Research Article

Designing Airline Hub-and-Spoke Network and Fleet Size by a Biobjective Model Based on Passenger Preferences and Value of Time

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This study presents a biobjective hub-and-spoke (HS) network design model for the global air passenger networks. The model explores the tradeoff between the total airline cost (airline preference) and lost time cost for passengers (user preference) as the model’s objectives. Most previous studies have focused on airline objectives and established HS networks based on the viewpoint of airlines, despite the importance of passenger objectives. Poor passenger service and inconvenience and dissatisfaction may lead to network breakdown. The major criteria for passenger dissatisfaction in HS networks are schedule and trip delays caused by nondirect flights. These delays (the lost time cost for passengers) are multiplied by the passengers’ value of time (VOT) and minimized as one of the model’s objectives. Another objective that is minimized is the transportation costs of the airline depending on the services provided (short-, medium-, and large-haul flights). The model is solved in a case study (Iranian Aeronautics Network) that is applied to the well-known yearbook of tourism statistics data. Pareto frontier was found for all candidate airports. Also, the number of aircraft required (short-, medium-, and large-haul), as well as the average load factor for different types of aircraft in various weights of the first objective (airline costs), was presented. The results of Pareto frontier indicated that Imam Khomeini International Airport should be selected as the global hub airport for Iran international flight network. Otherwise, Shiraz International Airport and Tabriz International Airport (as the first alternative), as well as Isfahan International Airport and Mashhad International Airport (as the second alternative), would be the best choices. The weight of the first objective (airline costs) seems to be between 0.7 to 1, a practical and logical weight that can reduce passenger costs (as the second objective) by 20% on average by adding only 15 long-haul, 40 medium-haul, and 37 short-haul aircraft to the airline’s fleet. Also, in this range, the average load factor for medium- and long-haul aircrafts is greater than 0.9, which seems to be ideal.

1. Introduction

Hub-and-spoke (HS) configuration is extensively used in airline and airport industries, emergency services, post delivery services, rapid delivery packing systems, telecommunication services, message delivery networks, and transportation networks [1]. The reasons for the growing use of HS configuration in transportation networks are as follows. First, HS networks, particularly in road and rail transportation, shorten the established links to fully connected networks, reducing fixed established costs [1]. The second reason is the economic scale of the flow of cost between hub nodes and even between nonhub and hub nodes so that with increased flow density, the costs decline [2]. The third benefit is related to resource management. For transportation networks with limited resources, HS configuration can provide service to more nodes with greater efficiency compared to a fully connected network [3]. In addition to the benefits, this system suffers from drawbacks such as increased travel time of users, sensitivity to congestion in hub nodes and links, and sensitivity to network disruptions [4].

In an air transportation network, HS configuration can save airline operational costs and increase the system
capacity [5]. In this type of network, due to the use of indirect connections, fewer flights, on-service aircraft, and crew staff are needed [3]. However, if users' preferences (e.g., delay, travel time, fare, and service frequency) are overlooked in designing the network by an airline, the system utility deteriorates and the airline sustains irrevocable damages [6, 7].

Delays in airline operations impose billions of dollars in additional costs to airlines, passengers, and the economy [8]. According to the NEXTOR study conducted by the University of California, Berkeley's Institute of Transportation Studies reported that in 2007, the US economy has incurred a $32.9 billion loss due to flight delays across the US airspace system. The US Federal Aviation Administration sponsored a report on the analysis of a variety of cost components induced by flight delays, including expenses incurred by airlines and passengers, as well as costs of lost demand and the indirect impact of delays on the US economy. According to this study, the direct cost of flight delays is $28.9 billion more than half of which is borne by passengers. The cost of passenger time lost due to airline and passenger schedule buffers, delayed flights, flight cancellations, and missed connections was estimated at $16.7 billion. The NEXTOR study estimated that air transportation delays shrank the US GDP by $4 billion in 2007 [9].

In addition to the financial losses resulting from the delays, flight delays on a route reduce passenger demand and raise airfares, wreaking havoc on both consumer (passenger) and producer (airline) welfare [10, 11]. Therefore, airlines strive to diminish delays in decisions by taking various strategies. As airlines need to reduce delays at all levels of decision-making, it is a good idea to prioritize delays in long-term decisions. Therefore, this research addresses tactical decisions (fleet planning) and strategic decisions (hub locating) together.

Hence, in a real-world application, the system (airline) and users' (passengers) preferences should be taken into account when designing HS networks [12]. Aside from hub location, fleet planning is another strategic decision whereby the airline can design its future fleet (the number and type of aircraft needed) for servicing demand over long periods [13]. Hub location without fleet planning (i.e., fleet size and diversity determination) can raise airline operational costs due to inappropriate allocation of aircraft to flight legs (e.g., long-haul aircraft on short-flight legs) and investment costs related to the purchase or rent of new aircraft to meet network demand [14]. Therefore, to enhance the performance of HS networks and reduce an airline's operational and investment costs, hub location and fleet planning should be simultaneously optimized.

This study proposes a biobjective uncapacitated single allocation $p$-hub median problem integrated with a fleet planning problem to satisfy the preferences of the system and users at the same time. The first objective function minimizes the airline's operational costs while the second objective decreases the passengers' lost time costs attributed to passenger delays. In the latter, two types of delay, planning delay and delay caused by the time difference between HS network and direct flight, as the most ideal travel type, are used. The hub location and fleet planning are performed simultaneously where flight frequencies and aircraft types are determined for the flight legs. One of the best methods for modelling such an approach is the biobjective model, which can consider both objective functions (airline costs and passenger costs) simultaneously. Also, to find the optimal solution, two objective functions can be converted into a single-objective function using the weight-sum method, and then it can be solved exactly and the optimal solution is obtained.

2. Literature Review

There are two aspects of the literature covered below. In Section 2.1, hub location problems (HLPs) are reviewed in the context of air transportation, and in Section 2.2, multiobjective HLPs are classified in terms of their objective functions and compared to the current research.

2.1. HLP in the Aviation Industry. In this section, HLPs in the aviation industry are reviewed based on three main elements of HS networks: hub airport, passengers, and airlines.

2.1.1. Hub Airport. Some researchers studied HLPs by accounting for specific characteristics of hub airports such as hub capacity, hub congestion, and disruption in hubs. Yang and Chiu proposed a two-stage stochastic HS network design model by considering seasonal demand variations and hub congestion effects [15]. The capacity of hub airports was investigated in the HLPs proposed by Mohri et al. and Yang [16, 17]. Mohri et al. measured the capacity of hub airports by drawing an envelope curve on daily inbound and outbound flight statistics [16]. Teymourian et al. proposed a novel model for a virtual hub-routing problem. A virtual hub is a predetermined replacement satellite node that can act as the main hub under certain situations to compensate for the service disruption in the main hub [18].

2.1.2. Passengers. Here, research on variations of the passenger demand matrix and its impact on designing hub airports' locations is investigated. Carmona-Benítez et al. proposed an econometric dynamic model for estimating passenger demand in the airline industry, which was subsequently used for locating hub airports [19]. Kawasaki explored the effects of scheduling in a monopoly airline market for hub location and their effect on demand and the traffic of passengers traveling between two cities [20]. Yang presented a stochastic HLP under seasonal demand variations [21].

2.1.3. Airlines. Competition, merging, or alliance of airlines are some characteristics of HLPs related to airlines. Martín and Román proposed the HLP as a spatial competition game that is played in two phases. The hub location is selected sequentially in the first phase while the competitive strategies are utilized in the second phase of the game [5]. Eiselt and Marianov studied the effect of competition between two
airlines in an HLP, where the passengers’ utility function of airlines was estimated according to the flying duration and ticket price [22]. The effect of code-share alliance agreements on designing HS networks was studied by Wen and Hsu [23]. Wang et al. included fleet size and allocation of various types of aircraft to air routes in an HS network. For the objective function, the net benefit of the fleet was maximized by accounting for the least fleet purchasing cost of six types of aircraft [24]. Hsu and Wen investigated the effect of various aircraft types of diverse capacities on maximizing the benefits of code-share alliance agreements for airlines using an interactive biobjective model [7]. Wei and Hansen looked into the effect of aircraft size and airline service frequency on minimizing airline operational costs in an HLP [25]. Sina Mohri et al. designed a hub network for an airline or a group of airlines to cover international flights between countries considering the fleet size and diversity on a global scale [26]. Table 1 summarizes recent HLP studies in the aviation industry based on the scope of their research.

2.2. Multiobjective HLP. This section reviews multiobjective HLPs. Various researchers have minimized the total operational and fixed costs as the cost objective function [12, 27–33]. Some researchers only minimized operational costs [6, 34–36]; however, some previous research decreased operational and fixed costs using two separate objective functions [35]. This study contributes to the literature by integrating fleet planning and hub location decisions in a strategic problem. Hence, this is the first study to investigate the minimization of total operational costs and fleet planning costs (i.e., aircraft purchasing costs) as an objective function.

Other objectives investigated in HLPs are mostly related to time (i.e., service time in hubs or travel time in the network) or the number of intermediate stops in trips. These objectives can account for customer satisfaction in designing HS networks. As Table 2 shows, five different types of objectives have been explored in the literature, minimizing the total service time in hubs [27, 30, 33, 35, 37], minimizing the maximum service time in hubs [27, 34, 37], minimizing the maximum travel time between origin and destination (OD) pairs [28, 31, 32, 38], minimizing the total travel time between OD pairs [29], and minimizing the total number of intermediate stops [12]. Table 2 outlines the objectives of the previous studies. As Table 2 indicates, operational or/and fixed costs are usually minimized as one of the HLP’s objective functions.

This study looks into a new time-related objective reflecting the passengers’ satisfaction with the hub services. It minimizes the subtraction of total travel time in the hub network from total travel time in a direct point-to-point network, where the passengers’ value of time (VOT) and the schedule delay in hubs are also investigated. VOT is important because passengers with high VOT are more sensitive to the quality of services, such as service time in hubs and travel time in routes. Hence, if an airline provides services with a high delay time in hubs or on routes, these passengers are more likely to receive services from other airlines, which consequently contracts the airline market share.

2.3. Contributions. The main contributions of this study to the literature are as follows:

(i) Fleet planning is studied simultaneously with hub location in an integrated problem.

(ii) Two new objective functions are considered for the proposed HLP: (1) minimizing total operational and fleet planning (i.e., fleet purchasing) costs and (2) minimizing the subtraction of total travel time in the hub network from total travel time in a direct point-to-point network, where the passengers’ VOT and the schedule delay in hubs are taken into account.

(iii) Determining flight frequency and aircraft type for airline network routes in the proposed biobjective HLP.

3. Problem Definition and Formulation

This study presents a biobjective uncapacitated single allocation HLP for a global air passenger network to satisfy passengers’ preferences. The proposed objective functions include: (a) minimizing the airline costs, including transportation costs and expenses of purchasing aircraft, and (b) minimizing costs incurred by the passengers due to the delay in routing and the use of HS network. In the designed global HS network, passengers on OD pairs may be scheduled for an indirect flight with an intermediate stop in a hub airport. To estimate the costs incurred by the passengers, the passengers’ VOT in each OD pair is also considered. The model aims to find the optimal HS network configuration and the optimal fleet size, where the aircraft type, load factor, and flight frequency for servicing network flows are determined.

3.1. Mathematical Formulation. Before introducing the model, the mathematical notations, including sets and indices, input parameters, and decision variables, are presented in Tables 3–5.

The proposed mathematical model is a mixed integer nonlinear model that is converted into a mixed integer linear model by the linearization of nonlinear terms. The initial mixed integer nonlinear model is as follows:
Table 1: Summary of HLP recent studies in the aviation industry.

<table>
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<th>Reference</th>
<th>Scope of contributions</th>
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\[ O_1 = \min \sum_{i \in N} \sum_{k \in N} \sum_{s \in S} \sum_{l \in L} C_{ik}^s Z_{ikl}^s + \sum_{k \in N} \sum_{j \in N} \sum_{s \in S} \sum_{l \in L} C_{kj}^s Z_{kjl}^s + \sum_{s \in S} n_{new} \cdot CP_s \]  

\[ O_2 = \min \sum_{i \in N} \sum_{j \in N} \sum_{k \in N} \sum_{l \in L} \left( t_{ik} + t_{k_j} - t_{ij} \right) X_k VOT_{ij} h_{ij} + \sum_{i \in N} \sum_{j \in N} \sum_{l \in L} SD_{ij} \cdot VOT_{ij} h_{ij} \]
Objective 1 \( (O_1) \) minimizes the total operational cost of the airline, which is comprised of three terms. The first and second terms denote routing operational costs from origins to hubs and from hubs to destinations, respectively. The third term indicates the cost of purchasing new aircrafts. Objective 2 \( (O_2) \), which minimizes the total delay imposed on passengers, includes two terms. The first term represents the on-route delay caused by taking an indirect flight with a stop in a hub airport as opposed to a direct flight. It is calculated from the difference between the direct trip time and HS trip time multiplied by the number of passengers and their VOTs. The second term represents the waiting time of passengers in the hub airport to receive service, which is called scheduling delay (SD). Also, passengers’ VOTs are multiplied by SD.

Equation (3) ensures that only one hub node in the network is selected. Equations (4) and (5) ensure that nodes \( i \) and \( j \) can only be allocated to the located hub airport.

\[
\sum_{k \in N_i} X_k = 1, \quad \forall i \in N
\]  
(3)

\[
Z_{ik}^k \leq M \times X_k, \quad \forall i \in N, \forall k \in N_1, \forall s \in S, \forall l \in L,
\]  
(4)

\[
Z_{kj}^{ls} \leq M \times X_k, \quad \forall j \in N, \forall k \in N_1, \forall s \in S, \forall l \in L.
\]  
(5)

Equations (6) and (7) guarantee passenger flow in the hub-and-spoke network. Equation (6) ensures that the passenger flow is established from all origins to the hub and equation (7) ensures that the passenger flows are maintained from the hub to all destinations.

\[
\sum_{k \in N_i} \sum_{s \in S} \sum_{l \in L} p_i Z_{ik}^{ls} q^l = \sum_{j} h_j \forall i,
\]  
(6)

\[
\sum_{k \in N_i} \sum_{s \in S} \sum_{l \in L} p_i Z_{kj}^{ls} q^l = \sum_{j} b_j \forall j.
\]  
(7)

Equations (8)–(11) represent a range restriction. According to equations (8) and (9), short-haul and medium-haul aircrafts are not allowed to service long-flight legs, and based on equations (10) and (11), short-haul aircrafts are not authorized to service medium-flight legs.

\[
\sum_{l \in L} \sum_{s \in \{1, 2\}} Z_{ik}^{ls} q^{\alpha} = 0, \quad \forall i \in N, k \in N_1, a = 3,
\]  
(8)

\[
\sum_{l \in L} \sum_{s \in \{1, 2\}} Z_{kj}^{ls} q^{\alpha} = 0, \quad \forall j \in N, k \in N_1, a = 3,
\]  
(9)

\[
\sum_{l \in L} \sum_{s \in \{1\}} Z_{ik}^{ls} q^{\alpha} = 0, \quad \forall i \in N, k \in N_1, a = 2,
\]  
(10)

\[
\sum_{l \in L} \sum_{s \in \{1\}} Z_{kj}^{ls} q^{\alpha} = 0, \quad \forall j \in N, k \in N_1, a = 2.
\]  
(11)

Equation (12) calculates the frequency of flights departing from origin \( i \) and arriving at hub \( k \), and equation (13) computes the frequency of flights departing from hub \( k \) and arriving at destination \( j \). In the selected hub airport for each OD pair (e.g., \( i \) to \( j \)), SD is estimated by equation (14), which is commonly used for SD estimation in the literature [7, 39–41]. Equation (15) makes sure the frequency of flights departing from each origin node is suitable and competitive. In this relation, \( F_{ij} \) is the biggest flight frequency between \( i \) and \( j \) offered by the other airlines.

\[
f_{i}^{\text{depart}} = \sum_{k \in N_1} \sum_{s \in S} \sum_{l \in L} f_{ik}^{\text{ls}}, \quad \forall i \in N,
\]  
(12)

\[
f_{j}^{\text{arrival}} = \sum_{k \in N_1} \sum_{s \in S} \sum_{l \in L} f_{kj}^{ls}, \quad \forall j \in N,
\]  
(13)

\[
SD_{ij} = \frac{T}{4 \times f_{\text{arrival}}} \forall i, j \in N,
\]  
(14)

\[
f_{i}^{\text{depart}} \geq F_{ij}, \quad \forall i, j \in N.
\]  
(15)

Equation (16) accounts for the number of short-haul, medium-haul, and large-haul aircrafts in the designed hub networks. Equation (17) also determines the number of new aircrafts that must be purchased.

\[
\sum_{i \in N} \sum_{k \in N_1} \sum_{s \in S} \sum_{l \in L} f_{ik}^{ls} + \sum_{j \in N} \sum_{k \in N_1} \sum_{s \in S} \sum_{l \in L} f_{kj}^{ls} \leq n' \forall s \in S,
\]  
(16)

\[
n' - n'^{\text{new}} \leq n'^{\text{new}} \forall s \in S.
\]  
(17)

Finally, the variation range and type of decision variables are specified by equations (18)–(20).

\[
n', n'^{\text{new}} \in \text{integer}, \quad \forall s \in S,
\]  
(18)

\[
X_k \in \{0, 1\}, \quad \forall k \in N_1,
\]  
(19)

\[
Z_{ik}^{ls}, Z_{kj}^{ls} \geq 0, \quad \forall i, j, k \in N, s \in S, l \in L, i \neq j.
\]  
(20)

Equation (14) is nonlinear. The values of \( SD_{ij} \) are illustrated in Figure 1(a). Using piecewise-linear programming, the values of the equation are approximated by two linear functions represented by Equation (21) as illustrated in Figure 1(b).

\[
SD_{ij} = \begin{cases} 
-122 f_{\text{arrival}}^{j} + 1340 & \text{if } f_{\text{arrival}}^{j} \leq 12 \\
-0.57 f_{\text{arrival}}^{j} + 81 & \text{if } f_{\text{arrival}}^{j} > 12 
\end{cases} \forall i, j \in N \quad i \neq j.
\]  
(21)

However, since equation (21) is still nonlinear, it is linearized and replaced with equations (22)–(28).
Accordingly, objectives (1) and (2) are replaced by equation (29).

\[
\min \ w_1 \left( \frac{O_1 - O_{1\text{ideal}}}{O_{1\text{nadir}} - O_{1\text{ideal}}} \right) + w_2 \left( \frac{O_2 - O_{2\text{ideal}}}{O_{2\text{nadir}} - O_{2\text{ideal}}} \right)
\]

where \( w_1 \) and \( w_2 \) are weighting coefficients for the model’s objectives, which are determined by the intrinsic knowledge of the decision maker (\( w_1 + w_2 = 1 \)). \( O_{1\text{ideal}} \) and \( O_{2\text{ideal}} \) are the ideal solutions for the first and second objective functions, and \( O_{1\text{nadir}} \) and \( O_{2\text{nadir}} \) are the nadir solutions for the first and second objective functions, respectively. The mathematical model is solved using the commercial software GAMS/Cplex.

4. Case Study and Model Set-Up

To test this biobjective model, a real-world case study is conducted for the international flight network of Iran. The objective is to expand Iranian airlines’ operational span in the Middle East and increase their market share by designing an optimal HS network and fleet. Hence, we seek to locate the optimal hub airport in Iran and design the optimal fleet for the leading Iranian airline. Given that the Iranian airline is deemed as a newcomer and its services should be highly competitive, it needs to consider a competitive frequency for its flights and assess customer satisfaction by minimizing delay. Accordingly, the necessary data (i.e., input parameters) for the above model is prepared in the following.

(i) OD flow matrix

To form OD matrix \((h_{ij})\), the historical passenger flights originating from/destined to 30 different world countries are studied. These 30 countries have had the highest passenger traffic to/from Iran. Apart from Iran which has five nominated airports in OD matrix, other countries only have one nominated airport, and therefore, \( |N| = 34 \). The countries considered in the demand matrix and their airports are shown in Figure 2 and their details are tabulated in Table 6 [45].

OD flow matrix is designed for 2025. The volume of OD flows \((h_{ij})\) in these matrices are projected by equations (30) and (31) based on 2015 tourism data.
and the gross domestic product (GDP) of the 34 countries between 2000 to 2019.

\[
\begin{align*}
\beta_{ij} &= \frac{GDP_{i}^{2025} \times GDP_{j}^{2025}}{GDP_{i}^{2015} \times GDP_{j}^{2015}}, \quad \forall i, j \in N, (30) \\
h_{ij} &= \frac{1}{2} \beta_{ij} h_{ij}^{2015}, \quad \forall i, j \in N, (31)
\end{align*}
\]

where \( \beta_{ij} \) is a growth factor for volumes of OD flows in 2015, which is used to calculate the volumes of OD flows in 2025. \( GDP_{i}^{2015} \) and \( GDP_{i}^{2025} \) are GDP of country \( i \) in 2015 and 2025, respectively. GDP data for 2015 was taken from the World Bank's website, and 2025 GDP was estimated based on the regression of GDP data from 2000 to 2018. Accordingly, a half of the projected passengers flow between countries \( i \) and \( j \) in 2025 \( (\beta_{ij} h_{ij}^{2015}) \) is considered the airline's targeted OD flow matrix \( (h_{ij}) \) due to airlines' competition.

(ii) Fleet size

The in-service fleet of the leading airline in Iran consists of 13, 17, and 3 short-, medium-, and long-haul aircrafts. Hence, \( n_{1} \), \( n_{2} \), and \( n_{3} \) are equal to 13, 17, and 3 aircrafts, respectively.

(iii) Flight categorization

In the literature on air aviation, distances less than 2000 km, between 2000 and 5000 km and over 5000 km are considered as short-flight, medium-flight, and long-flight legs [46, 47]. Hence, \( \delta_{ij}^{m} \) is set based on this information.

(iv) Travel time

The travel time (i.e., flight duration) between airports is calculated from the cruise speed of aircrafts and air routes' length. The cruise speed of some aircrafts (long-, medium-, and short-haul aircrafts) are shown in Figure 3. As the figure depicts, the cruise speed of different aircrafts does not vary significantly. Therefore, the cruise speed of every aircraft is estimated at 800 km/h. As such, the travel time is derived by dividing distance by cruise speed.

(v) Maximum flight hours per year for \( s \)-haul aircrafts

Factors, such as return time, maintenance check (check A, B, C, and D), weather conditions, and the number of airline pilots lead to delays in aircraft flights, thereby limiting the number of real aircraft flight hours during the year. The average return time may vary from 30 to 60 minutes depending on
the aircraft size [48]. As for the maintenance check, check A is due after 65 fight hours, check B is required between 300–600 flight hours, and checks C and D are conducted yearly [49, 50]. According to the 2014 to 2018 statistics taken from MIT’s Airline Data Project, which was carried out for USA airline companies, the longest average daily block hour utilization for long-, medium-, and short-haul aircrafts were 13.02, 14.78, and 13.91 hours, respectively. Therefore, in this study, the maximum flight hours \((y^*)\) would be 4800, 5400, and 5000 hours per year for short-, medium-, and long-haul aircrafts, respectively.

(vi) Maximum seating capacity of s-haul aircrafts

One of the main features of an aircraft is its maximum seating capacity, which is variable between aircrafts. In this study, the average maximum seating capacity \(q^*\) for short-, medium-, and long-haul aircrafts is estimated as 80, 150, and 300 seats, respectively [51, 52].

(vii) Operational cost per seat kilometer for s-haul aircrafts

The operational costs are directly and indirectly determined by a number of factors, such as route length, aircraft usage, fleet size, and flight staff cost, among other things. In this study, the operation cost per seat kilometer for short-, medium-, and long-haul aircrafts is considered as 10 cents, 8 cents, and 4 cents, respectively [51, 52]. Hence, \(C^i_{ij}\) is estimated for each \(i\) and \(j\).

(viii) Competitive frequency

A new airline in the air passenger market needs to provide a fair and competitive frequency compared to other airlines in the market. Hence, if the new airline seeks to handle a significant portion of demand on each OD pair, it should set the frequency based on the service level of competitors. Hence, for each \(i\) and \(j\), \(F_{ij}\) is estimated based on the service level of various airlines derived from exploring several websites for booking flights, such as Travelocity, Expedia, and CheapOair. In fact, the travel frequency of each OD pair is estimated from flight schedules provided by the websites.

(ix) Cost of aircraft purchase

Fleet planning is a long-term strategic decision that can influence network performance for decades. The purchasing aircraft investment can affect the balance sheet of airlines for the next 10 to 15 years through depreciation costs, long-term debts, and interest rates. In this study, installment payment has been considered for payment of aircraft purchasing costs. To determine the price for long, medium, and short-haul aircraft, the average cost of purchasing a new aircraft from the factory (the list price of Airbus and Boeing aircraft companies) is used.

(x) VOT

In this study, VOT is estimated using the production-based method according to equation (32) [53].

\[
VOT^*_m = \frac{\text{GDP}^*_m}{A^*_m \times P^*_m}, \tag{32}
\]

where \(\text{GDP}^*_m\) is the gross domestic product of country \(m\), \(A^*_m\) is the average working hours per year in country \(m\), which is estimated at 2920 hours for all countries, and \(P^*_m\) is the average number of people employed in the country \(m\). \(\text{GDP}^*_m\) and \(P^*_m\) are calculated from the latest available data.
are based on the World Bank dataset. Figure 4 shows \( \text{VOT}_i \forall i \in N \), which is equal to \( \text{VOT}_j \forall j \in M \).

(xi) Load Factor

In this study, three discredited levels are considered for the load factor: maximum, half, and minimum. Hence, the \( \rho_i \) volume is equal to 1, 0.5, and 0.1 when 1 is set to its maximum, half, and minimum values, respectively. Table 7 outlines the initial values for the models' parameters.

5. Result and Discussion

In the model, the Imam Khomeini International Airport in Tehran was selected as the hub airport in all Pareto solutions. However, a sensitivity analysis was conducted to calculate the values of model’s objectives when another nominated airport (e.g., Isfahan International Airport, Mashhad International Airport, Tabriz International Airport, and Shiraz International Airport) is selected as the hub airport. Given that there are 11 scenarios for the weighting system in which \( \omega_i \) varies from 0.0 to 1.0 by an incremental step of 0.1, and 5 scenarios for the location of international airport, the model is solved for 55 scenarios. The raw output data obtained from solving the model is outlined in Table 8. Figure 5 demonstrates the Pareto fronts when each of the five nominated airports is selected as the hub airport.

As Figure 5 shows, the Pareto fronts of Shiraz International Airport and Tabriz International Airport are identical. Hence, they can be selected as the first alternative hub airport for Imam Khomeini International Airport by the government. Also, since the Pareto fronts of Isfahan International Airport and Mashhad International Airport are identical, these airports could be introduced as the second alternative hub airport for Imam Khomeini International Airport. The Pareto front for Imam Khomeini International Airport is approximated with several linear functions to demonstrate the percentage by which passenger costs (the second objective) will drop for a percent increase in the optimal value of the airline costs (\( Z_1^* \)). Equation (33) represents the Pareto front as a multisegment function.

\[
\frac{\partial Z_1}{\partial Z_2} = \begin{cases} 
-0.152 \left( R^2 = 1.00 \right) & \text{if } 00.0\% \leq \frac{\Delta Z_1}{Z_1^*} \leq 06.8\%, \\
-0.026 \left( R^2 = 1.00 \right) & \text{if } 06.8\% \leq \frac{\Delta Z_1}{Z_1^*} \leq 73.5\%, \\
-0.015 \left( R^2 = 1.00 \right) & \text{if } 73.5\% \leq \frac{\Delta Z_1}{Z_1^*} \leq 251\%, \\
-0.005 \left( R^2 = 1.00 \right) & \text{if } 251\% \leq \frac{\Delta Z_1}{Z_1^*} \leq 324\%, \\
-0.000 \left( R^2 = 1.00 \right) & \text{if } 324\% \leq \frac{\Delta Z_1}{Z_1^*} \leq 390\%.
\end{cases}
\]

where \( \frac{\partial Z_1}{\partial Z_2} \) is the percentage of changes in variable \( Z_1 \) for one percent of changes in variable \( Z_2 \), \( \frac{\Delta Z_1}{Z_1^*} \) is the range of variations in variable \( Z_1 \), and \( R^2 \) is the coefficient of determination.

According to the results, more than 6.8\% movement from the optimal solution for the airline costs will cause an insignificant improvement in the first objective. Hence, the optimal distance from the optimal solution for the airline costs should be between 0\% and 6.8\%. This distance will improve passenger costs by nearly 15 percent.

In the optimal solution, when Imam Khomeini International Airport is selected as the hub airport, the following numbers of aircrafts are required, as shown in Figure 6.
Table 7: Initial values of the model’s parameters.

<table>
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<tr>
<th>Parameter definition</th>
<th>Initial value</th>
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<tbody>
<tr>
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<td>Aircraft type</td>
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<td>Flight cost from $i$ to $j$ by aircraft type $s$ ($C_{ij}^s$) (cent)</td>
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<tr>
<td>Cost of purchasing an aircraft of type $s$ ($CP^s$) (million $)</td>
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<td>Maximum seating capacity of an aircraft of type $s$ ($q^s$) (passenger)</td>
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<td>Maximum fight hours of an aircraft of type $s$ ($c^s$) (hour)</td>
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<td>Number of aircrafts of type $s$ currently owned by the airline ($n^s$) (number)</td>
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<td>Demand flow from $i$ to $j$ ($h_{ij}$) (passengers)</td>
<td>A binary matrix</td>
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<td>VOT of passengers planning to travel from $i$ to $j$ ($VOT_{ij}$) ($)</td>
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<tr>
<td>A desirable frequency from $i$ to $j$ to stay competitive ($F_{ij}$) (number of fights in a year)</td>
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<td>Travel time from $i$ to $j$ ($t_{ij}$) (hour)</td>
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<td>Load factor volume for index ($\rho$) (no dimension)</td>
<td>Full Capacity $\rho = 1$, Half - capacity $\rho = 0.5$, minimum capacity $\rho = 0.1$</td>
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<td>Desired time horizon ($T$) (hour/year)</td>
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Note: A binary input parameter, which is equal to 1 if the flight leg from $i$ to $j$ is a a-flight leg ($\delta_{ij}^s$) (no dimension).
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Note. IKIA is Imam Khomeini International Airport, SIA is Shiraz International Airport, TIA is Tabriz International Airport, IIA is Isfahan International Airport, and MIA is Mashhad International Airport.
As the figure shows, with a decrease in the weight of the first objective (airline costs), the total number of short-, medium-, and long-haul aircrafts increases. Hence, if the airline intends to decrease passenger costs, it should raise the number of aircrafts in its fleet but this growth is not uniform and keeps fluctuating. If the diagrams of this figure are combined with the optimal passenger costs in the Pareto front of Imam Khomeini International Airport, the increased number of fleets can be divided into three ranges. In the first range, where the weight is between 0.7 and 1, the fleet expansion seems justifiable, so that the addition of 15 long-haul, 40 medium-haul, and 37 short-haul aircrafts on average will reduce passenger costs by 20 percent. This growth fleet expansion is practicable and logical for the airline due to passenger convenience and satisfaction. In the second range, which covers 0.5 to 0.7 weight of the first objective ($w_1$), there is a significant increase in the number of fleets, particularly in medium and long aircraft. Accordingly, adding 300 long-haul, 260 medium-haul, and 50 short-haul aircrafts on average would cut passenger costs by 50 percent. In the third range, where $0 \leq w_1 \leq 0.5$, the passenger’s objective function has a greater weight, the fleet is expanded significantly, and there will be 568 long-haul, 370 medium-haul, and 67 short-haul aircrafts on average would cut passenger costs by 50 percent.
approximately. It is clear that the second and the third ranges do not present an appropriate choice for the airline due to the large number of feets imposed on the airline. In addition, the number of short-haul aircrafts has a low tolerance between 37 and 67 on average; therefore, the airlines are advised to avoid huge investments in purchasing short-haul aircrafts.

As shown in the Figure 7, in all alternative hubs (the first and second alternatives), long-haul aircrafts surpass the number of medium-haul aircrafts and the medium-haul aircrafts outnumber the short-haul aircrafts. Also, the diagram of long-haul aircrafts encloses that of medium-haul aircrafts and the same rule applies to the diagram of medium-haul and short-haul aircrafts. In addition, the number of long-haul aircrafts does not vary by changing alternative hubs (especially in the first alternative hub where the maximum number of long-haul aircrafts is about 800). Also, by increasing the weight of the first objective, the number of long-haul aircrafts would take a gradual downturn but the number of short-haul aircrafts, dependent on the alternative hub, follows a particular pattern in the alternative hub.

Another major characteristic of the obtained Pareto solutions is the average load factor for short-, medium-, and long-haul aircrafts as shown in Figure 8.

As shown in Figure 8, by decreasing the weight of the first objective (airline costs), the average load factors of different types of aircrafts drop. It suggests that should the
Figure 8: Average load factor for different types of aircrafts in each Pareto solution (Imam Khomeini International Airport).

Figure 9: Continued.
airline decides to prioritize optimization of the second objective (passenger costs) over the first objective (airline costs), it needs to decrease the aircraft load factor due to the increase in the number of aircraft’s empty seats. This reduction can be categorized into three ranges. In the first range, when $0.7 \leq w_1 \leq 1$, the average load factor for long- and medium-haul aircrafts is larger than 0.9. Also, for short-haul aircrafts, the average load factor is greater than 0.6. In the second range, where the weight of the first objective ($w_1$) is between 0.5 to 0.7, the average load factor for long-, medium-, and short-haul aircrafts is 0.6, 0.6, and 0.4, respectively. In the third range, where $0.5 \leq w_1 \leq 0$, the average load factor for all three types of aircrafts drops to 0.4. As the figure shows, the declining average of load factors for long- and medium-haul aircrafts is gradual while the load factor of short-haul aircrafts tolerance is approximately between 0.6 and 0.4. In addition, the second and third ranges are not economical for the airline due to the number of the aircraft’s empty seats (40% to 60% capacity) though it can save 50 to 80 percent of passenger costs (the second objective). Hence, the airlines are recommended to avoid setting the weight of the first objective to less than 0.7.

Moreover, as Figure 9 shows, in all alternative hubs, by increasing the weight of the first objective (airline costs), the load factor surges for long- and medium-haul aircrafts. As demonstrated by Figures 7 and 9, increasing the weight of the first objective (airline costs) will reduce the total number of medium- and long-haul aircrafts, which will lead to a high load factor (in all of the alternative hubs, where $0.8 \leq w_1 \leq 1$, medium- and long-haul aircrafts are approximately at full capacity). Also, the diagrams of load factor of long- and medium-haul aircrafts have identical patterns (especially for Shiraz, Tabriz, and Mashhad international airports), but it is not the case for short-haul aircrafts even if the weight of the first objective is high. For example, in Isfahan international airport, where $w_1 = 1$, the maximum load factor of short-haul aircraft is 0.8.

Table 9 indicates a summary results of the average load factor and the number of aircrafts of different types (short-haul, medium-haul, and long-haul) in each Pareto solution for 55 scenarios related to 5 candidate airports (Imam Khomeini International Airport, Shiraz International Airport, Tabriz International Airport, Isfahan International Airport, and Mashhad International Airport).
Table 9: Summary of the numerical results related to the number of fleets and average load factor.

<table>
<thead>
<tr>
<th>Number of fleets</th>
<th>Imam Khomeini International Airport</th>
<th>Shiraz International Airport</th>
<th>Tabriz International Airport</th>
<th>Isfahan International Airport</th>
<th>Mashhad International Airport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-haul</td>
<td>443</td>
<td>54</td>
<td>63</td>
<td>880</td>
<td>463</td>
</tr>
<tr>
<td>Medium-haul</td>
<td>178</td>
<td>175</td>
<td>798</td>
<td>384</td>
<td>770</td>
</tr>
<tr>
<td>Long-haul</td>
<td>80</td>
<td>98</td>
<td>93</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>Average load factor</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

0.0 0.39 0.1 0.23 0.18 0.41 0.14 0.24 0.15 0.18 0.32 0.11 0.1 0.1
0.1 0.28 0.37 0.4 0.3 0.29 0.3 0.42 0.21 0.22 0.2 0.23 0.32 0.1 0.47 0.6
0.2 0.29 0.37 0.24 0.44 0.36 0.42 0.21 0.21 0.31 0.31 0.4 0.18 0.46 0.52
0.3 0.3 0.39 0.4 0.25 0.43 0.4 0.43 0.23 0.25 0.35 0.45 0.49 0.2 0.49 0.4
0.4 0.33 0.38 0.47 0.27 0.45 0.4 0.4 0.25 0.31 0.41 0.45 0.34 0.33 0.51 0.47
0.5 0.44 0.46 0.46 0.48 0.49 0.53 0.4 0.5 0.49 0.55 0.31 0.58 0.57 0.38
0.6 0.63 0.65 0.68 0.51 0.51 0.47 0.56 0.67 0.71 0.75 0.79 0.35 0.68 0.61 0.57
0.7 0.87 0.92 0.51 0.58 0.62 0.55 0.66 0.9 0.75 0.95 0.8 0.45 0.91 0.67 0.6
0.8 0.94 0.94 0.68 0.94 0.94 0.64 0.94 0.94 0.8 0.94 0.94 0.45 0.88 0.93 0.78
0.9 0.98 0.98 0.63 0.98 0.98 0.8 0.98 0.98 0.85 0.98 0.98 0.71 0.92 0.98 0.8
1.0 0.99 1 0.84 1 1 1 1 1 0.99 0.95 1 1 0.8 0.97 0.99 0.85
6. Conclusion

This study proposed a biobjective hub network design model to design global air passenger networks. Poor passenger service, inconvenience, and dissatisfaction may lead to network breakdown. Hence, this study adopted a user-system approach to design global air passenger networks wherein two conflicting objectives of the users and the system (i.e., passenger costs and airline costs) are optimized. The passenger cost is a function of scheduling delay and time delay in the designed hub network. The airline cost is also a function of routing costs for different types of aircrafts and the cost of purchasing new aircrafts of various types. In this study, as a case study, the model was solved for a leading Iran international flight network to identify the optimal HS network and fleet in order to expand its operational span in the Middle East region and increase its market share. Solving the model and evaluating the results yielded the following insights:

(i) Imam Khomeini International Airport should be selected as the global hub airport for Iran international flight network. Otherwise, the best alternatives would be Shiraz International Airport and Tabriz International Airport.

(ii) Distancing up to 6.8% from the optimal solution for airline costs will significantly reduce passenger costs (nearly 15%).

(iii) Giving priority to the optimization of passenger costs over airline costs will increase the frequency of flights with medium and low load factors in HS network. In this regard, the results suggested that to reduce the number of flights with a low load factor, the airline costs should be twice as important as the passenger costs.

This study had a number of limitations that could be addressed in future research. First, here, the tourist dataset was used to identify the flight demand between countries. Future studies can explore other means of data collection, such as flight statistics released by leading international airlines. Second, the model’s parameters (e.g., demand as well as travel cost and time) are deterministic but uncertain in nature. Therefore, it is recommended that future research addresses this uncertainty. As another suggestion, incorporating the probability and consequences of disruptions in HS modelling approach can provide a robust HS network that is protected against unforeseen disasters. It should be noted that the proposed model is a single-period HS network design; hence, further research can be performed on its development into a multiperiod HS network design model. Moreover, statistical analysis can be incorporated into the proposed approaches [54–56]. Also, various machine learning methods and optimization algorithms are also recommended for further investigation in future research [57–60].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

In this study, Iranian governmental organizations have not been partners and sponsors, and this study is purely studious.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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