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RESEARCH

Selection of Secondary Hub Airport Location Based on Connectivity and Green Airport Solutions

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Abstract

The air transport systems can be represented as a network where airports serve as nodes and flight paths as links. The degree of connections between airports is defined as connectivity in air transport. With the increasing competition environment after liberalization in the air transport sector, the connectivity of airports is becoming an increasingly important issue. Thanks to Türkiye's advantageous geographical situation, and the hub and spoke system applied to the network structures of the airline companies operating, the city of Istanbul has become a major transfer point. However, considering the increasing demand for air transport, population growth, tourism and trade volume, capacity constraints of airports, and existing and ongoing transport infrastructure investments, it is considered that the establishment of a polycentric network structure in Türkiye will increase the connectivity in air transport. In this study, in order to contribute to the development of the multi-center air transport model; a hub location selection model has been developed considering the factors affecting the connectivity of airports. GAMS software was used for model solution. In order to measure high-speed train accessibility, green airport applications and the effects of the Covid-19 pandemic, different scenarios were produced, and the solution results were evaluated.

Keywords Hub airport · Hub location problem · Hub and spoke network structure · Airport connectivity

1 Introduction

Airports play an important role in increasing accessibility by connecting various locations in a limited time. Air transport system is a network structure in which airports are symbolized as nodes and routes between airports as links. The degree

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to which the nodes in this network are connected to each other is also defined as the connectivity (Burghouwt and Redondi 2013). A flight network consists of a cluster of interconnected airports. These airports are nodes or points and the routes between them are connections (Zhang et al. 2017). While the service provided directly between two airports is defined as direct connectivity, the service provided through hub airports is defined as indirect connectivity. Airport connectivity, which indicates the capacity of an airport to connect to other regions, is the sum of direct and indirect connectivity (Fig. 1). Hub connectivity is defined as the number of connecting flights departing from a hub airport, considering the shortest and longest connection times and the quality of connections served. Hub connectivity is defined as the number of connecting flights departing from a hub airport, taking into account the shortest and longest connection times and the quality of connections served. (ACI EUROPE 2019).

Access to more airline connections is essential for a country or city to develop economic ties with the rest of the world. Airline connections form the basis of international mobility of passengers and goods and are therefore a vital engine of economic growth worldwide (IATA 2020).

1.1 Factors Affecting Airport Connectivity

Factors affecting airport connectivity can be listed as economy, tourism, infrastructure capacity, connection to other transit modes, geography and socio-demographic structure.

Economy As connections with the global air transport network increase, job opportunities increase, resulting in better access to international capital markets and qualified human resources. As the business market improves, the economy grows, which encourages further increases in air transport demand and airline connections, providing another positive impact for growth in economic productivity (IATA 2020). Connectivity and economy have a mutual effect in air transport.

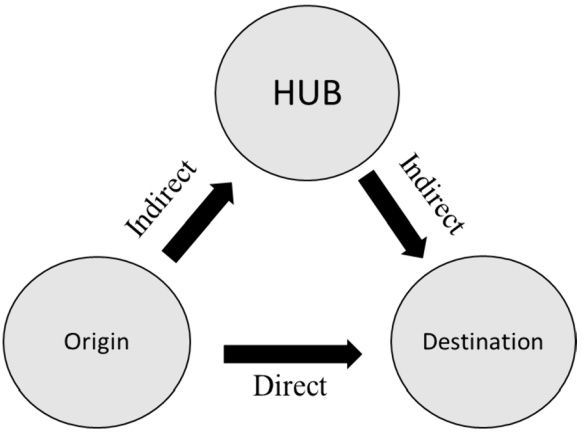


Fig. 1 Connectivity types

Tourism Air transport is an indispensable element for tourism. Airline connections expand markets and provide greater access to international hubs. Globally, 54% of international tourists travel by air (IATA 2020).

Infrastructure Capacity It is essential for an airport to have sufficient capacity to provide new connections. The lack of sufficient capacity of airports growing with central connections makes it difficult for existing airlines to find room to expand for new routes and for new airlines to enter the market, causing delays in flights and negatively affecting the growth of the traffic network. The limited capacity of the hub airports leads airline companies to longer-distance flights, which are more profitable routes. Domestic flights outside the main population centers are adversely affected by this situation. The size of the domestic market increases the passenger demand, so the loss of short-haul routes makes it difficult for the airline flight network to grow. In this direction, the development of the air transport infrastructure is an important issue both to ensure the development of the demand base of the local market and to establish new connections in international markets.

Connection to Other Transit Modes While most studies in the literature focus on the connectivity of only one mode of transport, many countries have several major modes of transport that complement each other. The development of high-speed train services over long distances and the connection of highways with city centers increase the competition between different types of transportation modes. Many studies show that high-speed train and airway transportation are alternatives to serve on the same route.

Although most studies show that high-speed trains are the predominant mode of transport only for distances under 700 km and for short and medium-haul routes, high-speed trains in China have become the better and dominant option over air transport for routes up to 1300 km (Zhu et al. 2017). In Europe, high-speed trains reduce demands for air travel on some routes. Eurostar trains connecting from London to Brussels, Paris, Lyon and Amsterdam carry half of the market traffic, reducing the density of airports reaching the capacity limit. In China, it is planned that some of the airline traffic will be shifted to Tianjin and Shijiazhuang airports due to the crowded airports in Beijing, and these cities will be connected to Beijing by high-speed train (Zhang et al. 2017). While the replacement of high-speed trains by air transport is a threat to the connectivity of airports, the planning of high-speed train and airport infrastructures in a way that complements each other is an opportunity that can alleviate the traffic of large hub airports with capacity problems or increase the passenger base of relatively smaller airports.

Geography Geographical location predominantly determines the characteristics of a country's air transport market, such as being a domestic market, an international market, or a transit hub for global traffic flow (PwC 2014). The geographical location of an airport is an important factor in terms of the quality of the routes it

provides and the connection time. A favorable geographical location is an advantage in terms of expanding the connectivity of airports.

Socio-demographic Structure Population influences the potential market size of a city, which is important for its attractiveness for tourism and business (PwC 2014). A city's level of connectivity depends on its population size. Regions with larger populations are naturally tied to more destinations and offer more seats (IATA 2020). In addition, as the population whose income level is above a certain level grows, the demand for air transportation increases. The study conducted by PwC (2014) to investigate the relationship between gross domestic product (GDP) per capita and air travel for approximately 200 countries shows that as GDP increases, flights increase.

With the increasing demand for air transport, operational efficiency and connectivity are becoming more important issues. Connecting the airports with the minimum number of connections and minimum connection time can be a factor affecting passenger demands.

Due to the competitive dynamics and economic factors that emerged with the liberalization in air transport, airline carriers have started to use the hub and spoke system in their flight networks. In the hub and spoke system, flights from different starting points to the same destination or from the same starting point to different destinations are collected at a transfer point called the Hub Airport.

1.2 Hub and Spoke System and Hub Airports

The most profitable routes from the air transport network are large markets where there is sufficient demand, but demand for direct flights is often insufficient for these markets. For this reason, airline companies have developed a hub and spoke system for their operations. This system has started to be implemented as a strategy by airline companies due to its effect on reducing airline transportation costs (Sugiyanto et al. 2015). Borenstein's (1989) study on the competitive conditions and economic factors that lead airline companies to the hub and spoke network structure showed that more efficient use of resources is ensured because fewer connections are sufficient to connect the points in the transportation network.

The hub and spoke network structure allows users to reach their destinations by transferring over a large central location (Sugiyanto et al. 2015). Regional air traffic and transfer traffic are combined at these major centres. Centers providing transfer point service have revealed the concept of hub airport, which can be located in different regions. The competitiveness of a hub is a joint result of the competitive strategies of airports and airlines (Redondi et al. 2011). Hub airports also benefit from the advantages of connectivity while facilitating the operations of airlines. However, there are special infrastructure requirements in order to carry out the center operations. Criteria such as geographical location, airport service quality, airport facilities, peak hour capacity, traffic rights portfolio for international flights and airport accessibility are important for the development of airports as a hub. Therefore,

relatively few airports have sufficient capacity for core operations of large airlines. Each new route added to the hub airport by the airline companies operating in the hub airport offers different connection possibilities that can be realized through the center. However, when a hub airport loses its function, it is not easy to regain it (Redondi et al. 2012).

1.3 Multi-Centered Transport Network

Hub and spoke system has the advantage of collecting air traffic at a single point for the activities of airline companies. However, in case the capacity of the airport designated as the hub starts to become insufficient, secondary hubs are used in order to continue the growth in the market. In this case, it is preferable to distribute airport traffic instead of building a secondary center to increase the capacity utilization of existing airports.

In case of multiple airports in the same region, high flight frequency at primary hubs attracts passengers, but delays in flights, long queues and high parking fees create opportunities for secondary airports (Zhang et al. 2017). However, competition between airports in the same region can adversely affect the relationship between connectivity and the local market. A single airport serving in a particular area is more advantageous than having more than one airport serving in the same market.

The simulation study carried out by Adler and Berechman (2001) revealed that the polycentric network structure is more profitable if implemented with effective geolocation. Similarly, the study by Düdden (2006) showed that effectively planned multi-center network structure maximizes profit.

Lufthansa airline has a 6-based network structure with Frankfurt, Munich, Berlin, Dusseldorf, Vienna and Zurich airports. Frankfurt is one of the three largest airports in Europe with an annual passenger capacity of 64 million. With an annual passenger capacity of 39 million, Munich is Germany's second largest airport. Düsseldorf, Vienna and Zurich serve with shorter transit times than other hubs, and Düsseldorf airport has more than 300 train connections. Berlin airport was added as a hub in 2020.

1.4 Sustainable Transport Network

Sustainability is becoming a growing concern, especially for companies and their operations. Consumers tend to buy the products/services they demand from environmentally friendly/responsible companies. However, successful adoption of sustainability in companies requires integrating sustainability issues into their strategies and policies. On the other hand, one aspect of incorporating sustainability into strategic activities and policies takes sustainability into account in long-term network planning (Mohammadi et al. 2014).

A transport network plays a key role in designing a sustainable logistics network. Transportation has a wide range of different environmental impacts such as resource consumption, land use, noise and greenhouse gas emissions. Among these, especially greenhouse gas and CO_2 emissions and noise are the most worrying issues as they have direct effects on human health (Mohammadi et al. 2014). Due to the

growing concerns over such dangerous effects of transport on human health, planning for transport networks needs to be revised to clearly take such adverse effects into account.

Increasing population causes more economic growth and increased demand for transportation activities. Therefore, more efficient transport networks are needed to meet these increasing demands. On the other hand, considering environmental impacts in the design of transportation networks attracts the attention of customers and relevant supporting government agencies, increasing the marginal profits of each organization (Mohammadi et al. 2014).

2 Hub Location Problem - HLP

The first study in the field of node optimization with concepts similar to center location selection was published by Hakimi (1964), but it is assumed that the center location problem started to be discussed in the 1980s, since there was no study on this subject for the next 20 years (Hekmatfar and Pishvaee 2009). The first study was published by Toh and Higgins (1985), an application of the center location problem in airline companies and airports.

The hub location problem in air transport is concerned with the design of networks that provide effective and economical transportation of cargo, freight, passengers, services and information between supply and demand nodes (Duyguvar 2018).

Centers are facilities that act as integration, connection and switching points for flows between projected origins and destinations (Farahani et al. 2013). The epicenter location problem is about finding the central facilities and allocating demand nodes to the centers in order to route the traffic between the origin-destination nodes (Sibel and Kara 2008). The main distinguishing features of the epicenter location problem are as follows (Campbell and O'Kelly 2012):

- Demand relates to flows between start-target pairs, not individual points.
- Flows are allowed through central facilities.
- Centers are facilities to be located.
- It has the advantage of performing flows through a center.
- There is a purpose that depends on the location of the central facilities and the direction of the flows.

Hubs are implemented to reduce the number of transport links between the origin and destination nodes (Farahani et al. 2013). Thus, with a single-centered network structure, services can be provided more efficiently by using less resources than a fully connected network structure (Farahani et al. 2013).

The main disadvantage of such a system (with respect to all nodes except the central node) is that multiple trips are required to travel between each origin-destination pair, as we have to traverse the central node to be able to travel from one decentralized node to the other (Hekmatfar and Pishvaee 2009).

There are two basic types of core network structures; single assignment and multiple assignment. They differ according to how the decentralized nodes are allocated to

the centers. In a single assignment, incoming and outgoing traffic of all demand centers is routed through a single center. In multi-assignment, demand centers can receive and send flows through more than one center (Sibel and Kara 2008). In multicenter networks, it is assumed that the central nodes are completely interconnected and each non-central node is connected with at least one central node (Hekmatfar and Pishvaee 2009).

The cost of a hub network depends on its structure (Farahani et al. 2013). Classical HLP models are being developed to minimize the cost of center installation and total transportation cost in the network (Mohammadi et al. 2014). Depending on the decision maker's approach and need, the number of centers to be located in the network can be limited to a certain number, a certain capacity limit can be placed on the centers (capacity limited / no capacity constrained), and the central node to which other nodes can be connected can be single or multiple (single allocated / multi-allocated) (Duyguvar 2018).

O'Kelly (1986a, b, 1987, 1992) has an important place in the modelling of hub location problems and created the single-hub base location model. In this model, all nodes are connected to a single center node and the points are connected to each other through the central node. Later, *single allocation hub location selection models were* developed (Daskin 1995). In this model, the number of central nodes is fixed and decentralized nodes are connected to a center. Campbell (1991) developed a model whose objective function is linear, unlike previous models. In this study, which is called the *multi-allocation hub location model*, decentralized nodes can be connected to more than one central node. O'Kelly (1992) developed a fixed-cost hub location model in which the number of core nodes is not known beforehand by determining a *fixed cost for hub location selection* . Campbell (1994) introduced several models called the *p-hub median problem* by including the cost of connecting to the core node, the *uncapacitated hub location problem* by applying a minimum value exceeding condition for connections between decentralized nodes and core nodes, the *p-hub center problem* by applying a capacity limit for the core node and the *hub covering problems*, which determines the set of centers that minimizes the maximum cost of all starting and destination node pairs.

Although one of the main users of hub location models is the telecommunications industry, it is also widely used in air transport, public transport, and logistics sectors (Farahani et al. 2013). *Multi-modal hub location selection models*, which include the effect of more than one transportation mode, have started to be developed in recent years (Alumur et al. 2012). Duyguvar (2018) developed a model for logistics centers that includes airline, rail and port connections and covers all three dimensions of sustainability.

When the studies in the literature on the problem of hub location selection in air transport are examined in terms of model approaches, it is seen that the studies that consider the factors affecting the connectivity in air transport are limited. Studies in this area have mostly focused on a single point. Although studies that include the impact of other transportation modes and sustainability factors in the model have increased in recent years, they are still limited (Table 1).

In this regard, a hub location selection model, which takes social, economic and environmental factors into account, has been proposed in order to determine the most suitable secondary hubs in following Istanbul. In this study, in order to

contribute to the development of the multi-center air transport model; a hub location selection model has been developed considering the factors affecting the connectivity of airports. GAMS software was used for model solution. In order to measure high-speed train accessibility, green airport applications and the effects of the Covid-19 pandemic, different scenarios were produced, and the solution results were evaluated.

3 Methodology

In this study, a multi-objective mixed integer model is proposed, which aims to minimize the cost of hub development. The models in the literature have been expanded to take the social, economic and environmental sustainability factors affecting connectivity in air transport into account; such as socio-economic development index, accessibility to national markets, number of tourists, airline connections, air traffic, high-speed train accessibility and green airport applications. A multimodal hub location selection model was developed to include the constraints (Table 2).

3.1 Mathematical Model

In the proposed model, all cities with airports are determined as candidate nodes (xi) for the hub location model in order to determine the hubs that will be the transfer point for international flights, in addition a hub airport. The criterion for determining whether the city has an airport is set as a binary variable. Hub development costs are included in the model relatively in line with the capacities of the airports. Model assumptions and constraints are as follows:

- All criteria have equal priority.
- The number of airports planned to be developed as a center will be determined by the decision maker.
- Budget constraint, geographical accessibility factor, accessibility factor to national markets, socio-economic development factor, high-speed train accessibility factor, connectivity factor, flight volume factor, import factor, export factor, tourism factor and population factor will be determined by the decision maker.
- The centers to be determined will have access to at least one mode of transportation (railway or port) other than highways.
- Lines under construction are included when calculating high-speed train accessibility.
- The centers to be determined should have a green airport certificate in terms of fuel storage-supply, terminal and ground services.

The objective function, which minimizes the cost of developing the hub, is used (Eq. 1). The number of airports planned to be developed as a hub will be determined by the decision maker (Eq. 2). The sum of the central hub development costs of the hubs to be selected should be less than a budget to be

Table 1 Literature review

Study	Scope of Work
Toh and Higgins (1985)	The relationship between the centrality of the central network structure and airline profitability has been tested.
Shaw (1993)	The headquarters structures of the selected US airlines were examined and the results of the analysis of the hub location models were evaluated.
Aykin (1995)	Different aspects of network policies for air passenger and cargo transportation have been evaluated.
Jaillet et al. (1996)	The capacity-constrained and flow-based core site selection model was applied for 39 US cities.
Bania et al. (1998)	The services provided by the 13 largest US airlines were evaluated.
Sasaki et al. (1999)	A single transfer multiple allocation hub location model was developed and the CAB dataset was used.
Martin and Roman (2003)	A hub location model was developed for the South-Atlantic airline market.
Adler and Hashai (2005)	A demand-based hub location model has been developed to identify potential regional transfer points.
Eiselt and Marianov (2009)	The competitive location model based on the gravity model was formulated and the AP dataset was used.
Alumur et al. (2012)	Integer programming formulation was proposed for the multi-modal hub location model aiming at cost minimization and a sensitivity analysis was performed in the Turkish network.
Saberi and Mahmassani (2013)	The continuous approximation models are developed for airline operations in restricted and unrestricted single-hub systems
Oktal and Özger (2013)	Integer programming model has been developed for the air cargo transport hub and-spoke network structure.
Lüer-Villagra and Marianov (2013)	A hub location model was developed for the new airline company aiming to maximize its profit, and the CAB dataset was used.
An et al. (2015)	A single and multiple allocation hub location selection model has been developed for the hub-and-spoke network system.
Alibeyg et al. (2016)	A hub location model was developed that optimizes the profit, installation cost and transportation cost together.
Hoff et al. (2017)	A capacity-constrained hub location model, aiming to minimize transportation costs, was developed and CAB, AP, USA423 datasets were used.
Dukkanci and Kara (2017)	A hierarchical multimodal hub covering model was developed and analyzed in the Turkish network. The CAB dataset was used.
Torkestani et al. (2018)	For the multimodal dynamic network structure, a hub location model was developed and CAB, ARWN datasets were used.
Dukkanci et al. (2019)	A hub location selection model to minimize total amount of emissions was developed and CAB, TR datasets were used.
Taherkhani and Alumur (2019)	Central location model has been developed that allows direct routes and aims to minimize the total transportation cost, center establishment cost and operating cost.
Soylu and Katip (2019)	Two objective function hub location model, which aims to minimize the total transportation cost and two-transfer routes, has been developed and implemented for Türkiye.

Table 1 (continued)

Study	Scope of Work
Najya and Diabat (2020)	A capacity-free and multi-allocation hub location model was developed and CAB, AP datasets were used.
Tiwari et al. (2021)	A hub location model was developed for new airlines aiming to maximize their market share, and CAB, AP datasets w

determined by the decision maker (Eq. 3). Budget constraint, geographical accessibility factor, accessibility factor to national markets, socio-economic development factor, high-speed train accessibility factor, connectivity factor, flight volume factor, import factor, export factor, tourism factor and population factor will be determined by the decision maker. The average of geographical accessibility, average of accessibility to international markets, average of socio-economic development index and average accessibility of high-speed trains of the centers to be selected should be higher than the total average (Eqs. 4, 5, 6 and 15). The connectivity of the centers to be selected should meet the total amount of air traffic, import volume, export volume, number of tourists and population (Eqs. 7, 8, 9, 10, 11 and 12). The centers to be determined must have access to at least one mode of transportation (railway or port) other than the highway (Eq. 13). The centers to be selected must have a high-speed train connection (Eq. 14). Lines under construction are included when calculating high-speed train accessibility. The centers to be determined must have a green airport certificate in terms of fuel storage-supply and terminal and ground services (Eqs. 16 and 17).

Objective Function:

$$Min \sum_{i=1} x_i c_i \tag{1}$$

$$\sum_{i=1} x_i = n \tag{2}$$

$$\sum_{i=1} x_i c_i \leq B \tag{3}$$

$$\sum_{i=1} x_i g_i / n \geq g_{avg}(1 + f_g) \tag{4}$$

Table 2 Social, economic and environmental sustainability constraints

Social	Economic	Environmental
• Population	• Import volume	• Rail link
• Socio-economic development	• Export volume	• Port connection
• Geographical accessibility	• Number of tourists	• Fuel storage and supply
• Accessibility to national markets	• Airline connections	• Terminal management and ground handling services
• High speed train accessibility	• Aircraft traffic	

$$\sum_{i=1} x_i a_i / n \geq a_{avg}(1 + f_a) \tag{5}$$

$$\sum_{i=1} x_i se_i / n \geq se_{avg}(1 + f_{se}) \tag{6}$$

$$\sum_{i=1} x_i con_i \geq con_{sum} f_{con} \tag{7}$$

$$\sum_{i=1} x_i v_i \geq v_{sum} f_v \tag{8}$$

$$\sum_{i=1} x_i m_i \geq m_{sum} f_m \tag{9}$$

$$\sum_{i=1} x_i e_i \geq e_{sum} f_e \tag{10}$$

$$\sum_{i=1} x_i t_i \geq t_{sum} f_t \tag{11}$$

$$\sum_{i=1} x_i p_i \geq p_{sum} f_p \tag{12}$$

$$\sum_{i=1} x_i (r_i + l_i + 1) / n \geq M_{sum} \tag{13}$$

$$\sum_{i=1} x_i (tcon_i) / n \geq 1 \tag{14}$$

$$\sum_{i=1} x_i tr_i / n \geq tr_{avg}(1 + f_{tr}) \tag{15}$$

$$\sum_{i=1} x_i fsr_i / n \geq G_{sum} \tag{16}$$

$$\sum_{i=1} x_i tmgh_i / n \geq G_{sum} \tag{17}$$

$$xi : \{0, 1\} \tag{18}$$

Parameters

i Candidate cities with airports

x_i The hub to be located at node i (0 or 1)

c_i The cost of the hub to be located at node i

B	Total budget
n	Number of hubs to be established
g_i	Geographic accessibility index for node i
g_{mean}	Average level of geographic accessibility
f_g	Geographical accessibility factor [0-1]
a_1	Index of accessibility to national markets for node i
a_{mean}	Average level of accessibility to national markets
f_a	Accessibility factor to national markets [0-1]
se_i	Socio-economic development index
se_{mean}	Average socio-economic development index
f_{se}	Socio-economic development factor
con_i	Connectivity index for node i
con_{sum}	Total connectivity
f_{con}	Connectivity factor [0-1]
v_i	Flight volume of node i
v_{sum}	Total flight volume
f_v	Flight volume factor [0-1]
m_i	Import volume of node i
m_{sum}	Total import volume
f_m	Import factor [0-1]
e_i	Export volume of node i
e_{sum}	Total export volume
f_e	Export factor [0-1]

t_i Number of tourists

t_{sum} Total number of tourists

f_t Tourism factor

p_i Population of node i

p_{sum} Total population

f_p Population factor [0-1]

r_i Rail accessibility of node i (0 or 1)

l_i Port accessibility of node i (0 or 1)

M_{sum} Total transport mode

tr_i High speed train accessibility of node i

tr_{avg} Average level of high-speed rail accessibility

f_{tr} High speed train accessibility factor [0-1]

trc_i High speed train connection of node i (0 or 1)

fsr_i Fuel storage-replenishment (0 or 1)

$tmgh_i$ Terminal management-ground handling (0 or 1)

G_{sum} Total number of green certificates

3.2 Scenarios

Different scenarios have been applied to measure the effects of high-speed train connections, environmental factors and the Covid-19 pandemic.

The hub location model for all scenarios includes the following constraints and inputs in common:

- Two hubs with a capacity of 30 million passengers and 3 hubs with a capacity of 15 million passengers were determined.
- The budget has been determined as 20 billion Turkish Lira.
- The geographic accessibility average of the hubs to be determined was requested to be at least 10% higher than the average of all nodes.

- It was requested that the average of accessibility to national markets of the hubs to be determined should be at least 10% higher than the average of all nodes.
- The average socio-economic development index of the hubs to be determined was requested to be at least 10% higher than the average of all nodes.
- Air traffic of the hubs to be determined was requested to cover at least 10% of the total aircraft traffic.
- The hubs to be determined were requested to cover at least 10% of the total import volume.
- The hubs to be determined were requested to cover at least 10% of the total export volume.
- It was requested that the hubs to be determined should cover at least 10% of the total number of tourists.
- It was requested that the hubs to be determined should cover at least 10% of the total population.
- It was requested that the hubs to be determined should be connected to at least one more transportation mode other than the highway.

In Scenario 1, the presence of high-speed train connection was required, and the green airport application criteria were expected to be at least in the fields of fuel-storage-supply or terminal operation-ground services. In Scenario 2, the necessity of having a high-speed train connection is not taken into account. In Scenario 3, high speed train connectivity was not taken into account and green airport application criteria were requested to be met separately in the fields of fuel-storage-supply and terminal operation-ground services. Scenario 4 measures the effects of the Covid-19 pandemic. The differences between the scenarios are summarized in Table 3.

4 Case Study

Türkiye is a transit center with its geographical location advantage. Istanbul Atatürk Airport had improved its central connectivity by 353.3% and became the 4th Airport in Europe (ACI EUROPE 2019). The five largest airports in Türkiye in terms of passenger traffic; Istanbul Airport, Istanbul Sabiha Gökçen Airport, Antalya Airport, Ankara Esenboğa Airport and Izmir Adnan Menderes Airport.

Turkish Airlines uses Istanbul Airport as the hub airport in its flight network. Ranking second, Istanbul Sabiha Gökçen Airport is the transfer hub of Pegasus airlines. Thanks to the flight network strategies of these two airlines, Istanbul is the only hub in Türkiye. However, airports in Istanbul are struggling to meet the increasing demand for air transport. Considering the increasing population, developing tourism, trade volume and regional aviation, the development of a multi-center structure will contribute to increasing connectivity. In this direction, a site selection model is needed to determine the most suitable centers.

Table 3 The difference between scenarios based on constraints

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
The hubs are required to cover at least 10% of the total airline connections.	✓	✓	✓	
The average high-speed train accessibility of the should be at least 10% higher than the average of all nodes.	✓	✓		✓
Hubs should have a high-speed train connection.	✓			
Hubs should have a green airport certificate **in at least one of the** areas of fuel storage-supply or terminal operation-ground services. For large hubs, both are required, for small centers it is sufficient to meet at least one.	✓	✓		✓
Hubs should have green airport certificates in **both** fuel storage-supply or terminal operation-ground services areas.			✓	
The model was run using pre-pandemic data.	✓	✓	✓	
The model was run using post-pandemic data.				✓

4.1 Data and Model Solution

The inputs and results of the model, which is formulated as a mixed integer linear programming model, are precise and discrete. The input data is gathered from; Turkish Statistical Institute statistics (TURKSTAT 2021) for population data, Ministry of Development (Simsek 2015) data for geographic accessibility and accessibility to international markets, Ministry of Industry and Technology (2019) data for socio-economic development index, Ministry of Commerce (2021a, b) statistics for import and export volume data, Ministry of Culture and Tourism (2020) statistics for tourist numbers, State Airports Administration statistics for all airline traffic, connectivity values and green airport criteria regarding airports (DHMI 2020), General Directorate of Civil Aviation (DGCA 2019) and ACI EUROPE (2019) data and Ministry of Transport and Infrastructure (2020) data are used for rail and port connections. The cities with airports and ports are shown in Fig. 2.

High-speed train accessibility data were calculated using the population and distance matrix. The railway map of Türkiye is shown in Fig. 2. GAMS software was used to solve the model for different scenarios.

4.2 Results

The developed model was run through GAMS software by applying different scenarios. A summary of the Scenario solutions obtained with GAMS is given in Table 4.

The geographical representation of the results is shown in Fig. 3. The first scenario required all airports to be determined to have a high-speed train connection and it was accepted to meet at least one of the green airport applications. According to the results obtained, Ankara and İzmir were determined as the two high capacity centers, while Adana, Gaziantep and Konya were assigned as the other centers. At three of the designated airports, green airport applications are carried out in both areas. While the scenario has the highest values in terms of accessibility criteria, import volume (40%) and export volume (42.7%), it accounts for 38.9% of airline connections, 29.37% of air traffic, 17.7% of tourists. It has the lowest values among the scenarios determined by covering the country and 19.9% of the population. It also has the highest budget allocation.

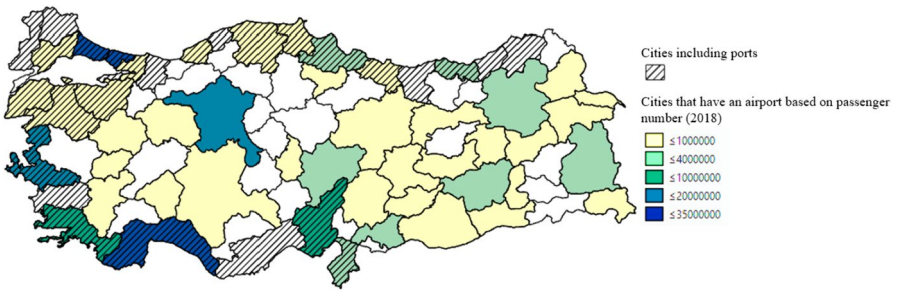


Fig. 2 Map of cities with airports and ports in Türkiye

Table 4 Scenario results

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Hubs with 30 million capacity	Ankara Izmir	Ankara Antalya	Ankara Antalya	Ankara Antalya
Hubs with 15 million capacity	Adana Gaziantep Konya	Adana Izmir Kayseri	Adana Erzincan Izmir	Adana Izmir Kayseri
Budget allocation (%)	86.25	58.75	65	58.75
Geographical accessibility (average 61.74)	76.3	74.9	71.48	74.9
Accessibility to national markets (average 15.61)	24.67	23.23	20.97	23.23
Socio-economic development (average -0.055)	1,183	1.44	1.3	1.44
Airline connections (%)	38.9	60.52	57.31	60.52
Aircraft traffic (%)	29.37	53.84	52.42	53.84
Import volume (%)	40	34.66	33.12	34.66
Export volume(%)	42.7	35.38	31.11	35.38
Number of tourists (%)	17.7	48.66	48.04	48.66
Population (%)	19.9	29.24	27.1	29.24
High speed train accessibility (average 41.15)	59.04	48.67	44	48.67
Other links	2 railways + port 3 railroads	2 railways + port 2 railroads 1 port	2 railways + port 2 railroads 1 port	2 railways + port 2 railroads 1 port
Green airport applications	3, in two areas 2, in one area	4, in two areas 1, in one area	5, in two areas	4, in two areas 1, in one area

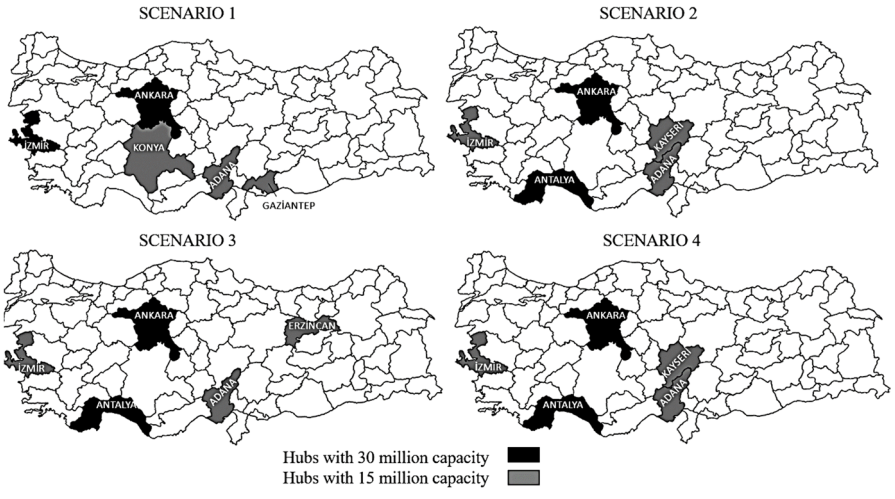


Fig. 3 Geographic representation of scenario results

In the second scenario, all airports to be determined are not required to have high-speed train connections, but high-speed train accessibility is taken into account. According to the results obtained, Ankara and Antalya were determined as two major centers, while Adana, İzmir and Kayseri were assigned as other centers. Green airport applications are carried out in both areas at four of the designated airports. The scenario has the highest values among the identified scenarios, covering 60.52% of airline connections, 53.84% of air traffic, 53.84% of tourists and 29.24% of the population. It also has the lowest budget allocation.

In the third scenario, the high speed train accessibility of the airports to be determined was not taken into account, but the airports to be determined were required to implement green airport practices in both areas. According to the results obtained, Ankara and Antalya were determined as two major centers, while Adana, Erzincan and İzmir were assigned as other centers. The scenario has the lowest values among the scenarios determined in terms of accessibility criteria and economic indicators. It covers 57.31% of airline connections, 52.42% of air traffic, 48.04% of tourists and 27.1% of the population.

5 Conclusion & Discussion

The liberalization of the airline industry in Türkiye has led to an increase in the demand for air transportation day by day. Istanbul, one of the fastest growing centers in the world, is Türkiye's center for international flights. For the connections established in the air transportation network to continue to growing, infrastructure is one of the most important elements. When capacity constraints at major airports begin to hinder growth in the transportation network, secondary hubs step in. It is anticipated that the difficulty experienced by the two major airports in Istanbul in meeting the rapid increase in demand will be met by the "Istanbul New Airport" project. However, considering the rapidly growing population, developing commercial connections and tourism industry and regional aviation activities, it can be seen that there is a need for further development in the air transportation infrastructure in Türkiye.

One of the elements that has the biggest impact on increasing connectivity in air transportation is regional aviation. Studies are continuing for the development of regional aviation in Türkiye. Aviation sector Transportation and Communication Target 2023 Strategies include ensuring that at least two regional airports, other than Istanbul Atatürk Airport, will be developed as main airports, serving as transfer centers for flights between the USA, Europe and Asia. In addition, it is aimed to build two airports with a capacity of 30 million and three airports with a capacity of 15 million. In addition to air transportation, Türkiye also makes significant investments in other transportation modes. Especially in the railway transportation sector, construction of high-speed train lines on new routes, as well as existing routes, continues.

The criteria to be taken into consideration when preparing air transportation network structure plans will greatly affect the operating performance of both existing airports and newly constructed airports. In this context, it seems that decision support models are needed to determine the most suitable transfer centers, taking into account the existing passenger potential, infrastructure and connection capacities. In

this direction, an epicenter location selection model has been developed to support decision makers in determining secondary hub airports after Istanbul in Türkiye. It is aimed to identify two airports with a capacity of 30 million passengers and three airports with a capacity of 15 million by ensuring the development of existing airport infrastructures as transit centers for international flights.

In this study, a hub location selection model has been developed to support decision makers in determining the secondary hub airports. In the developed model, the factors that affect the airport connectivity in air transport, which are determined in line with the literature review, are taken into consideration. Population, socio-economic development, accessibility, trade volume, tourism, transportation network connections, which affect the demand for air transport, were determined as inputs to the model. Accessibility is considered as access to both geographical and national markets. High-speed rail accessibility is also included, as it is thought that high-speed train connections will expand the airport demand. While calculating high-speed train accessibility, the lines under construction are taken into account. Import and export volumes were used as economic indicators, and tourist numbers were used for tourism. Airport connectivity values and all aircraft traffic are used for airline connections. The railway and port connections of the airports, which act as logistics centers, were also taken into consideration. Finally, as a factor to be considered in the planning of transportation networks due to their environmental impacts, the certification status of enterprises operating at airports as green organizations in fuel storage and supply, terminal management and ground handling services has also been determined as an input.

The developed model was run through GAMS software by applying different scenarios. The first scenario required all airports to be determined to have a high-speed train connection and was accepted to meet at least one of the green airport practices. While the scenario has the highest values in terms of accessibility criteria, import volume and export volume; it has the lowest values among the determined scenarios in terms of airline connections, aircraft traffic, number of tourists and population. It also has the highest budget allocation. In the second scenario, it is not mandatory for all airports to have a high-speed train connection, but high-speed train accessibility is taken into account. The scenario has the highest values among the determined scenarios in terms of airline connections, aircraft traffic, number of tourists and population. It also has the lowest budget allocation. In the third scenario, the high-speed train accessibility of the airports was not taken into account, but the airports to be determined were required to implement green airport practices in both areas. The scenario has the lowest values in terms of accessibility criteria and economic indicators among the scenarios.

It is seen that Ankara stands out in all scenarios with its accessibility, high-speed train connections, population, socio-economic development and trade volume. With the development of Ankara as a center, it is evaluated that both its direct connectivity with the increase in the number of daily connections and its indirect connectivity will increase thanks to the quality of the routes. The lack of high-speed train connection in Antalya, which has the largest airport in Türkiye after Istanbul, greatly affected the scenario results. The high level of passenger traffic and infrastructure adequacy made it possible to implement a lower cost and more comprehensive

scenario. İzmir, on the other hand, has come to the fore with its population and economic development. The fact that green airport practices are not yet implemented at all airports has also greatly affected the scenario results.

Decision maker's preferences will be effective in the selection of the appropriate scenario. The first scenario will be preferred when all airports are required to have a high-speed train connection, and the second scenario will be preferred when it is desired to reach a wider network with lower costs. The developed model includes factors that allow decision makers to include the desired criteria in the model to the desired extent. In the applied scenarios, it was preferred that the inputs of the centers to be determined should be higher than the average values at a certain rate. Considering the benefits, negative aspects and cost of the results obtained, Scenario 2 is considered to give a more appropriate result. The determined scenario covers a wider transportation network with less cost. In addition, the geographical location of the determined centers compared to each other gives more successful results. It is thought that the high-speed train line planned on the Konya-Adana-Gaziantep route, which is included in the first scenario results, may become a rival to the airports and adversely affect the airport connectivity. For this reason, in future studies, it was concluded that it would be beneficial to add the distance between centers to the model as a constraint, taking into account the passenger capacity, at the model stage.

Finally, the second scenario, which was determined as the most appropriate for measuring the impact of the Covid-19 pandemic, which greatly affected airline transportation, was re-run with post-pandemic data, but the results did not change. While travel for business purposes decreased, it is concluded that the increase in travel for tourism purposes or to visit relatives, especially in the summer months, has created this result.

In order for the development in the air transportation sector to continue to grow, a holistic approach to infrastructure investments should be provided and the development of intermodal transportation should be emphasized along with other transportation modes. Connections between transport modes should be improved and the development of common infrastructure should be supported. Increasing the accessibility of airports through investments in other transportation networks will contribute to a wider demand base, resulting in more efficient growth in connectivity. However, competition between different transportation modes on the same route can have a negative impact on connectivity. In this respect, it is important to plan investments to improve connections between different modes of transport in a way that will increase the accessibility of airports and reduce negative effects on connectivity. With the developed model, suggestions are presented to determine the airports that will be the secondary center after Istanbul, taking into account Türkiye's targets, infrastructure investments, socio-economic development, tourism and trade volume, high speed train accessibility, green airport applications and airport connections. Model inputs can be determined in line with the requests of the decision makers and can be used as a guide for transportation infrastructure planning. In future studies, different solution approaches can be developed in which different objective functions are used, the constraints determined as input to the model can be selected to be more detailed, and different criteria can be determined for environmental constraints.

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Availability of Data and Materials The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Competing Interests The authors declare no competing interests.

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