall i \qquad (20)$$

$$s_{i,k} \leq g_k \qquad \forall i,k \qquad (21)$$

$$\sum_{i=1}^{IT} af_{i,k} \leq \Gamma G_k . g_k \qquad \forall k \qquad (22)$$

$$\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}} anga_{i,k,l} + \sum_{i=1}^{IT}\sum_{n=1}^{l_{AT}} anaa_{i,l,n} \leq \Gamma A_l . a_l \qquad \forall l \qquad (23)$$

$$nga_{i,k,l} \leq g_k . a_l \qquad \forall\ i,k,l,\ i \neq k, k \neq l \qquad (24)$$

$$af_{i,k} \leq M . \sum_{l=1}^{l_{AT}} nga_{i,k,l} \qquad (25)$$

$$anga_{i,k,l} \leq M . g_k . a_l \qquad \forall i,k,l \qquad (26)$$

$$\sum_{n=1, n\neq l}^{l_{AT}} anaa^{i}_{l,n} - \sum_{n=1, n\neq l}^{l_{AT}} anaa^{i}_{n,l} = \sum_{j=1}^{IT} W_{i,j} . \sum_{k=1}^{k_{GT}} (nga_{i,k,l} - nga_{j,k,l}) \qquad \forall\ i,l \qquad (27)$$

$$\sum_{j=1}^{IT} (W_{i,j} + W_{j,i}).(nga_{i,k,l} - nga_{j,k,l}) \leq anga_{i,k,l} \qquad \forall i,k,l \qquad (28)$$

$$\sum_{n=1, n\neq l}^{AT} anaa_{i,l,n} \leq \sum_{j=1, j\neq i}^{IT} W_{i,j} . \sum_{k=1}^{GT} nga_{i,k,l} \qquad \forall i,\ l \qquad (29)$$

$$dt_{i,j,1} = \sum_{k=1}^{k_{GT}} (RO_i + (TNG_{i,k} + TNG_{j,k})).s_{i,k} . s_{j,k} \qquad \forall i,\ j \qquad (30)$$

$$dt_{i,j,2} = \sum_{k=1}^{k_{GT}}\sum_{m=1}^{k_{GT}}\sum_{l=1}^{l_{AT}} (RO_i + TNG_{i,k} + \alpha.(TGA_{k,l} + TGA_{m,l}) + LA_l + TNG_{j,m})).nga_{i,k,l} . nga_{j,m,l} \qquad \forall i,\ j \qquad (31)$$

$$dt_{i,j,3} = \sum_{k=1}^{k_{GT}}\sum_{m=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{n=1}^{l_{AT}} (RO_i + (TNG_{i,k} + \alpha.TGA_{k,l} + LA_l + TAA_{l,n} + LA_n + \alpha.TGA_{m,n} + TNG_{j,m})).nga_{i,k,l} . nga_{j,m,n} . aa_{l,n} \qquad \forall i,\ j \qquad (32)$$

$$nga_{l,k,l} = 0 \qquad \forall\ i,k,l \qquad (33)$$

$$\lambda g_k = \frac{\sum_{i=1}^{IT} af_{i,k}}{10} \qquad \forall k \qquad (34)$$

$$pg_{0k} = \sum_{v=0}^{NG_k - 1} \frac{\left(\frac{\lambda g_k}{\mu G_k}\right)^{v}}{v!} + \frac{\left(\frac{\lambda g_k}{\mu G_k}\right)^{v}}{NG_k!} . \frac{1 - \left(\frac{\lambda g_k}{NG_k . \mu G_k}\right)^{QC_k - NG_k + 1}}{1 - \left(\frac{\lambda g_k}{NG_k . \mu G_k}\right)} \qquad \forall k \qquad (35)$$

$$pg_{QC_k} = \frac{(\lambda g_k)^{QC_k}}{NG_k^{\ QC_k - NG_k} . \mu G_k^{\ QC_k} . NG_k!} . pg_{0k} \qquad \forall k \qquad (36)$$

$$lqg_k = \left(\frac{pg_{0k} \cdot \left(NG_k \cdot \left(\frac{\lambda g_k}{NG_k . \mu G_k} \right) \right)^{NG_k} \cdot \left(\frac{\lambda g_k}{NG_k . \mu G_k} \right)}{NG_k ! . \left(1 - \left(\frac{\lambda g_k}{NG_k . \mu G_k} \right) \right)^2} . \left[1 - \left(\frac{\lambda g_k}{NG_k . \mu G_k} \right)^{QC_k - NG_k + 1} - \left(1 - \left(\frac{\lambda g_k}{NG_k . \mu G_k} \right) \right) . \left(QC_k - NG_k + 1 \right) . \left(\frac{\lambda g_k}{NG_k . \mu G_k} \right)^{QC_k - NG_k} \right] \right) \quad \forall k \quad (37)$$

$$wqg_k = \frac{lqg_k}{\lambda g_k . (1 - pg_{QC_k})} \quad \forall k \quad (38)$$

$$\lambda a_l = \frac{\sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} anga_{i,k,l} + \sum_{i=1}^{IT} \sum_{n=1}^{l_{AT}} anaa_{i,l,n}}{10} \quad (39)$$

$$pa_{0l} = \sum_{v=0}^{NA_l - 1} \frac{\left(\frac{\lambda a_l}{\mu A_l} \right)^v}{v!} + \frac{\left(\frac{\lambda a_l}{\mu A_l} \right)^v}{NA!} . \frac{1 - \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right)^{QC_l - NA_l + 1}}{1 - \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right)} \quad \forall l \quad (40)$$

$$pa_{QC_l} = \frac{(\lambda A_l)^{QC_l}}{NA_l^{QC_l - NA_l} . \mu A_l^{QC_l} . NA_l !} . pa_{0l} \quad \forall l \quad (41)$$

$$lqa_l = \left(\frac{pa_{0l} \cdot \left(NA_l \cdot \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right) \right)^{NA_l} \cdot \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right)}{NA_l ! . \left(1 - \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right) \right)^2} . \left[1 - \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right)^{QC_l - NA_l + 1} - \left(1 - \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right) \right) . \left(QC_l - NA_l + 1 \right) . \left(\frac{\lambda a_l}{NA_l . \mu A_l} \right)^{QC_l - NA_l} \right] \right) \quad \forall l \quad (42)$$

$$wqa_l = \frac{lqa_l}{\lambda a_l . (1 - pa_{QC_l})} \quad \forall l \ \forall l \quad (43)$$

$$nga_{i,k,l}, g_k, a_l, aa_{l,n} \in \{0,1\} \quad \forall i,k,l,n \quad (44)$$

$$af_{i,k}, anaa_{i,l,n}, anga_{i,k,l}, \lambda g_k, \lambda a_l, wqg_k, wqa_l, \geq 0 \quad \forall i,k,l,n \quad (45)$$

Constraints (14) and (15) are used to represent multiple network allocations. Because demand nodes are allocated to various ground hubs, any demand node may be assigned to more than one ground hub. These two constraints also state that all streams or initial traffic from the demand node must be passed through and connected to a hub and that it must be linked to a node that must be a hub. Constraint (16) guarantees that the number of the ground hub is set to a predetermined value. Constraint (17) guarantees that the number of the air hub is set to a predetermined value. Constraints (18) and (19) create the loop structure for the top-level hierarchical network of airport hubs. These Constraints (guarantee that the number of airport pairing hubs is established.

Constraint (20) ensures that each client node is finally connected to the ground hub. Constraint (21) guarantees that each client node is connected to the ground hub if the ground hub was formed previously. The capacity limitation of the ground hub is the subject of Constraint (22). This constraint guarantees that the ground hub's input quantity does not exceed its capability. Constraint (23) refers to the airport hub's capacity constraint. This constraint guarantees that the airport hub's input volume does not exceed its capacity. In Constraint (24), there is a connection between the ground hub and the airport hub if a route connects the demand node and the ground hub and if the airport hub and the demand node are then assigned to the ground hub. By doing this, it ensures that airport hubs are built near to one another. Ensures that the client node is linked to the ground hub and related air hub if related hubs have formed before.

Due to the continuity of the assigning demand nodes to the ground hubs variable and the expression of potential connections in the network, Constraints (25) and (26) specify that a new variable zero and one has been utilized to link these variables to the variable zero and one in these constraints. These Constraints in the direction of subsequent communication in the network ensure that the network is as required and the communication model's assumptions between the ground hub and the airport are used. It seeks to establish a condition under which an airport hub node must be constructed so that other nodes can be assigned to it. Building an airport hub to connect ground and airport hubs is necessary.

The conservation of network flow is an issue of Constraint (27). Because of this, if the demand node is allocated to a ground hub and that hub is later linked to another airport hub, the same flow may occur between the first airport hub and the second airport hub. If these flows are established, linkages between hubs and non-hubs to hubs will be possible.

Constraint (28) indicates a high limit for the flow fraction taken from the demand node and connected to the ground and airport hub. Constraint (29) refers to the amount of flow taken from the source, which is the point of demand, to the ground and airport hub, indicating the traffic volume on these routes. This Constraint considers a high limit for this route from the network. The time it takes for the flow to go from the source to the destination node is the subject of constraints (30) to (32). Constraint (33) guarantees that there is no loop between ground hub and airport hub. The average flow to each ground hub is constrained by Constraint (34). Constraint (35) is related to the probability of being zero customers (goods) in-ground hub k. Constraint (36) is concerned with the probability of being QC_k customers (goods) in-ground hub *k*. Constraint (37) is associated with the length of the queue formed in ground hub *k*.

Constraint (38) related to waiting time elapsed in-ground hub *k*. Constraint (39) is related to the average amount of flow to each airport hub. Constraint (40) is related to the probability of zero customers (goods) in airport hub *l*. Constraint (41) is concerned with the probability of being QC_l customers (goods) in airport hub *l*. Constraint (42) is associated with the queue length formed in airport hub *l*. Constraint (43) relates to waiting time elapsed in airport hub *l.* Constraints (44) correspond to variables zero and one in the model. Constraints (45) correspond to the positive variables.

3.7. Linearization of the model

In Relation (24) and (26), we see the multiplication of two variables, zero and one, in each other, which is $g_k.a_l$, according to the upper limit of the variable, which is one, the linearization steps are as follows:

$$ga_{k,l} = g_k.a_l \qquad \forall k,l \qquad (46)$$

$$g_k + a_l - ga_{k,l} \le 1 \qquad \forall k,l \qquad (47)$$

$$ga_{k,l} \le g_k \qquad \forall k,l \qquad (48)$$

$$ga_{k,l} \le a_l \qquad \forall k,l \qquad (49)$$

In Relation (1) for the first objective function, we see the multiplication of two variables, zero and one, in each other, which is $a_l.a_n$, and according to the upper limit of the variable, which is one, the linearization steps are as follows:

$$aa_{l,n} = a_l.a_n \qquad \forall l,n \qquad (50)$$

$$a_l + a_n - aa_{l,n} \le 1 \qquad \forall l,n \qquad (51)$$

$$aa_{l,n} \le a_l \qquad \forall l,n \qquad (52)$$

$$aa_{l,n} \le a_n \qquad \forall l,n \qquad (53)$$

Also, in the third objective function, we see the multiplication of two variables, zero and one, and positive in each other, according to the variable's upper limit. The linearization steps are as follows:

$$anaaf_{i,l,n} = anaa_{i,l,n}.aa_{l,n} \qquad \forall i,l,n \qquad (54)$$

$$anaaf_{i,l,n} \le M.aa_{l,n} \qquad \forall i,l,n \qquad (55)$$

$$anaaf_{i,l,n} \le anaa_{i,l,n} \qquad \forall i,l,n \qquad (56)$$

$$anaa_{i,l,n} \leq anaaf_{i,l,n} + M.(1 - aa_{l,n}) \qquad \forall i,l,n \qquad (57)$$

Likewise, in the same objective function and Constraint (31), we see the multiplication of two variables, zero and one. In each other, which is $nga_{i,k,l}.nga_{j,m,n}$, and according to the upper limit of the variable, which is one, the linearization steps are as follows:

$$ngaf_{k,l,m,n}^{i,j} = nga_{i,k,l}.nga_{j,m,n} \qquad \forall i,j,k,l,n,m \qquad (58)$$

$$nga_{i,k,l} + nga_{j,m,n} - ngaf_{k,l,m,n}^{i,j} \leq 1 \qquad \forall i,j,k,l,n,m \qquad (59)$$

$$ngaf_{k,l,m,n}^{i,j} \leq nga_{i,k,l} \qquad \forall i,j,k,l,n,m \qquad (60)$$

$$ngaf_{k,l,m,n}^{i,j} \leq nga_{j,m,n} \qquad \forall i,j,k,l,n,m \qquad (61)$$

In the same objective function, we see the multiplication of two variables, zero and one, and positive in each other, according to the variable's upper limit. The linearization steps are as follows:

$$angaf_{i,k,l} = anga_{i,k,l}.nga_{i,k,l} \qquad \forall i,k,l \qquad (62)$$

$$angaf_{i,k,l} \leq M.nga_{i,k,l} \qquad \forall i,k,l \qquad (63)$$

$$angaf_{i,k,l} \leq anga_{i,k,l} \qquad \forall i,k,l \qquad (64)$$

$$anga_{i,k,l} \leq angaf_{i,k,l} + M.(1 - nga_{i,k,l}) \qquad \forall i,k,l \qquad (65)$$

Likewise, in the same objective function, we see the multiplication of two variables, zero and one, and positive in each other, according to the variable's upper limit. The linearization steps are as follows:

$$anaaaf_{i,l,n} = a_n.anaa_{i,l,n} \qquad \forall i,l,n \qquad (66)$$

$$anaaaf_{i,l,n} \leq M.a_n \qquad \forall i,l,n \qquad (67)$$

$$anaaaf_{i,l,n} \leq anaa_{i,l,n} \qquad \forall i,l,n \qquad (68)$$

$$anaa_{i,l,n} \leq anaaaf_{i,l,n} + M.(1 - a_n) \qquad \forall i,l,n \qquad (69)$$

In Constraint (30), we see the multiplication of two variables, zero and one in each other $s_{i,k}.s_{j,k}$, and giving to the upper limit of the variable, which is one. The linearization steps are as follows:

$$ssf_{i,j,k} = s_{i,k}.s_{j,k} \qquad \forall i,j,k \qquad (70)$$

$$s_{i,k} + s_{j,k} - ssf_{i,j,k} \leq 1 \qquad \forall i,j,k \qquad (71)$$

$$ssf_{i,j,k} \le ss_{i,k} \qquad \forall i,j,k \qquad (72)$$

$$ssf_{i,j,k} \le s_{j,k} \qquad \forall i,j,k \qquad (73)$$

Also, in Constraint (32), we see the multiplication of two variables, zero and one, in each other, which is $ngaf_{k,l,m,n}^{i,j}.aa_{l,n}$. Concerning the upper limit of the variable, which is one, the linearization steps are as follows:

$$ngaaf_{k,l,m,n}^{i,j} = ngaf_{k,l,m,n}^{i,j}.aa_{l,n} \qquad \forall i,j,k,l,m,n \qquad (74)$$

$$ngaf_{k,l,n,m}^{i,j} + aa_{l,n} \le ngaaf_{k,l,m,n}^{i,j} \qquad \forall i,j,k,l,m,n \qquad (75)$$

$$ngaaf_{k,l,m,n}^{i,j} \le ngaf_{k,l,n,m}^{i,j} \qquad \forall i,j,k,l,m,n \qquad (76)$$

$$ngaaf_{k,l,m,n}^{i,j} \le aa_{l,n} \qquad \forall i,j,k,l,m,n \qquad (77)$$

A maximization statement $\max\left\{DT_{i,j,u} - RT, 0\right\}$ in the second objective function should be linearized in the objective function. The linearization steps are as follows:

$$mxdr_{i,j,u} = \max\left\{DT_{i,j,u} - RT, 0\right\} \qquad \forall i,j,u \qquad (78)$$

$$mxdr_{i,j,u} \ge DT_{i,j,u} - RT \qquad \forall i,j,u \qquad (79)$$

$$mxdr_{i,j,u} \ge 0 \qquad \forall i,j,u \qquad (80)$$

3.8. Fuzzy mathematical model

The parameters related to airport and ground hubs' capacity and transportation time can be uncertain due to the possibility of change for various reasons. In the constraints concerning the uncertain parameters considered according to the assumption of the present problem, the constraints that change in the fuzzy model, as well as linearized mathematical expressions, are as follows:

$$\min \sum_{l=1}^{l_{AT}} \sum_{n=1, n\neq l}^{l_{AT}} aa_{l,n} \qquad (81)$$

$$\begin{aligned}\min &\sum_{k=1}^{k_{GT}} FG_k.g_k + \sum_{l=1}^{l_{AT}} FA_l.a_l \\ &+ \sum_{i=1}^{IT} \sum_{j=1, j\neq i}^{IT} (W_{i,j} + W_{j,i}).\sum_{k=1}^{k_{GT}} C_{i,k}.D_{i,k}.\sum_{l=1}^{l_{AT}} nga_{i,k,l} + \sum_{i=1}^{IT} \sum_{k=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \phi.C_{k,l}.D_{k,l}.anga_{i,k,l} \\ &+ \sum_{i=1}^{IT} \sum_{l=1}^{l_{AT}} \sum_{n=1, n\neq l}^{l_{AT}} \varphi.C_{l,n}.D_{l,n}.anaa_{i,l,n} + \sum_{i=1}^{IT} \sum_{j=1}^{IT} CP_{i,j}.\sum_{u=1}^{UT} mxdr_{i,j,u}\end{aligned} \qquad (82)$$

$$\max\sum_{l=1}^{l_{AT}}\sum_{n=1,n\neq l}^{l_{AT}}(RR_{l,n})^{1-\chi}\sum_{i=1}^{IT}anaaaf_{i,l,n}$$

$$+\sum_{k=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{n=1,n\neq l}^{l_{AT}}W_{k,n}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.a_n$$

$$+\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}}\sum_{m=1,m\neq k}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{n=1,n\neq l}^{l_{AT}}(RR_{i,k}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.(R_{nm})^{1-\chi}.(W_{i,m}.s_{i,m}.\sum_{j=1,j\neq i,j\neq k,j\neq l}^{IT}W_{i,j}.nga_{i,k,l})$$

$$+\sum_{i=1}^{IT}\sum_{j=1,j\neq i}^{IT}\sum_{k=1}^{k_{GT}}\sum_{m=1,m\neq k}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{n=1,n\neq l}^{l_{AT}}W_{i,j}(R_{i,k}.(R_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.(RR_{n,m})^{1-\beta}.RR_{m,j}).ngaf_{k,l,m,n}^{i,j} \tag{83}$$

$$+\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{j=1,j\neq i,j\neq k,j\neq l}^{IT}(W_{i,j}+W_{j,i}).RR_{i,k}.(RG_k)^{1-\delta}+$$

$$\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}RR_{i,k}.(RR_{k,l})^{1-\beta}.(RA_l)^{1-\chi}.angaf_{i,k,l}+$$

$$\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{n=1,n\neq l}^{l_{AT}}RR_{i,k}.(RR_{k,l})^{1-\beta}.(RR_{l,n})^{1-\chi}.anaaaf_{i,l,n}$$

The objective function (13)

s.t.

$$\sum_{i=1}^{IT}af_{i,k}\leq\Gamma_k.g_k \qquad \forall\ k \tag{84}$$

$$\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}}anga_{i,k,l}+\sum_{i=1}^{IT}\sum_{n=1}^{l_{AT}}anaa_{i,l,n}\leq\Gamma_l.a_l \qquad \forall\ l \tag{85}$$

$$DT_{i,j,1}=\sum_{k=1}^{k_{GT}}(RO_i+(TNG_{i,k}+TNG_{j,k})).ssf_{\ i,j,k} \qquad \forall i,j \tag{86}$$

$$DT_{i,j,2}=\sum_{k=1}^{k_{GT}}\sum_{m=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}(RO_i+TNG_{i,k}+\alpha.(TGA_{k,l}+TGA_{m,l})+LA_l+TNG_{j,m})).$$
$$ngaf_{k,l,m,n}^{i,j} \qquad \forall i,j \tag{87}$$

$$DT_{i,j,3}=\sum_{k=1}^{k_{GT}}\sum_{m=1}^{k_{GT}}\sum_{l=1}^{l_{AT}}\sum_{n=1}^{l_{AT}}(RO_i+(TNG_{i,k}+\alpha.TGA_{k,l}+LA_l+TAA_{l,n}+LA_n+$$
$$+\alpha.TGA_{m,n}+TNG_{j,m}))\times ngaaf_{k,l,m,n}^{i,j} \qquad \forall i,j \tag{88}$$

Constraints (14)-(21), (24)-(29), (34)-(80)

4. Solution methodologies

Combining objective functions and converting them into the objective function is one method for tackling multi-objective optimization issues. Multi-objective decision-making strategies are employed in this research, in which numerous objectives are generated concurrently to optimize. The methods used in this research are LP-metric and GA methods, which work as follows.

4.1. LP-metric method

For a problem with *n* objective functions, each objective function's optimal value must be calculated independently of the other objectives, considering all constraints. Therefore, we bring all the objectives closer to their optimal value with the objective functions introduced in this method. Following, we describe the mechanism of this approach briefly.

$$\underline{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}, \underline{y} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \tag{89}$$

$$norm_1(\underline{x} - \underline{y}) \sim \left\| \underline{x} - \underline{y} \right\|_1 = \sum_{i=1}^{n} \left| x_i - y_i \right|$$

Norm 1 is an absolute value model or a stepwise method for calculating the distance. Similarly, for $p = 2$, the expression norm two is known as the Euclidean distance and is presented as follows:

$$norm_2(\underline{x} - \underline{y}) \sim \left\| \underline{x} - \underline{y} \right\|_2 = \left(\sum_{i=1}^{n} \left(x_i - y_i \right)^2 \right)^{1/2} \tag{90}$$

According to the same relations, the infinite norm is as follows:

$$norm_\infty(\underline{x} - \underline{y}) \sim \left\| \underline{x} - \underline{y} \right\|_\infty = \max_i \left\{ \left| x_i - y_i \right| \right\} \tag{91}$$

In this way, we can prove the norm equation *p* by considering the following assumption:

$$\underline{x}_{n\times1} = \begin{pmatrix} \frac{f_1^*}{f_1^*} = 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \qquad \underline{y}_{n\times1} = \begin{pmatrix} \frac{f_1(\underline{x})}{f_1^*} \\ \frac{f_2(\underline{x})}{f_2^*} \\ \vdots \\ \frac{f_n(\underline{x})}{f_n^*} \end{pmatrix} \qquad \rightarrow D_p = \left\| \underline{x} - \underline{y} \right\|_p \tag{92}$$

Because the objective function values in the considered issue vary, the units in the denominator are divided by the optimum value when normalizing these values. In the below statement, *p* is a parameter controlling the intensity of approaching the optimal value. Given that the deviation is reduced, the lower the departure from the ideal values, the bigger the value of *p*.

The final mathematical expression of this method is as follows:

$$\begin{cases} \min D_p = \left(\sum_{j=1}^{k} w_i \left(\frac{f_j^* - f_j(x)}{f_j^*} \right)^p \right)^{1/p} \\ s.t: \qquad\qquad\qquad\qquad p \in \{1, 2, \ldots\}, Integer \\ \underline{X} \in x \end{cases} \tag{93}$$

4.2. Goal attainment method

This approach is one of the multiple decision-making methods. In this method, the decision-maker plays a vital role and sets an ideal value for each objective function. In general, this approach is as follows:

$$\sum_{j=1}^{k} w_j = 1 \tag{94}$$

$$\underline{b} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_k \end{pmatrix}, \underline{w} = \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_k \end{pmatrix} \tag{95}$$

$$\left.\begin{matrix} \max \ f_1(x) \\ \max \ f_2(x) \\ \vdots \\ \max \ f_k(x) \\ s.t: \\ \underline{X} \in x \end{matrix}\right\} \rightarrow \begin{cases} \min \quad Z \\ s.t: \\ f_j(x) + w_j.Z \geq b_j \\ \underline{X} \in x, z: \ free \end{cases} \tag{96}$$

In explaining the objective function, it should be noted that we are looking for the z value with this change. We minimize the difference between the ideal value and each objective function's value. We will have:

$$\begin{aligned}
&\min z \\
&\text{s.t.} \\
&f_1(x) + z \geq b_1 \rightarrow z \geq b_1 - (w_1 . f_1(x)) \\
&f_2(x) + z \geq b_2 \rightarrow z \geq b_2 - (w_2 . f_2(x)) \\
&\quad \vdots \qquad \vdots \qquad \vdots \\
&f_k(x) + z \geq b_k \rightarrow z \geq b_k - (w_k . f_k(x)) \\
&\underline{x} \in x, z : free
\end{aligned} \tag{97}$$

4.3. Method used to solve the fuzzy model

This model attempts to enter the degree of confidence in the model due to the impossibility of risk by the decision-maker so that the decision-maker may be in a better position. Charans and Cooper initially described and revised the chance-constrained programming approach [51]. This approach combines the decision-level maker's with the degree of confidence to provide an appropriate security margin. All constraints relating to uncertainty must be at least within the applicable limits.

Assume that x are the decision variables and ξ fuzzy parameters, respectively. $g_i(x,\xi)$ specifies the random constraint functions. Since $g_i(x,\xi)$ it is not defined as a definite set, it is common for random constraints to be kept at a confidence level γ, so the fuzzy constraints become crisp constraints as follows:

$$Cr\{g_i(x,\xi) \leq 0 \} \geq \gamma_i \qquad i = 1, 2, \ldots, m \tag{98}$$

Fuzzy programming with chance constraints is given below:

Objective functions (83)-(86)

$$Cr\{\sum_{i=1}^{IT} af_{i,k} \leq \Gamma_k . g_k\} \geq \gamma_1 \qquad \forall k \tag{99}$$

$$Cr\{\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}} anga_{i,k,l} + \sum_{i=1}^{IT}\sum_{n=1}^{l_{AT}} anaa_{i,l,n} \leq \Gamma_l . a_l\} \geq \gamma_2 \qquad \forall l \tag{100}$$

$$Cr\{DT_{i,j,1} = \sum_{k=1}^{k_{GT}} (RO_i + (TNG_{i,k} + TNG_{j,k})).ssf_{i,j,k}\} \geq \gamma_3 \qquad \forall i, j \tag{101}$$

$$Cr\{DT_{i,j,2} = \sum_{k=1}^{k_{GT}} \sum_{m=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} (RO_i + TNG_{i,k} + \alpha.(TGA_{k,l} + TGA_{m,l}) + LA_l + TNG_{j,m})). \qquad \forall i, j \qquad (102)$$

$$ngaf_{k,l,m,n}^{i,j}\} \geq \gamma_4$$

$$DT_{i,j,3} = Cr\{\sum_{k=1}^{k_{GT}} \sum_{m=1}^{k_{GT}} \sum_{l=1}^{l_{AT}} \sum_{n=1}^{l_{AT}} (RO_i + (TNG_{i,k} + \alpha.TGA_{k,l} + LA_l + TAA_{l,n} + LA_n + \qquad \forall i, j \qquad (103)$$

$$+\alpha.TGA_{m,n} + TNG_{j,m})).ngaaf_{k,l,m,n}^{i,j}\} \geq \gamma_5$$

Constraints (14)-(21), (24)-(29), (34)-(80)

We use a hybrid model that combines fuzzy constraint-chance programming and anticipated value to adapt the fuzzy uncertain model presented in this paper. The first authors to propose this hybrid Model were Pishvaei et al. [52] in 2012. In this way, constraint confidence is controlled without adding complexity. The objective functions in this method are based on the expected value model. The minimum confidence level in the constraints determines how to use the chance constraints, including fuzzy parameters. The following is the fundamental model of fuzzy programming:

$$\max \quad f(x) \qquad (104)$$

s.t.

$$g_i(x, \xi) \leq 0 \qquad \forall i = 1, 2, 3, \ldots, m \qquad (105)$$

As a result, we have the following for objective functions based on the expected value and constraints based on chance constraints:

Objective function: (104)

s.t.

$$\mathrm{Cr}\{g_i(x, \xi) \leq 0\} \geq \gamma_i \qquad \forall i = 1, 2, 3, \ldots, m \qquad (106)$$

According to Ghodratnama et al. [53], critical values may alter the aforementioned model depending on confidence. Given that it is assumed that all of the model's fuzzy parameters are fuzzy triangular numbers $\xi = (r_1, r_2, r_3)$. Figure 6 shows the triangular membership function.

{Please insert Figure 6 about here.}

The following expressions represent their critical values $\gamma \in [0,1]$ when the confidence level is taken into account:

$$\xi_{\sup}(\gamma) = \sup\left\{ r \left| Cr\left\{ \xi \geq r \right\} \geq \gamma \right.\right\} \quad (107)$$

$$\xi_{\inf}(\gamma) = \inf\left\{ r \left| Cr\left\{ \xi \leq r \right\} \geq \gamma \right.\right\} \quad (108)$$

γ-optimistic and γ-pessimistic values are related by Equations (107) and (108).

$$\xi_{\sup}(\gamma) = \begin{cases} 2.\gamma.r_2 + (1-2.\gamma).r_3, & if\, \gamma \leq 0.5 \\ (2.\gamma-1).r_1 + (2-2.\gamma).r_2, & if\, \gamma > 0.5 \end{cases} \quad (109)$$

$$\xi_{\inf}(\gamma) = \begin{cases} (1-2.\gamma).r_1 + 2.\gamma.r_2, & if\, \gamma \leq 0.5 \\ (2-2.\gamma).r_2 + (2.\gamma-1).r_3, & if\, \gamma > 0.5 \end{cases} \quad (110)$$

Calculating γ-optimistic and γ-pessimistic values is explained in Equations (109) and (110), respectively. On the other hand, Liu [54] it was shown that fuzzy programming is part of the model:

$$Cr\left\{ \xi \geq k \right\} \geq \gamma \;\Leftrightarrow\; k \leq \xi_{\sup}(\gamma) \quad (111)$$

$$Cr\left\{ \xi \leq k \right\} \geq \gamma \;\Leftrightarrow\; k \geq \xi_{\inf}(\gamma) \quad (112)$$

4.4. Equivalent auxiliary crisp model

Based on the above description and triangular fuzzy parameters, the final model is as follows:

Objective functions: (83) - (86)

s.t.

$$\sum_{i=1}^{IT} af_{i,k} \leq ((2.\gamma_1 - 1).\Gamma_k^1 + (2-2.\gamma_1).\Gamma_k^2).g_k \qquad \forall k \quad (113)$$

$$\sum_{i=1}^{IT}\sum_{k=1}^{k_{GT}} anga_{i,k,l} + \sum_{i=1}^{IT}\sum_{n=1}^{l_{AT}} anaa_{i,l,n} \leq ((2.\gamma_2 - 1).\Gamma_l^1 + (2-2.\gamma_2).\Gamma_l^2).a_l \qquad \forall l \quad (114)$$

$$dt_{i,j,1} \leq ((2.(\gamma_3/2)-1).(RO_i^1 + TNG_{i,k}^1 + TNG_{j,k}^1 + (2-(2.(\gamma_3/2)).(RO_i^2 + TNG_{i,k}^2 + TNG_{j,k}^2)).ssf_{i,j,k} \qquad \forall i,j,k \quad (115)$$

$$dt_{i,j,1} \geq ((2-2.(\gamma_3/2)).(RO_i^2 + TNG_{i,k}^2 + TNG_{j,k}^2 + (2-(2.(\gamma_3/2)).(RO_i^3 + TNG_{i,k}^3 + TNG_{j,k}^3)).ssf_{i,j,k} \qquad \forall i,j,k \quad (116)$$

$$dt_{i,j,2} \le ((2.(\gamma_4/2)-1).(RO_i^1 + TNG_{i,k}^1 + TGA_{k,l}^1 + TGA_{m,l}^1 + LA_l^1 + TNG_{j,m}^1) + (2-(2.(\gamma_4/2)).(RO_i^2 + TNG_{i,k}^2 + TGA2_{k,l}^2 + TGA_{m,l}^2 + LA_l^2 + TNG_{j,m}^2)).ngaf_{i,j,k,l,m,l} \quad \forall i,j,k,l,m \qquad (117)$$

$$dt_{i,j,2} \ge ((2-(2.(\gamma_4/2)).(RO_i^2 + TNG_{i,k}^2 + TGA2_{k,l}^1 + TGA_{m,l}^2 + LA_l^2 + TNG_{j,m}^2) + (2.(\gamma_4/2)-1).(RO_i^2 + TNG_{i,k}^2 + TGA_{k,l}^2 + TGA_{m,l}^3 + LA_l^3 + TNG_{j,m}^3)).ngaf_{i,j,k,l,m,l} \quad \forall i,j,k,l,m \qquad (118)$$

$$dt_{i,j,3} \le (((2.(\gamma_5/2)-1).(RO_i^1 + TNG_{i,k}^1 + TGA_{k,l}^1 + LA_l^1 + TAA_{l,n}^1 + LA_n^1) + (\alpha.(TGA_{m,n}^1 + TNG_{j,m}^1))) + ((2.(\gamma_5/2)).(RO_i^2 + TNG_{i,k}^2 + TGA_{k,l}^2 + LA_l^2 + TAA_{l,n}^2 + LA_n^2) + (\alpha.(TGA_{m,n}^2 + TNG_{j,m}^2)))).ngaaf_{i,j,k,l,m,n} \quad \forall i,j,k,l,m,n \qquad (119)$$

$$dt_{i,j,3} \ge (((2.(\gamma_5/2)).(RO_i^2 + TNG_{i,k}^2 + TGA_{k,l}^2 + LA_l^2 + TAA_{l,n}^2 + LA_n^2) + (\alpha.(TGA_{m,n}^2 + TNG_{j,m}^2))) + ((2.(\gamma_5/2)).(RO_i^3 + TNG_{i,k}^3 + TGA_{k,l}^3 + LA_l^3 + TAA_{l,n}^3 + LA_n^3) + (\alpha.(TGA_{m,n}^3 + TNG_{j,m}^3)))).ngaaf_{i,j,k,l,m,n} \quad \forall i,j,k,l,m,n \qquad (120)$$

Constraints (14)-(21), (24)-(29), (34)-(80)

5. Computational experiments

Due to the proposed model's limitations and non-linear mathematical expressions, this research model is an MINLP model. To this end, the challenge in this research is to solve this model. The model is created and runs on a computer with 6.00 GB of installed memory (RAM) and an Intel (R) Core (TM) i7 CPU, 4702 MQ @ 3.2 0GHz processor using the GAMS commercial software environment version 25.1.2. The current model in this study is developed using random data and applied in various sizes to ensure validity. The BARON solver is used to solve the model because the problem is non-linear. Additionally, our computational results are divided into deterministic and in-deterministic models, the two main categories. We explain our findings in more detail below.

5.1. Deterministic model

The parameters related to each test problem according to Table 2 and the methods of solving the LP-metric and GA from different test problems according to Table 3, as well as the ideal values expressed for each test problem according to experts, are used in the two considered solution approaches. The major measures (i.e., the first, second, third, and fourth objective function values as well as CPU time) are examined using the GA and LP-metric techniques. Weights of associated objective functions are examined via them as shown in Table 4 (primary measures) (scenario).

{Please insert Table 2 about here.}
{Please insert Table 3 about here.}
{Please insert Table 4 about here.}

From Tables 5 to 8, we report computational results regarding each defined scenario noting that the first objective function is zero for all test problems because we defined just one air hub in test problem one and no air hub in test problem 2. Consequently, there will be no routes between at most one air hub. Interestingly for test problem no.2 second objective function has less value compared with test problem no.1. That is because the air hub is not considered, and also, its establishment's costs are not regarded. Also, using the GA approach, the value of objective function 3 is very high compared to the LP-metric approach.

Maybe LP-metric tries to improve other objective functions. Also, regarding weights dedicated to each objective function, it is evident that more weight-optimizing software tries to yield the related objective functions. However, as a whole, there is resistance throughout related weights, and the results are almost the same. That is because of the size of the test problems. Maybe for larger-size test problems, there would be bigger differences in computational results. Also, we investigated the impact of each objective function solely by dedicating the weight one to the related objective function and zero for others.

{Please insert Table 5 about here.}
{Please insert Table 6 about here.}
{Please insert Table 7 about here.}
{Please insert Table 8 about here.}

Figure 7 shows the non-dominated solutions obtained by two approaches. It is worth noting that the convexity of the fitted hyperplane certifies the conflict among considered objective functions.

{Please insert Figure 7 about here.}

5.2. Ranking (LP-metric and GA)

In this work, the most effective technique is determined using the SAW method to demonstrate which approach is superior to the others (for more details on the SAW method, please see [55]). For this reason, Table 9 shows the average values of four objective function values and the CPU time of two different solution approaches. The average values of four objective function values and CPU time for two different solution techniques are shown in Table 10 for this purpose. Concerning these values and the degree of importance for the decision-maker, a weight is determined as given in the decision matrix of Table 9. Associated with the rank shown in Table 11, the GA method performs better than the LP-metric method. After that, the decision matrix is unscaled to obtain the best option by considering the weight of each indicator. So, we have Table 10.

{Please insert Table 9 about here.}
{Please insert Table 10 about here.}
{Please insert Table 11 about here.}

5.3. Indeterministic (fuzzy) model

This part considers one test problem to verify the fuzzy model for the issue used in this study. Due to the nonlinearity and NP-hardness of the present problem and the high computational time, its sizes are considered low. The confidence level (γ) value of the alleged test issue, which is the same for all fuzzy constraints in each scenario, is connected to the differences between the first, second, and third scenarios. Tables 12 to 15 show the considered test problem size, fuzzy parameters, confidence level values for each scenario, and other certain parameters of the problem, respectively:

{Please insert Table 12 about here.}
{Please insert Table 13 about here.}
{Please insert Table 14 about here.}
{Please insert Table 15 about here.}

As seen from the data in Tables 16 to 17, the behavior of the objective functions in the issue alters in response to changes in confidence level. This table shows that the first and fourth objective function results are the same. But when the confidence level for the second objective function, which aims to lower, is raised, the optimal value increases with a higher confidence level. The third objective function, which we aim to maximize, is very big for the 0.6 confidence level and then falls and becomes higher. That is because of the impact of confidence level on feasible formed solution space. This habit is also the same for the GA approach. Figure 8 shows the results of schematically solving a fuzzy test problem, showing how to allocate nodes to hubs and higher levels vs. defined confidence levels for both solution approaches. Interestingly both approach yields unique location and allocation results.

{Please insert Table 16 about here.}
{Please insert Table 17 about here.}
{Please insert Figure 8 about here.}

6. Conclusion and future directions

The present study discussed the subject, the importance of doing it, its necessity in the real world, and the problem's assumptions. The relevant definitions and the literature on the location of hierarchical hubs and research conducted in recent years were fully addressed in the following. This research was associated with the centrality of hierarchical hub location in which reliability and congestion were integrated. One of the necessities of this research is the importance of the hub discussion in related issues due to the significant reduction in network-related costs compared to the network's overall scale. In the present study, due to the importance of real-time delivery time for existing customers, land and air transportation modes have been used to provide service time in large countries where distances were significantly reduced accordingly. In this regard, two types of air and ground hubs have been used in the model. The research's objective functions aimed to minimize the number of flights due to their high cost compared to the less time air transport than land transportation over long distances. Another objective function was to minimize network-related expenses, such as the fixed cost of creating hubs and the cost of traffic conveyance throughout the network.

To validate the mathematical model in the present study, three small test problems have been used because of the NP-hardness of the problem. Due to its multi-objective feature, two multiple-decision methods have been used to solve the model: the LP-metric method and GA. The results of these two methods were shown, and to evaluate the two methods and compare their performance, a simple additive weighting method has been used. It is evident that according to the average values obtained from different samples of each method and the average solution time, and because of the importance of the objectives function for the decision-maker. When solving the model, it was found that the GA technique performed better than the LP-metric method. The definite model's uncertainty has been considered to bring the model in this study as close as possible to reality, which used chance-constrained programming. For this purpose, due to the reality and the uncertainty in the amount of traveling time and the capacity of existing hubs, these two problem parameters were considered fuzzy. In this regard, three test problems of the same size have been used in this study to validate the integration model but with different confidence levels. In the final part, the results were presented. It was shown that the values related to the objective function became much poorer and moved away from the ideal condition as the sample's confidence increased.

According to many researchers' literature and studies, not much attention is paid to these problems' environmental problems. Due to the growing importance of environmental problems, this problem should be seen in these problems. Its applications include minimizing the amount of vehicle pollution in the network, and the number of pollutant emissions and fuel consumption can be considered according to the harmful damages that will occur in the future. The following are other suggestions for future research:

- Considering the completeness of the graph in the present study, the hub network can be considered incomplete.

- Different periods can be considered in the problem. Other periods have traffic rates, congestion on each route, and busy hours in different periods.
- Heuristic or meta-heuristic solving methodologies may be employed to better solve such methods due to the high execution time of reasonable solutions and NP-hard problems.
- In this case, the variable cost of transportation can be considered due to the different modes.
- Vehicle routing with simultaneous pick-up and delivery may be employed in this instance.
- Given the growing concern and importance of greenhouse gas emissions, this can be considered the problem. In such a way, the amount of exhaust gas from vehicles is considered another objective.

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Biography

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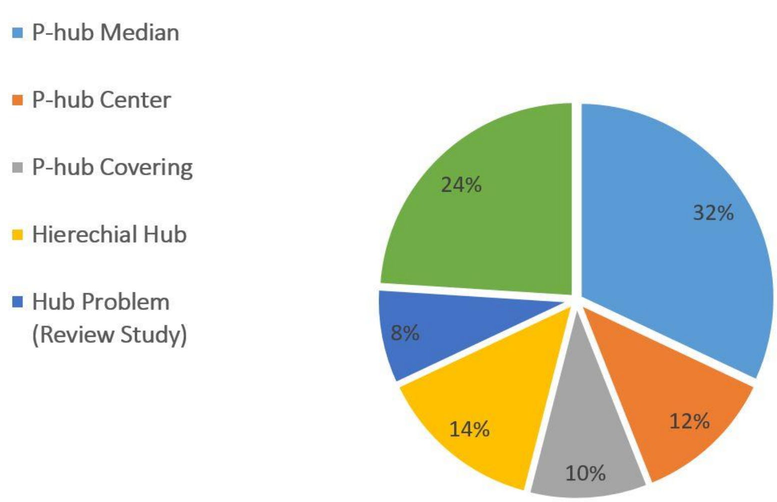


Figure 1. Percentage of the published paper on the subject of this research.

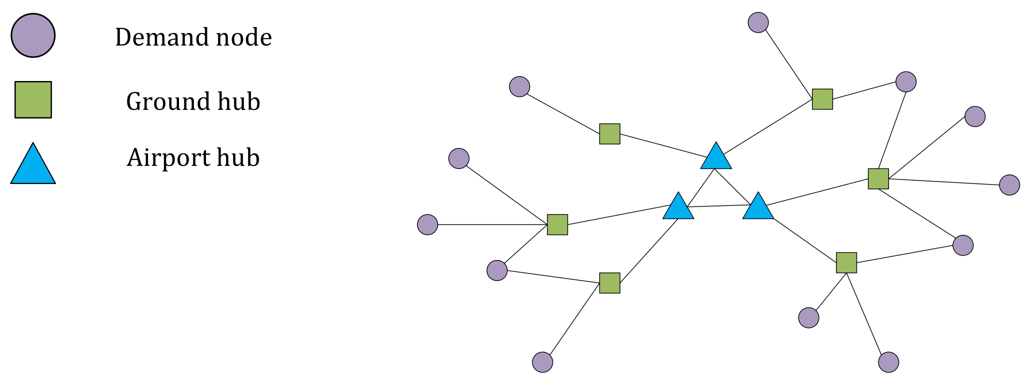
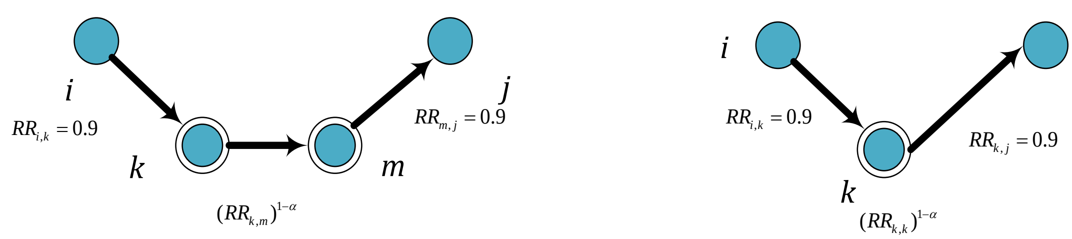


Figure 2. Hierarchical hub network structure in this study.



(a) Inter-hub route $i \to k \to m \to j$		(b) One-hub-stop route $i \to k \to j$	
Parameters	Reliability of $i \to k \to m \to j$	Parameters	Reliability of $i \to k \to j$
$\alpha = 0.9, RR_{k,m} = 0.8$	$RR_{k,m}^{i,j} = 0.792$	(b1) $\alpha = 0.9, \gamma = 0.7$	$RR_{k,k}^{i,j} = 0.782$
		(b2) $\alpha = 0.9, \gamma = 0.9$	$RR_{k,k}^{i,j} = 0.782$

Figure 3. Calculation of reliability with factors α and γ.

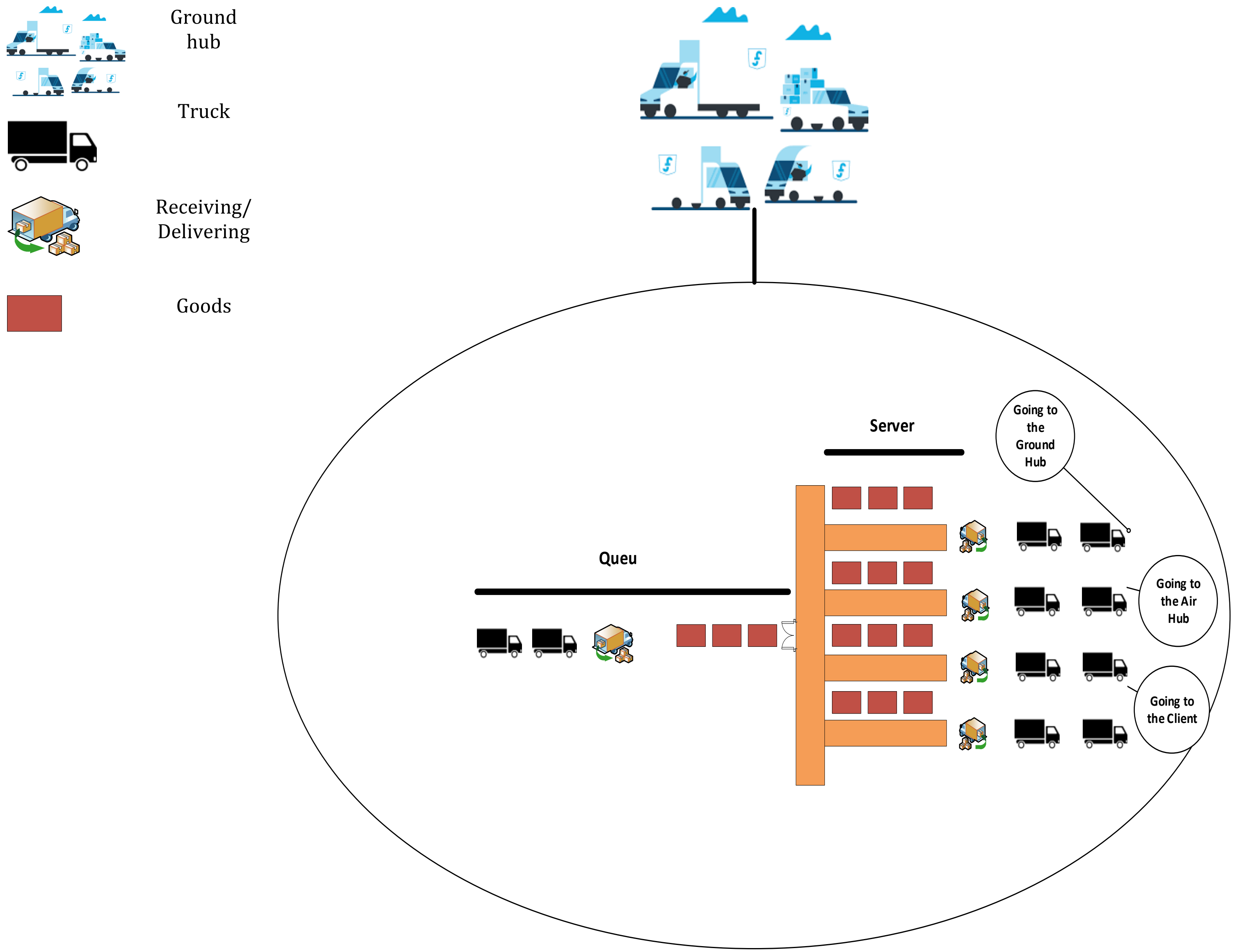


Figure 4. Congestion, unloading, loading, and departure in the ground hub.

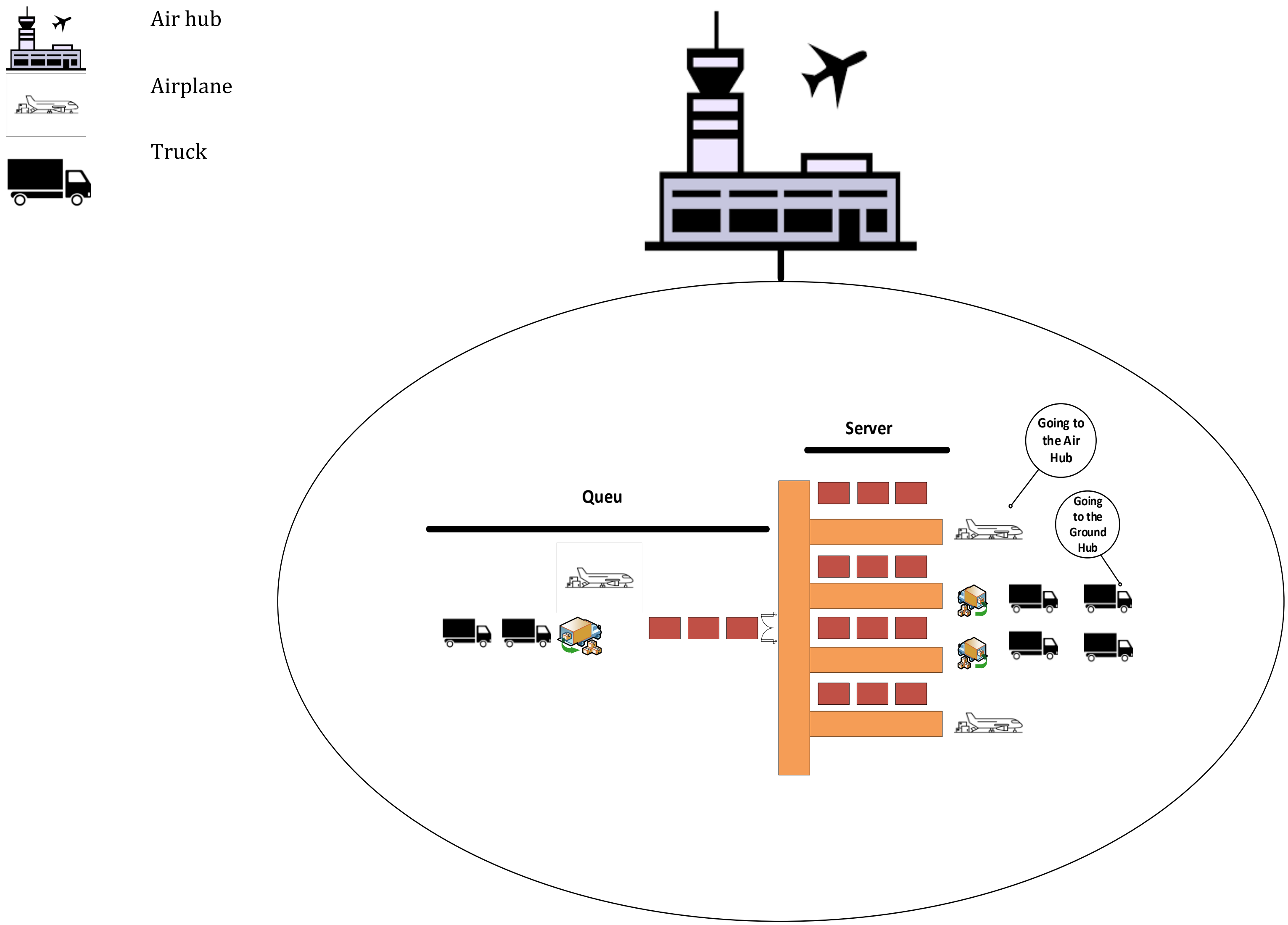


Figure 5. Congestion, unloading, loading, and departure in the air hub.

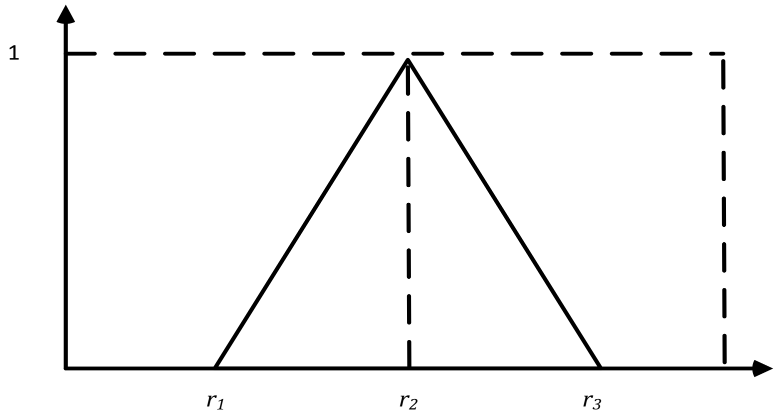


Figure 6. Triangular fuzzy membership function.

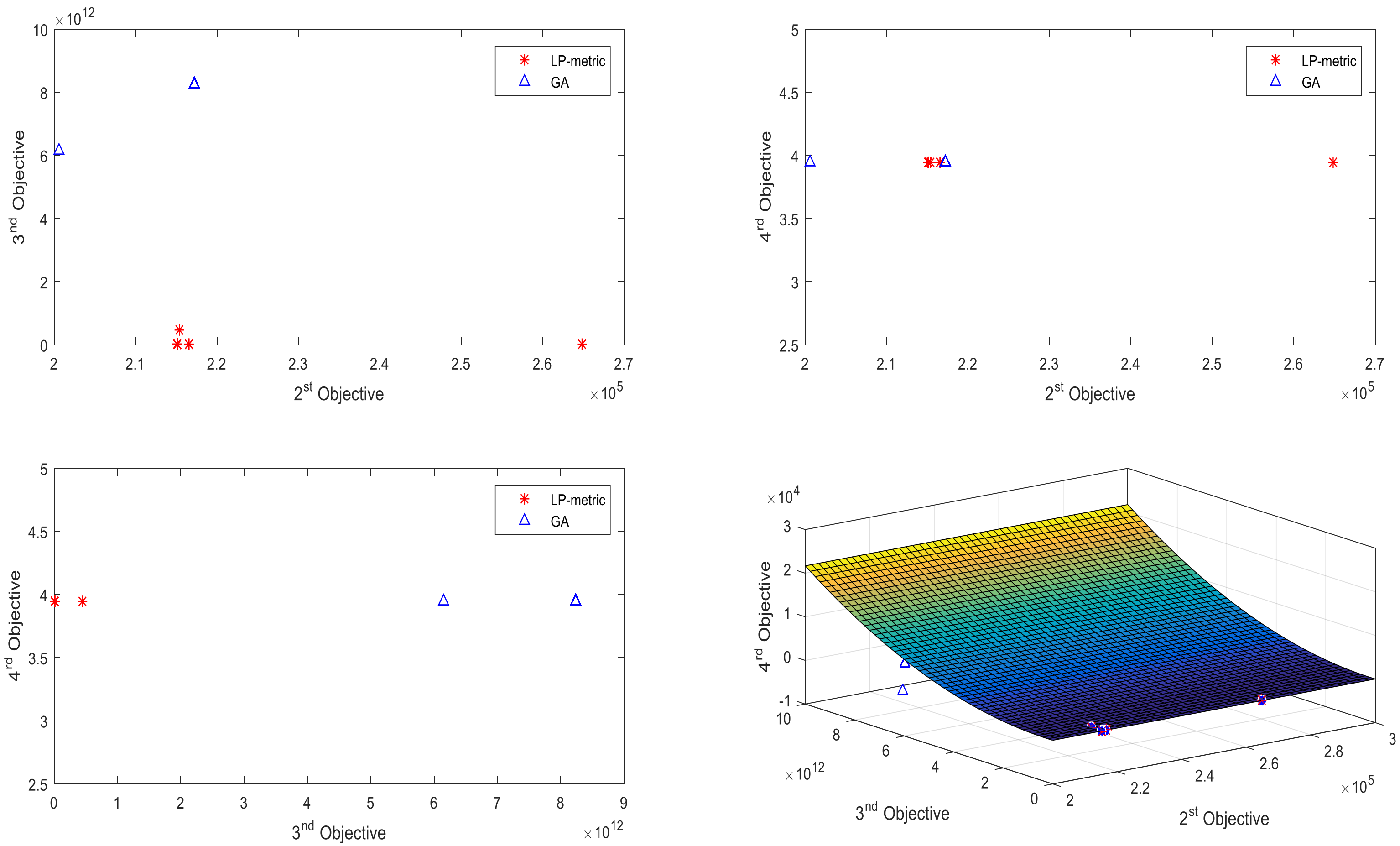


Figure 7. Non-dominated solutions obtained by LP-metric and GA approaches and fitted convex hyperplane. (test problem no.1).

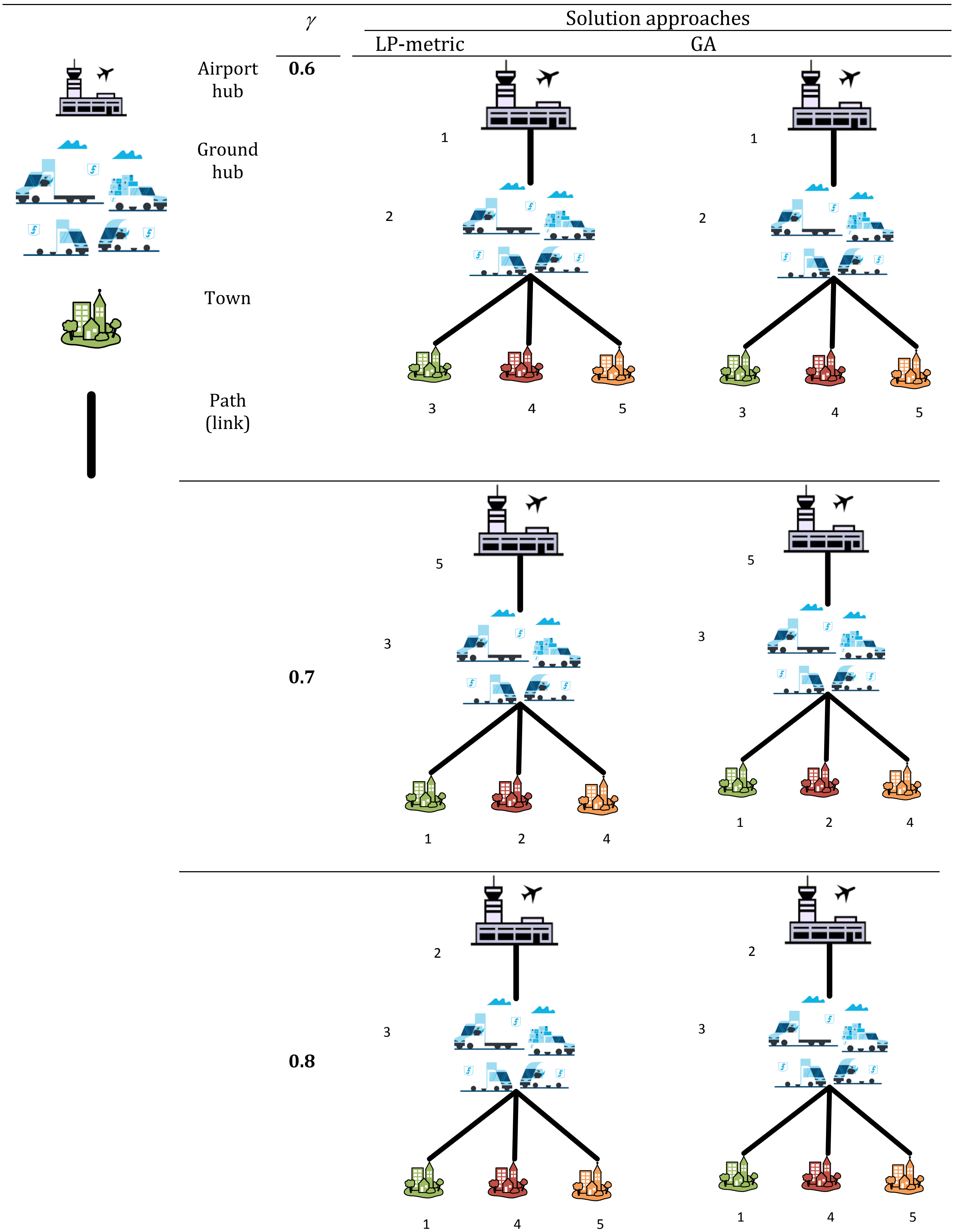

γ
Solution approaches
LP-metric
GA
Airport hub
Ground hub
Town
Path (link)
0.6
1
2
3
4
5
1
2
3
4
5
0.7
5
3
1
2
4
5
3
1
2
4
0.8
2
3
1
4
5
2
3
1
4
5

Figure 8. Hub network and components from the one obtained solution.

Tables

Table 1. Review of the existing literature.

Author	Year	Mathematical model	Objective function	Uncertainty	Allocation		Congestion		Solution Approach
					Single	Multiple	Parameter	Approach	
Yaman [11]	2009	Single Allocation *p*-hub median HHLP	Cost		✓				TS
Alumur and Yaman [12]	2012	HHLP	Cost		✓				Branch & bound method
Sun and Baek [15]	2012	Single Allocation *p*-hub median HHLP	Cost		✓				ACO
Korani and Sahraeian [16]	2013	Maximal covering HHLP	Cost		✓				Meta-heuristics
Sun [18]	2016	Single-allocation HHLP	Cost		✓				NSGA-II, ACO
Torkestani et al. [19]	2018	Multi-Modal HHLP	Cost		✓				Paper swarm optimization algorithm
Khodemani et al. [31]	2018	HHLP	Cost	✓	✓		Waiting time	$M/M/1$ $M/M/C$	NSGA-II, GVIWO, HSA
This study		Single-allocation *p*-hub median HHLP	Flight number, reliability, cost	✓	✓	✓	Waiting time	$M/M/C$ $M/M/C/K$	

Table 2. Parameters for the numerical problem.

	Problem No.		
	1	2	3
α	0.75	0.75	0.75
β	0.93	0.93	0.93
χ	0.95	0.95	0.95
δ	0.99	0.99	0.99
ϕ	0.7	0.7	0.7
φ	0.6	0.6	0.6
RG_k	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)
RA_l	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)
$RR_{i,j}$	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)
FG_k	$\sim$ uniform(5000,10000)	$\sim$ uniform(5000,10000)	$\sim$ uniform(5000,10000)
FA_l	$\sim$ uniform (15000, 25000)	$\sim$ uniform (15000, 25000)	$\sim$ uniform (15000, 25000)
$W_{i,j}$	$\sim$ uniform (10, 20)	$\sim$ uniform (10, 20)	$\sim$ uniform (10, 20)
ΓG_k	$\sim$ uniform (100000, 200000)	$\sim$ uniform (100000, 200000)	$\sim$ uniform (100000, 200000)
ΓA_l	$\sim$ uniform (200000, 300000)	$\sim$ uniform (200000, 300000)	$\sim$ uniform (200000, 300000)
μG_k	$\sim$ uniformint (3, 4)	$\sim$ uniformint (3, 4)	$\sim$ uniformint (3, 4)
μA_l	$\sim$ uniformint (4, 5)	$\sim$ uniformint (4, 5)	$\sim$ uniformint (4, 5)
NG_k	$\sim$ uniformint (3, 4)	$\sim$ uniformint (3, 4)	$\sim$ uniformint (3, 4)
NA_l	$\sim$ uniformint (5, 6)	$\sim$ uniformint (5, 6)	$\sim$ uniformint (5, 6)
QCG_k	$\sim$ uniformint (10, 20)	$\sim$ uniformint (10, 20)	$\sim$ uniformint (10, 20)
QCA_l	$\sim$ uniformint (10, 20)	$\sim$ uniformint (10, 20)	$\sim$ uniformint (10, 20)
$C_{i,j}$	$\sim$ uniform (330, 2730)	$\sim$ uniform (330, 2730)	$\sim$ uniform (330, 2730)
$D_{i,j}$	$\sim$ uniform (2, 9)	$\sim$ uniform (2, 9)	$\sim$ uniform (2, 9)
RT	480	480	480
$CP_{i,j}$	$\sim$ uniform (1.5, 2)	$\sim$ uniform (1.5, 2)	$\sim$ uniform (1.5, 2)
$TNG_{i,k}$	$\sim$ uniform (3, 7)	$\sim$ uniform (3, 7)	$\sim$ uniform (3, 7)
TGA_{kl}	$\sim$ uniform (3, 5)	$\sim$ uniform (3, 5)	$\sim$ uniform (3, 5)
$TAA_{l,n}$	$\sim$ uniform (1, 2)	$\sim$ uniform (1, 2)	$\sim$ uniform (1, 2)
RO_i	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)	$\sim$ uniform (0,1)
LA_l	$\sim$ uniform (2, 3)	$\sim$ uniform (2, 3)	$\sim$ uniform (2, 3)
M	1000000	1000000	1000000

Table 3. Test problems.

Index	Description	Problem No.		
		1	2	3

IT	No. of all nodes	4	4	4
GT	No. of potential ground hubs	1	1	0
AT	No. of potential airport hubs	1	0	1

Table 4. Scenarios regarded for each test problem.

Scenario no.	Weights			
	w_1	w_2	w_3	w_4
1	0.7	0.1	0.1	0.1
2	0.1	0.7	0.1	0.1
3	0.1	0.1	0.7	0.1
4	0.1	0.1	0.1	0.7
5	0.4	0.4	0.1	0.1
6	0.1	0.4	0.4	0.1
7	0.1	0.1	0.4	0.4
8	0.4	0.1	0.1	0.4
9	0.4	0.1	0.4	0.1
10	0.1	0.4	0.1	0.4
11	0.25	0.25	0.25	0.25
12	1	0	0	0
13	0	1	0	0
14	0	0	1	0
15	0	0	0	1

Table 5. Numerical outcomes reported by the LP-metric approach for problem no. 1 (CPU–time and OFV).

Scenario no.	Objective function					CPU–time (s)
	z_1	z_2	z_3	z_4	z	
1	0	215161.852	23.804	3.950	0.099	2045
2	0	215161.852	23.804	3.950	0.093	2264
3	0	215426.283	23.804	3.95	0.661	1280
4	0	215161.852	23.804	3.950	0.099	1452
5	0	215161.852	23.804	3.950	0.096	2288
6	0	215161.852	23.804	3.95	0.396	1338
7	0	215161.852	23.804	3.95	0.399	2246
8	0	215161.852	23.804	3.95	0.099	1400
9	0	215161.852	23.804	3.95	0.399	1339
10	0	215161.852	23.804	3.95	0.096	1332
11	0	215161.852	23.804	3.95	0.248	1539
12	0	216486.278	23.804	3.95	0.00	1334
13	0	215161.852	23.804	3.95	0	1320
14	0	216486.278	23.804	3.95	1	1351
15	0	264886.827	25.323	3.950	0	1330

Table 6. Numerical outcomes reported by the LP-metric approach for problem no. 2 (CPU–time and OFV).

Scenario no.	Objective function					CPU–time (s)
	z_1	z_2	z_3	z_4	z	
1	0	200569.017	16.648	3.950	0.1	85
2	0	200569.017	16.648	3.950	0.1	66
3	0	200569.017	16.648	3.950	0.7	80
4	0	200569.017	16.648	3.950	0.1	58
5	0	200569.017	16.648	3.950	0.1	79
6	0	200569.017	16.648	3.950	0.4	67
7	0	200569.017	16.648	3.950	0.4	49
8	0	200569.017	16.648	3.950	0.1	83
9	0	200569.017	16.648	3.950	0.4	82
10	0	200569.017	16.648	3.950	0.1	82
11	0	200569.017	16.648	3.950	0.25	80
12	0	231220.068	6.567	3.950	0	52
13	0	200569.017	16.648	3.950	0	78
14	0	231220.068	6.567	3.950	1	83
15	0	510620.094	46.598	3.95	0	191

Table 7. Numerical outcomes reported by the GA approach for problem no. 1 (CPU–time and OFV).

Scenario no.	Objective function					CPU–time (s)
	z_1	z_2	z_3	z_4	z	
1	0	217248.579	8.23579E+12	3.95	0	1275
2	0	217248.579	8.23579E+12	3.95	0	1305
3	0	217248.579	8.23579E+12	3.95	0	1353
4	0	217248.579	8.23579E+12	3.95	0	1408
5	0	217248.579	8.23579E+12	3.95	0	1394
6	0	217248.579	8.23579E+12	3.95	0	1468
7	0	217248.579	8.23579E+12	3.95	0	1301
8	0	217248.579	8.23579E+12	3.95	0	1280
9	0	217248.579	8.23579E+12	3.95	0	1292
10	0	217248.579	8.23579E+12	3.95	0	1285
11	0	217248.579	8.23579E+12	3.95	0	1304
12	0	217248.579	8.23579E+12	3.95	0	1193
13	0	217248.579	8.23579E+12	3.95	0	1286
14	0	200569.017	6.14340E+12	3.95	0	1039
15	0	217248.579	8.23579E+12	3.95	0	1196

Table 8. Numerical outcomes reported by the GA approach for problem no. 2 (CPU–time and OFV).

Scenario no.	Objective function					CPU–time (s)
	z_1	z_2	z_3	z_4	z	
1	0	200569.017	6.14340E+12	3.95	0	1041
2	0	200569.017	6.14340E+12	3.95	0	1041

3	0	217248.579	8.23579E+12	3.95	0	1304
4	0	200569.017	6.14340E+12	3.95	0	1042
5	0	200569.017	6.14340E+12	3.95	0	1043
6	0	200569.017	6.14340E+12	3.95	0	1044
7	0	200569.017	6.14340E+12	3.95	0	1042
8	0	200569.017	6.14340E+12	3.95	0	1046
9	0	200569.017	6.14340E+12	3.95	0	1042
10	0	200569.017	6.14340E+12	3.95	0	1041
11	0	200569.017	6.14340E+12	3.95	0	1048
12	0	200569.017	6.14340E+12	3.95	0	1045
13	0	200569.017	6.14340E+12	3.95	0	1042
14	0	200569.017	6.14340E+12	3.95	0	1041
15	0	200569.017	6.14340E+12	3.95	0	1044

Table 9. Decision matrix.

Solution approaches	Objective function				CPU–time (s)
	z_1	z_2	z_3	z_4	
LP-metric	0	221998.5	20.6029	3.95	835.7667
GA	0	208908.8	7.19E+12	3.95	1176.167
Weight	0.2	0.2	0.2	0.2	0.2

Table 10. Non-scaled weighted decision matrix.

Solution approaches	Objective function				CPU–time (s)
	z_1	z_2	z_3	z_4	
LP-metric	1	0.941037	2.86566E-12	1	1
GA	1	1	1	1	0.710585
Weight	0.2	0.2	0.2	0.2	0.2

Table 11. Results reported by the SAW method.

Solution approaches	Obtained Score	Rank
LP-metric	0.588207	2
GA	0.8	1

Table 12. Fuzzy test problem.

Index	Description	Fuzzy problem
IT	No. of all nodes	5
GT	No. of potential ground hubs	1
AT	No. of potential airport hubs	1

Table 13
Confidence level values considered for each alternative.

$\gamma_i \quad i = 1, 2, \ldots, 5$	Alternative 1	Alternative 2	Alternative 3
	0.6	0.7	0.8

Table 14. Fuzzy parameters related to the considered fuzzy test problem.

Parameter	Values	Parameter	Values
ΓG_k^1	$\sim$ uniform(10000, 20000)	$TGA_{k,l}^1$	$\sim$ uniform(3,5)
ΓG_k^2	$\sim$ uniform(20000, 30000)	$TGA_{k,l}^2$	$\sim$ uniform(5,6)
ΓG_k^3	$\sim$ uniform(30000, 40000)	$TNG_{k,l}^3$	$\sim$ uniform(6,7)
ΓA_l^1	$\sim$ uniform(30000, 40000)	$TAA_{l,n}^1$	$\sim$ uniform(1,1.25)
ΓA_l^2	$\sim$ uniform(40000, 50000)	$TAA_{l,n}^2$	$\sim$ uniform(1.25,1.75)
ΓA_l^3	$\sim$ uniform(50000, 60000)	$TAA_{l,n}^3$	$\sim$ uniform(1.75, 2)
$TNG_{i,k}^1$	$\sim$ uniform(3,5)	RO_l^1	$\sim$ uniform(0, 0.3)
$TNG_{i,k}^2$	$\sim$ uniform(5,6)	RO_l^2	$\sim$ uniform(0.3, 0.6)
$TNG_{i,k}^1$	$\sim$ uniform(6,7)	RO_l^3	$\sim$ uniform(0.6,1)
LA_l^1	$\sim$ uniform(2, 2.3)	RT^1	$\sim$ uniform(50, 70)
LA_l^2	$\sim$ uniform(2.3, 2.6)	RT^2	$\sim$ uniform(70, 90)
LA_l^3	$\sim$ uniform(2.6, 3)	RT^3	$\sim$ uniform(90,110)

Table 15. Certain parameters related to the fuzzy test problem under consideration.

Parameter	Values	Parameter	Values
α	0.75	$D_{i,j}$	$\sim$ uniform (3,4)
M	1000000	$C_{i,j}$	$\sim$ uniform (330, 2730)
β	0.93	$W_{i,j}$	$\sim$ uniform (0,1)
δ	0.9	$CP_{i,j}$	$\sim$ uniform (1.5, 2)
RG_k	$\sim$ uniform (0,1)	μG_k	$\sim$ uniformint (2,3)
RA_l	$\sim$ uniform (0,1)	μA_l	$\sim$ uniformint (3,4)
$RR_{i,j}$	$\sim$ uniform (0,1)	NNG_k	$\sim$ uniformint (2,3)
FG_k	$\sim$ uniform(9000,10000)	NNA_l	$\sim$ uniformint (3,4)
FA_l	$\sim$ uniform (10000, 20000)	QCG_k	$\sim$ uniformint (10, 20)
QCA_l	$\sim$ uniformint (10, 20)		

Table 16. Numerical results obtained related to the considered alternative LP-metric.

Confidence level	Objective function				CPU–time (s)
	z_1	z_2	z_3	z_4	
$\gamma_i = 0.6 \quad i = 1, 2, \ldots, 5$	0	80450.011	1.23203E+13	4.940	5912
$\gamma_i = 0.7 \quad i = 1, 2, \ldots, 5$	0	82508.845	26.570	4.940	3905
$\gamma_i = 0.8 \quad i = 1, 2, \ldots, 5$	0	82956.774	36.012	4.940	1515

Table 17. Numerical results obtained related to the considered alternative GA.

Confidence level		Objective function				CPU–time (s)
		z_1	z_2	z_3	z_4	
$\gamma_i = 0.6$	$i = 1, 2, \ldots, 5$	0	80450.011	1.23203E+13	4.940	5674
$\gamma_i = 0.7$	$i = 1, 2, \ldots, 5$	0	82508.845	26.570	4.940	2876
$\gamma_i = 0.8$	$i = 1, 2, \ldots, 5$	0	82956.774	36.012	4.940	1326