



# A combined approach using structural equation modeling and analytic hierarchy process in hub airports selection

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## ABSTRACT

This study presents a method to assist airlines in selecting a hub airport using Structural Equation Modeling (SEM) combined with Analytic Hierarchy Process (AHP). This approach aims to determine the most essential elements in this selection process using observed variables collected from 300 major airports worldwide. Research on key aspects for hub airport selection is still scarce in the literature. Furthermore, most studies rely on multicriteria analyses with weights obtained through expert interviews, potentially introducing subjectivity. Therefore, this paper presents a unique approach: criteria and sub-criteria values in the AHP are determined by the results achieved in the SEM, providing a reliable scale of priorities among variables in the process of choosing a hub. The SEM tested two hypotheses that were supported by comparing two latent variables related to airport and region characteristics with another latent variable referring to aspects present in the activity of the dominant airline within each facility. Subsequently, an AHP was implemented, with criteria and sub-criteria weights based on the standardized loading factors and regression coefficients from the SEM, using sets of airports for each established world region in the study. Results indicated that airport characteristics, particularly those related to the passenger terminals, have a greater influence on the main carrier activity than region characteristics. A regional analysis revealed that in the Americas, Europe, the Middle East, and Africa, this predominance is even more pronounced, whereas in Asia-Pacific region, there is a contrary trend in which the socioeconomic factors of the city appear to be more important than airport infrastructure. The weights assigned in the AHP, based on SEM values, confirmed cohesion between the two stages of the proposed model.

## 1. Introduction

The importance of hubs in the global passenger transport context is relevant since it is impossible to serve all possible routes by aircraft through direct connections. The hub's function is therefore essential for the distribution of flights and passengers in the air transport network, especially regarding more peripheral regions. For airlines, it is an operation gain as they manage to serve their entire range of destinations using fewer aircraft and, consequently, less crew. Another advantage is that adding a city to the network requires only one additional route. Carriers use hubs as a platform, usually located in the center of the region served, that combines all flights of smaller aircraft from medium-small cities in order to rearrange passengers to their final destination, which can be a medium-small city, a large city or another hub city. In the last two cases larger aircraft can be employed as the number of passengers per route increases and, because seating capacity increases

faster than operating and capital cost given the aircraft size, seat mile costs decline (Cook and Goodwin, 2008).

Regarding competition, hub airports rival airports around the world that also offer hub services, this means that the hub competition is not regional, but worldwide. Hence, the fact that any one hub is dominated by a single carrier does not constitute a monopoly position because people can opt for alternative routings (Button and Lall, 1999). Even for routes that are currently served by only one strong hub carrier, the existence of a competitor installing a well-placed hub will create a potential competition which can reduce fares (Huston and Butler, 1991). The pressure exerted by airlines alliances and codeshare flight agreements tend to generate more than one option for the connection between any given airport pair, thus creating an opportunity for airports to compete for hub roles (Redondi et al., 2011). The function of a hub can also vary according to the world region. Cheung et al. (2020) demonstrated that in North America and North Asia, hubs serve as central

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connectors in regional development, catering to short and medium-haul routes to address these demands. Meanwhile, in Western Europe, Southeast Asia, and the Middle East, the role of a hub involves being global platforms serving long-haul and international flights. Given the considerations presented, the hub selection by an airline becomes a decision-making process with various determining factors to be analyzed and several possible airports alternatives within the coverage area of its network.

Knowledge of the determining factors for the success of a hub airport is of paramount importance for governments and/or airport operators to avoid common pitfalls in their 'hubsession' (i.e., obsession to become a carrier hub). Selecting a hub is a market choice, not a government or operator choice, which makes the decision process even more complex, since it brings together interested stakeholders such as airlines and passengers. When analyzing successful hub cases around the world, such as Singapore and Dubai, strategically located at the crossroads of major trade flows, it is denoted that location alone is not the reason for the success of these cities in being a global hub, both governments provide well implemented air transport policies and strategies to develop tourism and their business (Lohmann et al., 2009). Therefore, it can be concluded that several aspects determine the potential of a hub and not just its geographical location. The global attraction of a region to become a hub can be expressed by quality and efficiency of public institutions; political and macro-economic stability; market accessibility; market potential; labor market attractiveness; geographical location attractiveness; and availability and quality of infrastructure (Essaadi et al., 2016).

The key aspects for selecting hub airports can be grouped into characteristics of the airport, particularly related to infrastructure and airport capacity, and characteristics of the region where the airport is located, such as socioeconomic factors and market attractiveness. This paper aims to examine the relationship between the two groups of characteristics listed in hub selection and the characteristics that identify whether a particular airport is a hub or not, in this study being attributed to the activity of the dominant airline operating in its facilities. The relationships and causalities among these three latent variables and between these and their respective observed variables are explained through Confirmatory Factor Analysis (CFA) followed by Structural Equation Modeling (SEM), using the software IBM SPSS AMOS version 28. The values found in the regression of the hypotheses of relationships between the latent variables and the loading factors of each observed variable were used as the basis for applying weights in multicriteria analysis through the Analytic Hierarchy Process (AHP), using the software SuperDecisions version 3.2 and carried out after this initial stage to choose potential hubs given sets of airports from the sample. A comparison analysis among world regions was also conducted to identify specificities in the hub selection process based on the continent where the airport is located. The study then addresses a new combined approach between SEM and AHP with the goal of finding the determining factors in hub selection without the possible subjectivity of expert opinions when assigning weights.

## 2. Background

### 2.1. Hub selection

Some studies addressed aspects involving hub selection. Huston and Butler (1991) reported that the hub airport must be in a position to provide convenient connections for numerous routes. Furthermore, demographic factors such as population and type of traffic can influence airline decisions when installing a hub. The authors also warned that even with central locations, abundance of area and a lower congestion, the absence of local traffic can make airports away from large urban centers unattractive to potential hub operators. Dennis (1994) identified three main factors when an airline installs its operations in a hub: (a) geographical location in relation to the markets served, (b) good airport

facilities and (c) feasibility of coordinating schedules. According to Martín and Román (2004), when an airline chooses where a hub should be located there are several factors to put on the scale, such as: (a) potential traffic generating at the hub cities, (b) central geographical location in relation to the markets served, (c) good airport facilities that allow an optimal coordination of schedules with minimum connecting time, (d) good weather conditions and (e) location of competitors' hubs and their strategic behaviors.

Uher (2005) mentioned that when choosing a hub an airline has to take into account important factors such as: (a) geographic position, (b) competition at the hub, (c) distance to an alliance or competitive hub, (d) connection with other modes of transport, (e) catchment area, (f) airport infrastructure – including competitive minimum connecting time, shopping facilities, lounges, hotels, check-in counters, distance to own catering logistic, office buildings, hangars for maintenance, (g) airport enlargement – including slots, terminal size and design, runways layout and length. The lack of terminal space and runway slots might be a significant strategic constraint. Ashford et al. (2013) described that the effectiveness of a hub airport depends on: (a) geographical location, (b) availability of flights to multiple destinations, (c) capacity of the airport system to handle aircraft movements and passenger volumes and (d) ability of the terminal layout to accommodate passenger transfer. Hubs must accommodate a large number of passengers moving between gates at the terminals rather than from the landside to the gate.

### 2.2. Structural equation modeling (SEM)

SEM is a group of statistical models that helps to simplify and describe relationships among multiple latent variables and differentiates between the direct and indirect paths among those constructs (Hair et al., 2010). Latent variables represent theoretical, abstract concepts or phenomena, such as behavior patterns, that cannot be directly measured or observed by the researcher, whereas observed variables, those contained in a database or spreadsheet, allow latent constructs to be measured by considering latent measurement errors (Bowen and Guo, 2012). In addition, the SEM model can accommodate a latent variable as a dependent variable, something that cannot be done in the traditional regression analysis (Washington et al., 2011). The SEM is a tool that was developed in the past largely by clinical sociologists and psychologists, but has currently been used widely in various disciplines, becoming an essential analytical method in academic research (Hair et al., 2010).

SEM's have two components, a measurement model and a structural model (Washington et al., 2011). While the measurement model tests the relationships between latent variables and their observable indicators, the structural model focuses on the relationships between latent variables (Hair et al., 2010). The measurement model is concerned with how well various measured variables measure the stipulated variables in the model. A CFA is a measurement model and requires the researcher to hypothesize, in advance, the number of factors, dealing with theory testing and determining whether the hypothesized structure provides a good fit to the data, or said otherwise, that a relationship between the observed variables and their underlying latent, or unobserved, constructs exist (Child, 2006). The structural model represents a natural extension of a measurement model containing a mature statistical modeling framework, concerned with how the model variables are related to each other. It is the structural component of SEMs that allows substantive conclusions about the relationship between latent variables, and the underlying mechanisms of a process or phenomenon (Washington et al., 2011). Thus, the main design difference between the measurement model and the structural model is that in the former, there are no directed arrows between latent factors (George, 2013). This paper developed a two-step analysis involving both models. Firstly, the measurement model was estimated through CFA, followed by testing research hypotheses in the structural model.

Previous studies on air transport have already employed SEM to investigate the relationship between constructs in the following topics:

competitive advantages provided by the low-cost carrier model (Singh et al., 2021); passengers' intentions to use low-cost carriers (Pan and Truong, 2018); airport competitiveness (Cui et al., 2013); airport location in multiple airport regions (Yang et al., 2016); airport service quality (Allen et al., 2020); transfer passengers' perceptions of airport service quality (Jin-Woo and Se-Yeon, 2011). However, the studies most similar to the model proposed in this paper were those that correlated transport infrastructure, whether in maritime transport (Deng et al., 2013; Munim and Schramm, 2018) or in road transport (Li et al., 2018), regional economy, and transport volume. Therefore, this study aims to fill a gap in the literature by exploring the relationship between the characteristics of airport infrastructure, the socioeconomic characteristics of the region in which the airport is located, and characteristics of air transport volume that configure these facilities as hubs.

Deng et al. (2013) examined among others the relationship between: port supply – namely, port quay length, number of production and non-production use port berths and port infrastructure investment; port demand – which encompasses port container throughput across types of routes and trade; and regional economy – in which variables include the Gross Domestic Product (GDP) and GDP per capita. Munim and Schramm (2018) employed SEM to provide empirical evidence of significant economic impacts of port infrastructure quality and logistics performance. For this purpose, latent variables such as port infrastructure; seaborne trade – represented by observed variables container port traffic and liner shipping connectivity; and national economy – represented by observed variable GDP per capita; were compared. Li et al. (2018) explored the relationships between road infrastructure and the local economy, as well as the mediating factors. They evaluated the impact of road coverage on the region's GDP by examining the interactions among mediating constructs such as employment, market openness, transportation volume, investments, and policies, in the correspondence between infrastructure and economy.

### 2.3. Analytic hierarchy process (AHP)

Saaty (1980) developed the AHP, a Multi-Criteria Decision-Making (MCDM) method which consists of defining a goal/objective and determining the alternatives to achieve it, listing relevant criteria and sub-criteria to be evaluated through a comparison of the importance between them defined by decision makers or experts. It is an analysis that helps structure complex problems into hierarchical levels to facilitate the visualization of the elements that influence this selection/ranking process. The AHP method consists of three steps: (a) decomposition of the problem, (b) comparative judgment, and (c) synthesis of priorities (Saaty, 1980; Saaty and Vargas, 1987). The first deals with constructing a hierarchical schematic representation composed of interrelated decision elements (i.e., overall objective, criteria, sub-criteria and decision alternatives). The second includes the formation of the pairwise matrices and their comparison at levels, more precisely at the level where all alternatives are compared with each sub-criterion and respective criterion, and at the level where sub-criteria and criteria are compared with respect to the overall objective. Estimation of relative weights and definitions of priorities through pairwise judgments supported by expert opinion are based on Saaty's fundamental scale, in which 1 signifies both elements being of equal importance and 9 denotes one element having extreme importance over the other. Logical consistency is an important premise in the AHP method, and thus, it is necessary to verify the Consistency Index (CI) of the analysis, which is affected by expert subjective judgment. If the condition for CI is fulfilled, the third step is carried out in order to compute the overall score for each alternative.

The AHP model is widely used in transport planning problems. Dozić (2019) conducted a literature review to recognize and classify problems in the aviation industry that were solved by MCDM methods. Among all the MCDM methods, AHP was the most applied, present in 40% of reviewed papers. Of the 40 studies examined in the area of Airports, only

1 focused on selection of a passenger hub in air transport (Janic and Reggiani, 2002). Janic and Reggiani (2002) applied AHP and other MCDM methods to identify the location of a second new hub airport for a hypothetical airline. The findings of the study revealed that what most impacts the decision of the best alternative are the weights assigned to the criteria and sub-criteria, rather than the MCDM method itself. The determining factors for this hub selection were defined as follows: (a) population of airport catchment area, (b) per capita income of the region, (c) airport size (in terms of millions of passengers per year), (d) minimum generalized surface access cost, (e) total airline cost of operating two hub-and-spoke networks, (f) the average airport cost per service, (g) airport capacity (in terms of aircraft movements per hour), (h) market share of the incumbent at given airport, and (i) utilization of airport capacity during peaks. In the AHP method, these factors were considered sub-criteria grouped into four criteria, namely: market (a, b, c), accessibility (d), cost (e, f) and capacity (g, h, i). The study proposed three different scenarios. The first assumed equal weights for all factors, the second used weights generated through uniform distribution by simulation and the third used the entropy method to assign their weights, which tends to give the greatest importance to the criteria with the greatest difference in their values.

### 2.4. Combined approach using SEM and AHP

Previous papers in other fields have utilized the combined SEM-AHP technique to identify key factors influencing the research object. Most of these studies employed SEM to test research hypotheses and the significance of the relationship between the analyzed factors, while AHP dealt with assigning weights to criteria and sub-criteria and the relative importance of the factors. In the first technique, data are usually collected through survey questionnaires encompassing various types of respondents. In the second technique, information is obtained through the opinion of subject matter experts. This paper thus proposes a novel approach to data collection in this combined technique, wherein the data used in the SEM are obtained through a database created for the study, gathering various sources, and the weights of the AHP are assigned based on values found in the SEM rather than the experts' opinion. The order of application of the techniques may vary. In studies aiming to obtain performance scores (Pipatprapa et al., 2016; Yontar and Ersöz, 2021), SEM is performed first to synthesize the measurement model and dimension performance, so that AHP can be subsequently performed to obtain the final performance score. The relative weight of the attributes is determined by the SEM model, while the relative weight of the alternatives with respect to each attribute is determined by the AHP model (Punniyamoorthy et al., 2012). The results of SEM can also serve as inputs to the AHP model, in which only the factors considered significant in the first are applied in the second (Mansour et al., 2020). In other papers, AHP was employed first to determine the importance of the factors from the experts' point of view, and subsequently SEM tested the relationships between these factors (Yadegaridehkordi et al., 2018).

## 3. Methods

### 3.1. Definition of variables and data collection

Since this paper deals with a pioneering study employing a new approach to hub selection, it was necessary to seek assistance from other literature references to establish the determining factors in this selection process. As mentioned earlier, studies in other modes of transport addressed, through SEM, the relationship between transport infrastructure, local economy, and productivity in terms of volume handled (Deng et al., 2013; Munim and Schramm, 2018; Li et al., 2018). Papers analyzing the productivity and efficiency of airports employed aspects related to airport infrastructure as inputs and the movement of passengers and aircraft as outputs (Chaouk et al., 2020; Merkert and Mangia, 2014). Other relevant works sought to understand the

relationship between economic, demographic, and tourism factors in the region with air transport demand (Boonekamp et al., 2018; Akhavan et al., 2020). The characteristics defining a hub proper lack consensus in the literature; for some authors, a hub is not just a large terminal that handles a high number of passengers per year but also a flight and destination distribution center for the main airline operating at its facilities, as well as a traffic generator that improves airport connectivity (Costa et al., 2010; Rodríguez-Déniz et al., 2013). Therefore, some studies sought to understand the behavior of dominant airlines at hub airports in terms of destinations, flights and frequencies (Fageda, 2014; Burghouwt, 2014).

Table 1 provides a list of the measurement variables analyzed by the study as well as the references justifying them in this approach. The observed variables were grouped into three latent variables, namely airport characteristics, region characteristics, and airline characteristics. The first pertains to aspects related to infrastructure, capacity and area of the airport. The second concerns the socioeconomic and global integration aspects of the city or region where the airport is situated. Finally, the third relates to the activity of the dominant airline operating at each airport. In this study, the dominant airline is defined as the carrier offering the highest number of destinations from a given airport, based on market data from November 2023. In case of a tie, intercontinental destinations, longest flights and codeshare agreements served as tie-breakers. The observed variables for the main carrier help determine whether an airport functions as a base for a low-cost carrier, a hub for a full-service carrier, or simply a focus city, regardless of the airline's business model. Full-service airlines typically prioritize intercontinental routes and codeshare agreements at their hubs, unlike low-cost carriers. The focus on intercontinental flights rather than international ones highlights the need to account for differences in domestic market sizes. Data were collected from 300 major international airports worldwide which are listed in Appendix A. The airports in the database were grouped into three world regions according to the International Air Transport Association (IATA) Traffic Conference Area, where Zone 1, now referred to as AMERICAS, includes North America, Latin America, and the Caribbean; Zone 2, now referred to as EURMEAF, includes Europe (including the part of Russia west of the Ural Mountains), the Middle East and Africa; and Zone 3, now referred to as ASIAPACIFIC, includes Asia (including the part of Russia east of the Ural Mountains and excluding the Middle East) and Oceania. Zone 1 is represented by 93 airports in the sample, Zone 2 by 112, and Zone 3 by 86.

A challenge encountered in the research was the requirement to obtain standardized data for all airports in the sample, as sources classify their variables based on different types of measurement depending on the region of the world. Thus, for some variables, particularly those related to airport characteristics, the authors conducted their own calculations with the aid of aerial images of these facilities. In the case of variables related to the dominant airline characteristics, since these can vary depending on the month consulted, and to facilitate the

interpretation of the results obtained in the AHP for subsequent comparison analysis of rankings between alternatives, they were categorized on an ordinal scale of 1–5 with intervals established by the authors based on exploratory analysis. Appendix B presents descriptive statistics of the observed variables and their respective consulted sources. Appendix C shows the description of each type of variable and how it was calculated for introduction into the analysis. Appendix D exhibits the intervals chosen in the case of categorical variables.

### 3.2. Research hypotheses

SEM requires the specification of relationships between unobserved variables. A direct relationship is where the independent variable influences the dependent variable, and is shown with a directional arrow, with the direction of influence going from the exogenous to the endogenous variable. An indirect relationship is when an independent variable influences a dependent variable indirectly through a third independent variable. (Washington et al., 2011). Therefore, some hypotheses based on theoretical grounding about how the various latent variables in the model are associated should be provided before SEM is constructed to test the hypotheses and then provide the related equations. The network of relationships among the three constructs of the model, namely AIRPORT, REGION and AIRLINE, and the rationale for the proposed connections are organized below.

Due to the absence of studies found in the literature examining the causality between aspects of airport infrastructure and air transport demand, it was necessary to resort to research in the maritime transport field, drawing an analogy to the aviation industry's reality. These papers typically address the relationship between port infrastructure, logistics facilities, port throughput, and economic growth, indicating that causality points from infrastructure to port demand. According to López and Poole (1998) the total port throughput is a function of the number of berths, capacity per berth and berth occupancy rate. Deng et al. (2013) after analyzing the relationship between port infrastructure and container throughput, indicated that port supply had a positive effect on port demand. Felício et al. (2015) verified strong influence of port and terminal characteristics on container terminal performance. Bensassi et al. (2015) concluded that the number, size and quality of logistics facilities positively influence export flows. Munim and Schramm (2018) revealed that logistics performances had a significant positive effect on seaborne trade. Wang et al. (2021) documented the long-run equilibrium between the logistics infrastructure and the economic development and causality, in general, running from the former to the latter. Li et al. (2023) suggested that improvements in port connectivity have a significant and fairly durable effect on regional economic growth, and that port infrastructure expansion is one potential channel for realizing this effect. Performing a comparison with air transport, extensive airport infrastructure enables the dominant airline to have greater operational capacity in handling flights and passengers at the airport site. This

**Table 1**  
List of latent and measurement variables.

| Latent Variables                           | Measurement Variables                                       | References                                                                                                                                                                                                                                                                                                                                            |
|--------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Airport Characteristics (AIRPORT)          | RWYLENGTH<br>TERMINALAREA<br>GATES<br>AIRPORTAREA           | total lenght of all runways<br>passenger terminal area + apron area<br>number of gates equipped with airbridges<br>airport site area<br>(Merkert and Assaf, 2015; Yoshida and Fujimoto, 2004)<br>(Fragoudaki et al., 2016; Merkert and Mangia, 2014)<br>(Chaouk et al., 2020; Lai et al., 2015)<br>(D'Alfonso et al., 2015; Merkert and Mangia, 2014) |
| Region Characteristics (REGION)            | GDPPERCAPITA<br>POPULATION<br>CITYGLOB                      | GDP per capita of the region<br>inhabitants of the metropolitan area<br>city globalization index<br>(Boonekamp et al., 2018; Albayrak et al., 2020)<br>(Akhavan et al., 2020; Matsumoto and Domae, 2018)                                                                                                                                              |
| Dominant Airline Characteristics (AIRLINE) | CARRIERDEST<br>CARRIERFLIGHTS<br>INTERCONTDEST<br>CODESHARE | dominant carrier overall destinations<br>dominant carrier longest flights<br>dominant carrier intercontinental destinations<br>dominant carrier codeshare agreements<br>(Fageda, 2014; Burghouwt, 2014)                                                                                                                                               |

provides the primary carrier with mechanisms to offer more destinations and the possibility to include intercontinental destinations, since this facility is equipped to accommodate larger aircraft due to its widely infrastructure. Thus, [Hypothesis 1](#) is proposed.

**Hypothesis 1.** Airport characteristics have a positive effect on dominant airline characteristics.

Socio-economic indicators such as GDP, unemployment rate and population, are closely related to air transport demand. Several studies have examined the causality between air transport and economic growth, but the results regarding the direction of causality have shown diversity ([Ozmeç-Ban and Babić, 2023](#)). Air transport may be a key tool to advance economic development. However, it is uncertain whether air transport boosts economic development, or vice versa. Both views have theoretical and empirical support ([Tolcha et al., 2020](#)). Regional economic development driven by other factors can lead to more air traffic; however, it is also possible that, by generating traffic, airports act as a catalyst for local investment ([Button et al., 2010](#)).

Depending on the region analyzed, causality can go unidirectionally from GDP to air transport ([Brida et al., 2018](#)), vice versa ([Brida et al., 2016a](#)), or even exhibit a positive and bidirectional relationship ([Brida et al., 2016b](#)). For [Zhang and Graham \(2020\)](#), the reciprocal causal relationship is more likely to prevail in less developed economies, whereas for developed economies the causality runs from air transport to economic growth. Even when studying the same region, the conclusions regarding directionality can be conflicting ([Marazzo et al., 2010](#); [Fernandes and Pacheco, 2010](#)). According to [Mukkala and Tervo \(2013\)](#), the causality processes are homogenous from regional growth to air traffic; however, there is causality from air traffic to regional growth in peripheral regions. [Tolcha et al. \(2020\)](#) found that for less developed countries the direction of causality runs from economic development to air transport demand; although the presence of a large home-based airline and comparative geographic advantage as a natural hub may reverse this direction. [Hakim and Merkert \(2016\)](#) confirmed that causality runs from GDP to air passenger traffic and air freight volumes, the results also proposed that spatial dimensions (i.e. low income and large populations) and context matter in this type of analysis. [Hakim and Merkert \(2019\)](#) suggested that per capita income play a vital role in determining air passenger demand in low-income countries. [Pot and Koster \(2022\)](#) indicated that causality mainly runs from economic growth to air accessibility, especially considering dense regions with lagging per capita GDP levels, and in turn having smaller airports.

Since this paper encompasses airports worldwide, in both developed and less developed regions, we sought to find a corresponding direction of causality for the variables of the region and the dominant airline defined in the study. Airports located in densely populated cities tend to have a higher demand for air transport, leading the airline to offer more destinations at that facility. Cities with higher GDP per capita have inhabitants more likely to fly and thus contribute to the activity of the main carrier in that locality. Highly globalized cities attract businesses, multinational companies, fairs, and conferences; this can lead to an increase in intercontinental destinations provided and code-share agreements with other international airlines. Thus, [Hypothesis 2](#) is proposed.

**Hypothesis 2.** Region characteristics have a positive effect on dominant airline characteristics.

### 3.3. Measurement model

CFA was conducted to measure the correlation between the latent variables AIRPORT, REGION, and AIRLINE, and the respective loading factors of the measured variables contained within each one. A group containing airports worldwide and separate groups for each of the pre-established study zones, namely AMERICAS, EURMEAF, and ASIAPACIFIC, were estimated for subsequent comparisons and identification of regional patterns. Except for GDPPERCAPITA, POPULATION and

CARRIERDEST, all other observed variables obtained loading factors greater than 0.7. Regarding the cutoff point for loading factors accepted for analysis, authors support different thresholds. [Stevens, 2002](#), suggested that the value of a factor loading should exceed 0.4 for meaningful interpretations, while [Hair et al. \(2010\)](#) argued that all standardized loadings factors should be at least 0.5, ideally at least 0.7. However, the challenges of obtaining an adequate model for CFA can result in the elimination of significant content for measuring constructs and sometimes make it difficult to maintain the recommended minimum of 3 items per construct. In these cases, the construct content should be prioritized above model fit adjustments ([Hair et al., 2010](#)). Therefore, the authors chose to maintain all the variables observed in the analysis since GDPPERCAPITA, POPULATION and CARRIERDEST adapted to the cutoff score of 0.4 for standardized loading factors. AMOS provides modification indices that contribute to model adjustment through correlations between errors (disturbances) related to measured variables. The tool proposed correlations between the errors of RWY LENGTH and GATES, RWY LENGTH and AIRPORTAREA, and GDPPERCAPITA and POPULATION. These modifications were accepted as they make sense from the perspective of the relationship between variables. A long runway length indicates an airport with a large area, which may reflect an airport with more gates in its terminals. Furthermore, population and GDP per capita are related economic factors.

Since the CFA and the SEM were carried out using the Maximum Likelihood (ML) method, which performs accurate estimations for continuous and normally distributed data, it is necessary to check the normality of the database used ([Hair et al., 2010](#)). Use of unadjusted ML with nonnormal continuous variables will negatively impact fit and will tend to underestimate standard errors for parameter tests. However, the parameter estimates (e.g., loadings, correlations, predictive paths) are generally not affected by nonnormality ([Finch et al., 1997](#)). In case of ordinal data that have at least 5 categories and there is no extreme violation of normality assumptions, the ML method provides the sufficiently accurate estimates while computing the correlation of covariance matrix ([Schumacker and Beyerlein, 2000](#)). Once it is difficult to investigate all of the aspects of multivariate normality, at least the inspection of univariate distribution of each observed variable is required ([Dragan and Topolšek, 2014](#)). The ML method can be used to estimate CFA and SEM parameters, when particularly there are no gross violations of the normality assumption ([El-Basyouny and El-Bassiouni, 2013](#)). [West et al. \(1995\)](#) suggest that skewness >2 and kurtosis >7 are indicative of moderate or serious nonnormality. Consequently, since the primary objective of the combined SEM-AHP approach in this study is the utilization of parameters found in the first stage of the model in the subsequent stage, and all measurement variables (continuous and ordinal) exhibited values below 2 for skewness and 7 for kurtosis, analyses in AMOS were conducted using the ML method.

A "good model fit" is the indication that the model is plausible. Several fit indices recommended by researchers and their respective cutoff scores were used to assess adequate measurement model fit ([Hu and Bentler, 1999](#); [Hair et al., 2010](#); [Byrne, 2010](#)). The statistic X2/DF (degrees of freedom), also known as normed chi square, has been suggested as a useful fit measure, in which the recommended value is somewhere less than 5, with values less than 3 and close to 1 being preferred ([Washington et al., 2011](#)). The root mean square error of approximation (RMSEA) and the standardized root mean square residuals (SRMSR) are also referred to as badness-of-fit, where values close to 0 represent a desirable fit. Incremental fit indices assess how well the estimated models fit relative to some alternative baseline model, normally being the null model ([Hair et al., 2010](#)). Among the incremental fit measures, the Normed Fit Index (NFI), the Tucker Lewis Index (TLI) and the Comparative Fit Index (CFI) are the most widely reported. These indices are referred to as goodness-of-fit, where values close to 1 indicates better fit, with values above 0.95 being desirable ([Hu and Bentler, 1999](#)). Fit indices are merely guidelines and should not be regarded as measures of the usefulness of a model in a mechanical decision

process for its selection. Model selection should be a subjective process that involves the use of judgment (Browne and Cudeck, 1992). Table 2 shows that the three-factor model (AIRPORT, REGION and AIRLINES) yielded acceptable fit for most indices. In the case of NFI and TLI, values were close to recommended level of 0.90; thus, marginal acceptance can be given to these measures.

After evaluating the model fit, reliability and validity of the model were estimated. Table 3 shows the results for the reliability and validity tests among the model constructs calculated using the Master Validity Tool for AMOS (Gaskin et al., 2019). Construct reliability assessment was conducted using construct reliability (CR) values. As shown in Table 3, the CR values for all constructs exceeded the recommended threshold of 0.7 (Hair et al., 2010), suggesting satisfactory convergence among scale items. Reliable constructs are those in which indicators are highly intercorrelated. Construct validity was evaluated by convergent and discriminant validity of the constructs. Two measures of convergent validity - standardized factor loading and average variance extracted (AVE) - were assessed for the CFA model. All standardized loading estimates of the observed variables were within the acceptable range ( $>0.70$ ), except for the variables already mentioned and their maintenance in the model justified, thus demonstrating adequate convergent validity. As indicated in Table 3, the AVE values for the AIRPORT and AIRLINE constructs exceeded the suggested threshold (0.50), while the REGION AVE was close to the cutoff, possibly due to having indicators with factor loadings below 0.7, and it was retained in the model due to authors' considerations. AVE is often too strict, and validity can be established through CR alone (Malhotra and Dash, 2011). Higher values of AVE are observed when indicators are genuinely representative of the latent variable. AVE estimates for two factors should exceed the square of the correlation between the two factors to provide evidence of discriminant validity (Hair et al., 2010). The results of discriminant validity, also indicated in Table 3, thus point to adequate discriminant validity of the constructs. In summary, the results regarding the model fit quality and measurement model assessment were successfully validated and support subsequent structural model analysis.

### 3.4. Structural model (SEM) and analytic hierarchy process (AHP)

The structural model then tested the two research hypotheses, namely, the positive effect of airport characteristics and region characteristics, exogenous variables, on the characteristics of the dominant airline, an endogenous variable. The direction of the arrows in the SEM displayed in Fig. 1 illustrates these hypothesized causal relationships. The arrow from AIRPORT to AIRLINE reflects that robust airport infrastructure enables dominant airlines to expand operations and offer more destinations. Similarly, the arrow from REGION to AIRLINE highlights that factors such as GDP, population, and city attractiveness drive air travel demand, prompting airlines to enhance their networks and establish international agreements. The bidirectional arrow between AIRPORT and REGION reflects the necessity of covarying exogenous constructs in SEM models using AMOS to account for the interdependence of independent variables, which are rarely entirely independent in practice. This procedure helps prevent overestimating or underestimating the effects of AIRPORT and REGION on AIRLINE.

Once both hypotheses were validated, the first stage of the model, it

**Table 2**  
Model fit indices.

| Indices     | Observed Values | Recommended Criteria                     |
|-------------|-----------------|------------------------------------------|
| $\chi^2/DF$ | 3.874           | $<3$ good fit; $<5$ acceptable fit       |
| RMSEA       | 0.069           | $<0.05$ good fit; $<0.08$ acceptable fit |
| SRMR        | 0.061           |                                          |
| NFI         | 0.899           | $>0.90$ acceptable fit; $>0.95$ good fit |
| CFI         | 0.922           |                                          |
| TFI         | 0.887           |                                          |

**Table 3**

Model reliability and validity analysis.

|         | Discriminant Validity |        |         | Reliability and Convergent Validity |       |
|---------|-----------------------|--------|---------|-------------------------------------|-------|
|         | AIRPORT               | REGION | AIRLINE | CR                                  | AVE   |
| AIRPORT | 0,829                 |        |         | 0,896                               | 0,688 |
| REGION  | 0,596*                | 0,694  |         | 0,717                               | 0,482 |
| AIRLINE | 0,777*                | 0,636* | 0,808   | 0,880                               | 0,653 |

\* Significance of correlation  $p < 0.001$ .

is time to apply these results achieved in the AHP analysis, the second stage. Fig. 1 also shows the combined SEM-AHP approach, indicating that the standardized regression coefficients of the relationship between constructs obtained in the SEM (cw - referring to the group of airports worldwide; c1 - referring to the group of zone 1 AMERICAS; c2 - referring to the group of zone 2 EURMEAF; c3 - referring to the group of zone 3 ASIAPACIFIC) were used for the direct judgment of weights in the comparison of nodes between levels 1 and 2. The standardized loading factors of each indicator found in the CFA (lw - referring to the airports from the worldwide group; l1 - AMERICAS group; l2 - EURMEAF group, l3 - ASIAPACIFIC group) were employed in the judgment of weights between levels 2 and 3. Thus, the observed variables in the SEM become the sub-criteria of the AHP, just as the latent variables of the SEM are equivalent to the criteria of the AHP. Most of the time, it is difficult to gather a large number of experts in a particular subject to opine on the importance between criteria and sub-criteria, and this judgment tends to be subjective. The new SEM-AHP approach proposed in this paper eliminates these challenges by relying on previous statistical analyses of a database when defining the weights of the multicriteria analysis, leading to more reliable results. The second stage of the model then consisted of an AHP, testing three different sets of alternatives to discover peculiarities among regions of the world. The first with airports from the AMERICAS group, verifying how the ranking behaves with the coefficients and loadings found in the worldwide analysis and in the analysis of this specific region; and likewise the second and third with airports from the EURMEAF and ASIAPACIFIC groups, respectively.

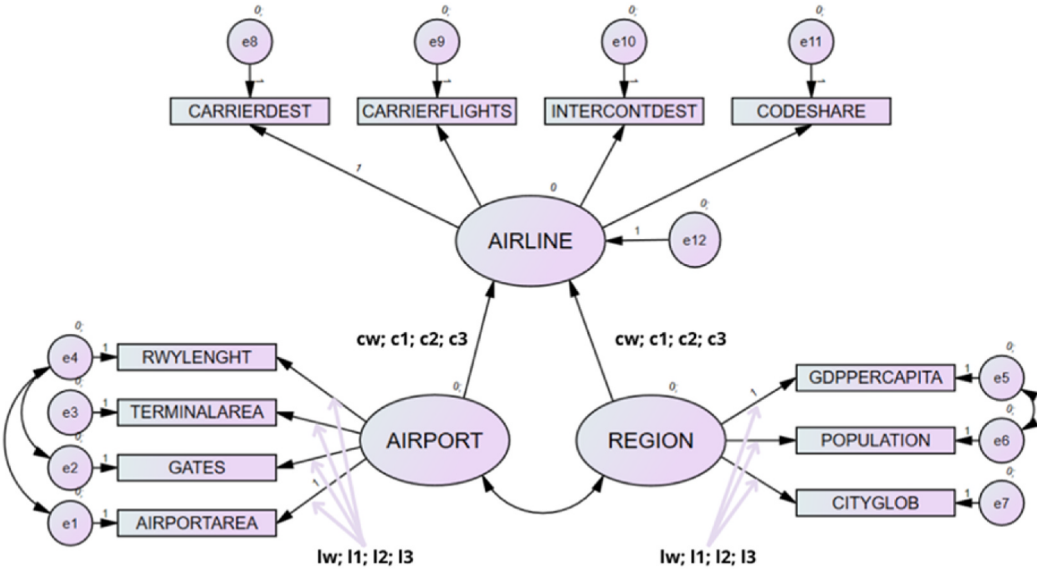
## 4. Results and discussion

### 4.1. Standardized loading factors

When analyzing the results of the measurement model for the worldwide group in Table 4, it is noted that within the latent variable AIRPORT, aspects related to the passenger terminal, TERMINAL AREA and GATES, exert a greater influence on this construct than aspects related to the airport site and runways, AIRPORT AREA and RWY-LENGTH. Decision-makers when selecting a hub should therefore pay more attention to elements involving the passenger terminal building than the airside elements. In the latent variable REGION, a notable greater importance is observed for the level of city globalization compared to its population and GDP per capita. A hub would thus be more related to the city's global attractiveness characteristics than its economic factors per se. Finally, when examining the AIRLINE construct, it is found that aspects connected to intercontinental flights, CARRIERFLIGHTS and INTERCONTDEST, have the highest loading factors, while CARRIERDEST is the item with the least influence. This indicates a tendency that when investigating the activity of the dominant airline to determine if such an airport functions as a hub, its global connectivity is one of the key factors.

Table 4 also presents the results for the specific groups of each zone established in the study. It is important to note that two loading factors have values greater than 1. Standardized coefficients greater than 1 are uncommon, yet they are theoretically valid and can arise legitimately due to multicollinearity or moderate correlations among variables, as outlined by Jöreskog (1999) and Deegan (1978). These values should be

SEM



AHP

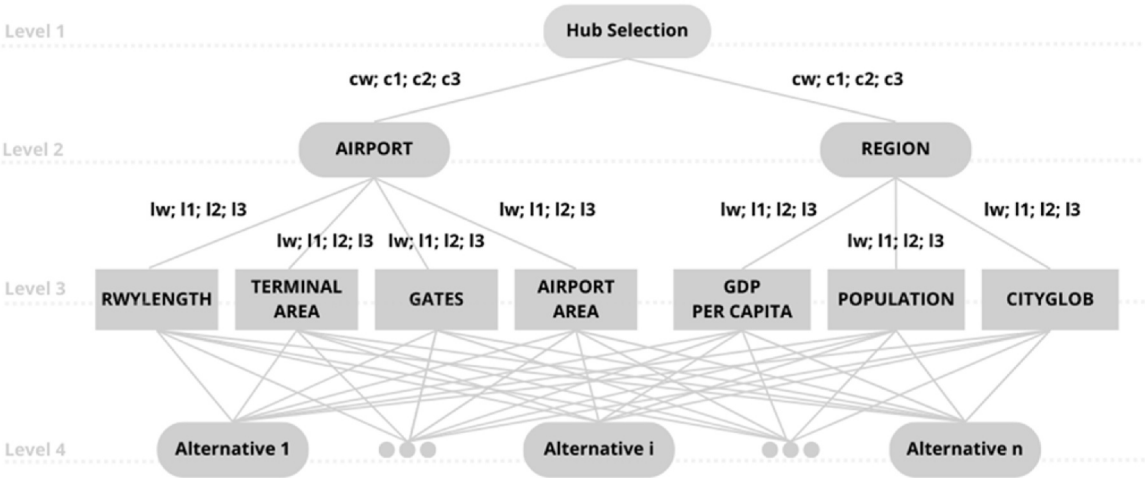


Fig. 1. Combined SEM-AHP approach.

Table 4  
Standardized loading factors estimates.

| Latent Variable | Item           | Standardized Loading Factors |          |         |             |
|-----------------|----------------|------------------------------|----------|---------|-------------|
|                 |                | Worldwide                    | AMERICAS | EURMEAF | ASIAPACIFIC |
| AIRPORT         | RWYLENGTH      | 0,711                        | 0,809    | 0,743   | 0,791       |
|                 | TERMINALAREA   | 0,963                        | 0,981    | 0,997   | 1002*       |
|                 | GATES          | 0,891                        | 0,967    | 0,945   | 0,975       |
|                 | AIRPORTAREA    | 0,723                        | 0,632    | 0,711   | 0,878       |
| REGION          | GDPPERCAPITA   | 0,408                        | 0,202    | 0,542   | 0,577       |
|                 | POPULATION     | 0,661                        | 0,693    | 0,601   | 0,761       |
|                 | CITYGLOB       | 0,917                        | 1115*    | 0,932   | 0,927       |
| AIRLINE         | CARRIERDEST    | 0,590                        | 0,807    | 0,500   | 0,695       |
|                 | CARRIERFLIGHTS | 0,907                        | 0,915    | 0,931   | 0,865       |
|                 | INTERCONTDEST  | 0,889                        | 0,911    | 0,928   | 0,853       |
|                 | CODESHARE      | 0,807                        | 0,819    | 0,809   | 0,806       |

\*See Jöreskog (1999) and Deegan (1978) for an explanation of how standardized loadings could be greater than 1.

interpreted as regression coefficients without concern for model bias, particularly when the overall model fit is satisfactory. Observing the AMERICAS group, it is noted that in the AIRPORT construct, the total

runway length gains greater importance within the latent variable, while the airport area presents a lower loading factor. This trend can be linked to the fact that airports in the United States, which dominate the

sample of airports in the Americas, generally have a large airport site that does not necessarily reflect in considerable airport traffic. In turn, the main airports in this region have a large number of runways. When examining the REGION construct, it is found that the globalization index has much greater importance than the other two items, and GDP per capita hardly influences the hub selection process. This is in line with the landscape described by some studies (Schaafsma, 2003; Rodríguez-Déniz, 2013), which show that the largest domestic hubs in United States are located in geographically central cities and not necessarily in the most populous ones, the latter mostly only playing a role as international gateways. Finally, exploring AIRLINE, attention is drawn to the fact that the destinations of the dominant carrier carry more weight in this construct, which could possibly be explained by the lesser presence of low-cost carriers in this part of the world.

Analyzing the EURMEAF group, it is evident that in the AIRPORT construct, the differences between items related to the passenger terminal and those related to the airside are even more pronounced, with the former exerting greater influence on this latent variable. The justification for this could be that in this world region, the main airports do not differ as much in terms of airport area and number of runways. In the REGION construct, socio-economic and demographic factors gain greater importance in explaining the characteristics of the location where the airport is situated. Lastly, when examining the AIRLINE construct, it is noticed that the destinations of the dominant airline have the lowest loading factor compared to the other groups. One explanation for this is the dominance of low-cost airlines in the region, especially in Europe, where these carriers often hold the majority of the market share at secondary airports without serving as hubs at these facilities. In the ASIAPACIFIC group, upon examining the AIRPORT construct, it is observed that this is the group in which indicators related to the passenger terminal have the highest loading factor. The airport area also gains significant influence, meaning that hub airports are those that have a larger airport site. In the latent variable REGION, it is noted that the Asia-Pacific zone is the one with the best scores for population and GDP per capita, indicating that economic factors have a considerable influence on the determination of a hub. In the construct related to the characteristics of the dominant airline, this group gives less importance to intercontinental destinations, which may point to a tendency for its hubs to play more of a connector role within the Asian and Oceania continent than globally.

#### 4.2. Hypotheses testing and standardized regression coefficients

Table 5 summarizes the results of the research hypotheses tests, revealing the estimated values of path coefficients and their respective t-values and p-values. When examining the relationships of the worldwide group, it is found that the two hypotheses proposed by the model are supported: airport characteristics and region characteristics indeed have a positive effect on the characteristics of the dominant airline. The path AIRPORT - > AIRLINE was considered significant (i.e., t-value > 1.96; p-value < 0.001) and in the expected direction, obtaining a standardized regression coefficient of 0.618. The path REGION - > AIRLINE also

proved to be significant and in the expected direction, reaching a standardized regression coefficient of 0.268. From these results, two conclusions can be drawn: first, airport infrastructure has a greater influence than external factors of the region when trying to explain the key factors for an airport to have hub status. The second is that improving airport infrastructure and capacity increases the chances of the dominant airline behaving as a hub carrier, operating a hub-and-spoke network at the site with a considerable percentage of connecting passengers. Similarly, an airport located in a city with better socioeconomic indicators and highly connected globally is more likely to become a hub for an airline.

In order to further investigate whether the conclusions are similar for all regions of the world, it is necessary to analyze the path coefficients of the specific groups. In the AMERICAS group, it is observed that airport characteristics have a stronger relationship with the characteristics of the main carrier, while in the REGION - > AIRLINE path, the relationship becomes weaker. In the EURMEAF group, this same path has an even lower coefficient, emphasizing the importance of airport characteristics over region characteristics. It is noted that for these groups, the relationship between REGION and AIRLINE, t-values and p-values were close to the pre-established significance intervals, and thus, they were considered marginally significant with  $p < 0.1$ , and their hypotheses were supported. Lastly, ASIAPACIFIC was the region of the world that presented different results from those found in the model with all airports under study, meaning that for the Asia-Pacific region, socioeconomic factors and the globalization index affect the characteristics of the dominant airline more than airport infrastructure. These theories were then examined in the subsequent stage of the model.

#### 4.3. Application of results in the analytic hierarchy process (AHP)

Since the judgment of criteria and sub criteria weights in this AHP analysis was obtained directly from the SEM results, rather than from expert opinion, the condition for CI was fulfilled. Appendix E presents the pairwise comparison matrices of criteria and sub criteria for the global model and for each of the specific groups. The arrow points to the most important factor of the comparison, meaning that for the worldwide group, the AIRPORT criterion is 2.306 times more important than the REGION criterion, and so on. Table 6 displays, for each group studied, the local weights of the criteria and the computed global weights of the sub criteria, which are the local weights of each sub criteria multiplied by the local weights of the criterion in which it is located. Starting with the worldwide group as the base, it is found that in AMERICAS and EURMEAF groups, the most apparent change is that the sub criteria RWYLENGTH surpasses AIRPORTAREA in terms of importance in the analysis, which can also be confirmed by the direction of the arrows in Appendix E. On the other hand, the ASIAPACIFIC group is the one that exhibits the most significant modifications in preferences among sub criteria. Since the criterion REGION has a higher local weight than AIRPORT in the Asian-Pacific area, the most influential sub criteria in this analysis become the globalization index and the population of the airport city, followed by aspects of the passenger terminal. Even

**Table 5**  
Hypotheses testing and standardized regression coefficients.

| Hypothesis   | Group       | Path                | Estimate | t-value | p-value | Result    |
|--------------|-------------|---------------------|----------|---------|---------|-----------|
| Hypothesis 1 | Worldwide   | AIRPORT - > AIRLINE | 0,618    | 7595    | ***     | Supported |
|              | AMERICAS    | AIRPORT - > AIRLINE | 0,762    | 5751    | ***     | Supported |
|              | EURMEAF     | AIRPORT - > AIRLINE | 0,722    | 4744    | ***     | Supported |
|              | ASIAPACIFIC | AIRPORT - > AIRLINE | 0,391    | 3293    | ***     | Supported |
| Hypothesis 2 | Worldwide   | REGION - > AIRLINE  | 0,268    | 3797    | ***     | Supported |
|              | AMERICAS    | REGION - > AIRLINE  | 0,192    | 1816    | 0,069   | Supported |
|              | EURMEAF     | REGION - > AIRLINE  | 0,140    | 1691    | 0,091   | Supported |
|              | ASIAPACIFIC | REGION - > AIRLINE  | 0,546    | 3538    | ***     | Supported |

\*\*\*p < 0,001.

**Table 6**

Local weight of criteria and computed global weight of sub criteria.

|              |              | Worldwide    |               | AMERICAS     |               | EURMEAF      |               | ASIAPACIFIC  |               |
|--------------|--------------|--------------|---------------|--------------|---------------|--------------|---------------|--------------|---------------|
|              |              | Local Weight | Global Weight | Local Weight | Global Weight | Local Weight | Global Weight | Local Weight | Global Weight |
| Criteria     | AIRPORT      | 0,618        |               | 0,762        |               | 0,722        |               | 0,391        |               |
|              | REGION       | 0,268        |               | 0,192        |               | 0,140        |               | 0,546        |               |
| Sub Criteria | AIRPORTAREA  | 0,723        | 0,447         | 0,632        | 0,482         | 0,711        | 0,513         | 0,878        | 0,343         |
|              | GATES        | 0,891        | 0,551         | 0,967        | 0,737         | 0,945        | 0,682         | 0,975        | 0,381         |
|              | RWYLENGTH    | 0,711        | 0,439         | 0,809        | 0,616         | 0,743        | 0,536         | 0,791        | 0,309         |
|              | TERMINALAREA | 0,963        | 0,595         | 0,981        | 0,748         | 0,997        | 0,720         | 1002         | 0,392         |
|              | CITYGLOB     | 0,917        | 0,246         | 1115         | 0,214         | 0,932        | 0,130         | 0,927        | 0,506         |
|              | GDPPERCAPITA | 0,408        | 0,109         | 0,202        | 0,039         | 0,542        | 0,076         | 0,577        | 0,315         |
|              | POPULATION   | 0,661        | 0,177         | 0,693        | 0,133         | 0,601        | 0,084         | 0,761        | 0,416         |

GDPPERCAPITA, which is the least relevant sub criteria in the other groups, surpasses RWYLENGTH in this world region.

Three sets of fifteen airports were selected to represent each region of the world established in this study, with the ranking based on two scenarios: the first considering the weights obtained in the worldwide group, and the second considering the weights acquired in each specific group. To confirm the coherence between the two stages of the SEM-AHP approach, additional indicators were investigated on these selected airports, associated with the definition of a hub airport existing in the literature, to strengthen the basis of the results achieved by the model. Thus, the ranking of the sets was compared with the categories of the observed variables present in the AIRLINE construct of the SEM, along with two other external references. The first corresponds to the Global Airport Connectivity Index (GACI) developed by [Cheung et al. \(2020\)](#), with scores corresponding to the year 2022, which combines traditional centrality indicators, such as degree, closeness, and eigen-vector, with two new volume-based measures — flow betweenness and regional importance — to analyze the evolution of aviation networks. This methodology helps assess an airport's competitive position and its influence on other airports within the network. Airports with a GACI score of 2 or higher were classified as hubs, though it is important to note that the post-pandemic recovery in 2022 may have influenced some airport scores. The second refers to studies that attempted to estimate the rate of connecting passengers in relation to the total number of passengers at these facilities, as this information is rarely disclosed by airport operators ([Maertens et al., 2020](#); [Cheung et al., 2020](#); [Maertens and Grimme, 2015](#)).

#### 4.3.1. North America, Latin America and the Caribbean

[Table 7](#) shows the result of the AHP containing airports from North America, Latin America, and the Caribbean, along with their rankings in scenarios considering weights designated by the Worldwide group and the AMERICAS group. "Normals" refers to the normalized values found in the analyses for each of the alternatives. The airports in the set were selected from those present in studies that estimated the passenger transfer rate at certain facilities. The transfer rates and their respective sources and reference years are contained in [Table 7](#). The enumerated categories from 1 to 5 associated with the variables of the dominant airline at a given airport that served as the basis for defining a hub in the SEM, and the GACI score of each alternative also appears in [Table 7](#). Likewise, [Tables 8 and 9](#) perform these comparisons for EURMEAF and ASIAPACIFIC groups, respectively.

Upon examining the standard worldwide ranking, it is observed that, except for DTW, all airports positioned in the top ten have a GACI value greater than 2.5, and those with GACI values exceeding 2.7 belong to the top six alternatives, indicating a strong relationship between airport connectivity and this AHP analysis. Regarding the percentage of passengers in connection, it is noted that airports with low transfer rates, such as LAS and FLL, ranked at the bottom positions, while six out of the top ten airports have estimated transfer rates of more than 30%. It is worth noting that JFK and LAX, although not having a considerable number of connecting passengers, are important international gateways due to the cities they are located in, with significant connectivity in the global air transport network and therefore identified as hubs by the model. In turn, the top two, DFW and ORD, have GACI scores higher than 3 and transfer passenger rates exceeding 40%. Meanwhile, MSP, CLT, and PTY, despite having high transfer rates, seem to serve only as

**Table 7**

AMERICAS group ranking.

| Airport               | Ranking World-wide | Normals | Ranking AMERICAS | Normals | GACI | Transfer Rate %               | CARRIER DEST | CARRIER FLIGHTS | INTER CONT DEST | CODE SHARE |
|-----------------------|--------------------|---------|------------------|---------|------|-------------------------------|--------------|-----------------|-----------------|------------|
| DALLAS (DFW)          | 1                  | 0,0956  | 1                | 0,0988  | 3056 | 54% (a, 2018)                 | 5            | 5               | 3               | 3          |
| CHICAGO (ORD)         | 2                  | 0,0932  | 2                | 0,0947  | 3175 | 43% (a, 2018)                 | 5            | 5               | 4               | 4          |
| NEW YORK (JFK)        | 3                  | 0,0925  | 4                | 0,0861  | 2749 | 17% (a, 2018)                 | 5            | 4               | 4               | 4          |
| DENVER (DEN)          | 4                  | 0,0859  | 3                | 0,0888  | 2796 | 37% (a, 2018)                 | 5            | 4               | 2               | 2          |
| LOS ANGELES (LAX)     | 5                  | 0,0795  | 6                | 0,0763  | 3023 | 21% (a, 2018)                 | 3            | 5               | 3               | 4          |
| ATLANTA (ATL)         | 6                  | 0,0766  | 5                | 0,0792  | 2904 | 62% (a, 2018)/65,5% (c, 2011) | 5            | 5               | 4               | 3          |
| HOUSTON (IAH)         | 7                  | 0,0707  | 7                | 0,0704  | 2613 | 50% (a, 2018)                 | 5            | 5               | 3               | 3          |
| TORONTO (YYZ)         | 8                  | 0,0659  | 9                | 0,0655  | 2508 | 28,6% (c, 2011)               | 5            | 5               | 4               | 4          |
| DETROIT (DTW)         | 9                  | 0,0642  | 8                | 0,0663  | 1908 | 41% (a, 2018)                 | 5            | 4               | 3               | 2          |
| SAN FRANCISCO (SFO)   | 10                 | 0,0600  | 10               | 0,0585  | 2552 | 23% (a, 2018)                 | 5            | 5               | 4               | 4          |
| MINNEAPOLIS (MSP)     | 11                 | 0,0520  | 11               | 0,0524  | 2067 | 42,9% (c, 2014)               | 5            | 4               | 3               | 2          |
| CHARLOTTE (CLT)       | 12                 | 0,0475  | 12               | 0,0483  | 2211 | 67% (a, 2018)                 | 5            | 4               | 3               | 1          |
| LAS VEGAS (LAS)       | 13                 | 0,0449  | 13               | 0,0472  | 2330 | 14% (c, 2013)                 | 3            | 2               | 1               | 1          |
| FORT LAUDERDALE (FLL) | 14                 | 0,0400  | 14               | 0,0369  | 2208 | 4,8% (c, 2013)                | 3            | 2               | 1               | 1          |
| PANAMA CITY (PTY)     | 15                 | 0,0313  | 15               | 0,0307  | 1649 | 77% (a, 2018)                 | 4            | 3               | 1               | 3          |

a - [Maertens et al. \(2020\)](#); b - [Cheung et al. \(2020\)](#); c - [Maertens and Grimme \(2015\)](#).

**Table 8**  
EURMEAF group ranking.

| Airport           | Ranking World-wide | Normals | Ranking EUR-MEAF | Normals | GACI | Transfer Rate %                               | CARR-IER DEST | CARR-IER FLIGHTS | INTER CONT DEST | CODE SHARE |
|-------------------|--------------------|---------|------------------|---------|------|-----------------------------------------------|---------------|------------------|-----------------|------------|
| PARIS (CDG)       | 1                  | 0,1092  | 1                | 0,1110  | 2975 | 34% (a, 2018)/50,1% (b, 2011)                 | 5             | 5                | 5               | 5          |
| MADRID (MAD)      | 2                  | 0,0958  | 2                | 0,1004  | 2447 | 33% (a, 2018)                                 | 5             | 4                | 4               | 4          |
| LONDON (LHR)      | 3                  | 0,0883  | 4                | 0,0854  | 2925 | 31% (a, 2018)/36,4% (b, 2013)                 | 5             | 5                | 5               | 4          |
| AMSTERDAM (AMS)   | 4                  | 0,0807  | 3                | 0,0862  | 2913 | 39% (a, 2018)/49,7% (b, 2013)                 | 5             | 5                | 5               | 5          |
| DUBAI (DXB)       | 5                  | 0,0805  | 5                | 0,0810  | 3043 | 53% (a, 2018)/61% (b, 2016)                   | 5             | 5                | 5               | 4          |
| CAIRO (CAI)       | 6                  | 0,0797  | 8                | 0,0715  | 1817 | 19,5% (c, 2013)                               | 4             | 4                | 3               | 4          |
| FRANKFURT (FRA)   | 7                  | 0,0692  | 7                | 0,0718  | 3178 | 55% (a, 2018)/57,8% (b, 2011)/55,1% (c, 2014) | 5             | 5                | 5               | 5          |
| ABU DHABI (AUH)   | 8                  | 0,0684  | 6                | 0,0733  | 1683 | 72% (a, 2018)/66% (c, 2013)                   | 3             | 5                | 5               | 3          |
| DOHA (DOH)        | 9                  | 0,0608  | 10               | 0,0620  | 2436 | 76% (a, 2018)/68% (c, 2013)                   | 5             | 5                | 5               | 4          |
| MUNICH (MUC)      | 10                 | 0,0604  | 9                | 0,0621  | 2143 | 40% (a, 2018)/26,7% (b, 2013)/39,1% (c, 2014) | 5             | 4                | 4               | 4          |
| LONDON (LGW)      | 11                 | 0,0583  | 11               | 0,0492  | 2049 | 2,8% (c, 2013)                                | 5             | 2                | 1               | 1          |
| COPENHAGEN (CPH)  | 12                 | 0,0469  | 12               | 0,0471  | 1866 | 21,1% (b, 2014)                               | 4             | 4                | 3               | 4          |
| HELSINKI (HEL)    | 13                 | 0,0415  | 13               | 0,0413  | 1737 | 38% (a, 2018)                                 | 4             | 4                | 4               | 2          |
| ATHENS (ATH)      | 14                 | 0,0376  | 14               | 0,0356  | 1748 | 13% (c, 2013)                                 | 5             | 2                | 1               | 4          |
| ADDIS ABABA (ADD) | 15                 | 0,0227  | 15               | 0,0222  | 1871 | 66% (a, 2018)/56% (c, 2013)                   | 5             | 4                | 3               | 2          |

a - Maertens et al. (2020); b - Cheung et al. (2020); c - Maertens and Grimme (2015).

**Table 9**  
ASIAPACIFIC group ranking.

| Airport            | Ranking World-wide | Normals | Ranking ASIA-PACIFIC | Normals | GACI  | Transfer Rate %                               | CARR-IER DEST | CARR-IER FLIGHTS | INTER CONT DEST | CODE SHARE |
|--------------------|--------------------|---------|----------------------|---------|-------|-----------------------------------------------|---------------|------------------|-----------------|------------|
| SHANGHAI (PVG)     | 1                  | 0,1010  | 1                    | 0,0875  | 2192  | 14% (a, 2018)                                 | 5             | 5                | 3               | 4          |
| SEOUL (ICN)        | 2                  | 0,0881  | 5                    | 0,0785  | 2007  | 14% (a, 2018)/21,7% (b, 2013)/20,6% (c, 2013) | 4             | 5                | 4               | 4          |
| SINGAPORE (SIN)    | 3                  | 0,0842  | 3                    | 0,0799  | 2433  | 27% (a, 2018)/40,3% (b, 2013)/27,1% (c, 2014) | 3             | 5                | 4               | 5          |
| BEIJING (PEK)      | 4                  | 0,0825  | 7                    | 0,0743  | 2065  | 12% (a, 2018)                                 | 5             | 5                | 4               | 4          |
| GUANGZHOU (CAN)    | 5                  | 0,0754  | 8                    | 0,0687  | 2437  | 14% (a, 2018)                                 | 5             | 5                | 3               | 4          |
| KUALA LUMPUR (KUL) | 6                  | 0,0719  | 9                    | 0,0676  | 1984  | 17% (a, 2018)                                 | 3             | 4                | 2               | 5          |
| JAKARTA (CGK)      | 7                  | 0,0716  | 6                    | 0,0758  | 2,14  | 7% (a, 2018)/4,3% (c, 2013)                   | 2             | 4                | 2               | 4          |
| TOKYO (HND)        | 8                  | 0,0689  | 2                    | 0,0802  | 2216  | 6% (a, 2018)                                  | 3             | 5                | 3               | 4          |
| BANGKOK (BKK)      | 9                  | 0,0683  | 10                   | 0,0652  | 2,12  | 24% (a, 2018)                                 | 3             | 4                | 3               | 5          |
| TOKYO (NRT)        | 10                 | 0,0666  | 4                    | 0,0787  | 2082  | 15,9% (b, 2013)                               | 2             | 5                | 3               | 5          |
| NEW DELHI (DEL)    | 11                 | 0,0623  | 11                   | 0,0645  | 2114  | 12% (a, 2018)                                 | 3             | 5                | 4               | 4          |
| HONG KONG (HKG)    | 12                 | 0,0600  | 12                   | 0,0599  | 1961  | 29% (a, 2018)/26,5% (b, 2013)                 | 3             | 5                | 4               | 4          |
| OSAKA (KIX)        | 13                 | 0,0389  | 14                   | 0,0426  | 1397  | 7% (c, 2013)                                  | 1             | 3                | 2               | 4          |
| SEOUL (GMP)        | 14                 | 0,0341  | 13                   | 0,0463  | <1000 | 3,6% (c, 2013)                                | 1             | 1                | 1               | 2          |
| CHENNAI (MAA)      | 15                 | 0,0260  | 15                   | 0,0304  | 1321  | 8,2% (c, 2013)                                | 3             | 2                | 2               | 2          |

a - Maertens et al. (2020); b - Cheung et al. (2020); c - Maertens and Grimme (2015).

regional hubs, as they fall into categories 1 to 3 regarding intercontinental destinations and code-share agreements, and therefore, the model recognized them as non-hubs, placing these airports at the bottom positions. Analyzing the aspects of the dominant airline, it is noted that in the top positions, for the most part, their variable values are contained in category 5 of CARRIERDEST, at least in category 4 of CARRIER-FLIGHTS, and at least in category 3 of INTERCONTDEST and CODE-SHARE. Thus, it is concluded that a hub airport in this region is one where its main carrier offers more than 100 destinations departing from its runways, with at least 6 of them being intercontinental, and the sum of its four longest flights exceeding 15,000 nautical miles. Additionally, it has more than 5 code-share agreements with other partner airlines also operating at its facilities.

Comparing the ranking obtained with the weights from the worldwide group with the ranking generated by the weights characteristic of the AMERICAS group, three changes in positions can be noted. The first involves DEN surpassing JFK and thus coming into third place. While the

GACI values of the two airports are similar, DEN exhibits a considerably higher transfer passenger rate. However, concerning aspects related to the dominant carrier's ability to act as a global connector, particularly INTERCONTDEST and CODESHARE, JFK stands out over DEN. The second is related to the position exchange between ATL and LAX, where the former overtakes the latter to reach the fifth position. ATL boasts the highest transfer passenger rate in the region, exceeding 60%, while LAX has better global connectivity with a GACI score exceeding 3. Lastly, the third change involves DFW surpassing YYZ. Although DFW has a higher transfer rate, according to the GACI index, it is not determined as a hub. In contrast, YYZ has a GACI score exceeding 2.5 and superior categories in terms of the dominant airline's characteristics. Therefore, it is concluded that both the ranking considering the worldwide weights and the ranking based on region-specific weights successfully identified the airports most likely to become a hub. While the worldwide weights highlighted airports with higher global connectivity, including those serving as international gateways, the region-specific weights gave

slight importance to airports functioning as regional hubs in the United States and boasting high percentages of connecting passengers.

#### 4.3.2. Europe, Middle East and Africa

Table 8 displays the results of the AHP analysis for the selected airports covering Europe, the Middle East, and Africa. Regarding the worldwide ranking, concerning the GACI scores of the fifteen alternatives, it is noticeable that the bottom four positions were those with airports determined as non-hubs by the index. Among the top seven positions, only in two, MAD and CAI, the GACI value is below 2.9, and in the latter, it is even below 2. Examining the passenger transfer rates in this ranking, it's evident that airports with percentages below 30%, such as LGW, CPH, and ATH, ranked lower. Once again, the exception was CAI, indicating a possible misclassification of the model for this specific airport. Concerning airports with considerable transfer passenger rates, the highest values are found in Middle Eastern airports, DXB, AUH, and DOH, positioned respectively in fifth, eighth, and ninth places. This fact may indicate a trend that the worldwide weights in this region focus more on airport connectivity than on its transfer passenger rate. Therefore, the major European airports ranked at the top, along with Dubai, which has a GACI value exceeding 3, while other Middle Eastern airports were placed in median positions.

It is also worth mentioning ADD, which despite having a significant passenger transfer rate, upon analyzing its GACI value and the INTERCONT and CODESHARE categories, it was found that its global connectivity does not correspond to that of a hub airport according to the study's premises. Furthermore, ADD is located in a region with low economic indicators and, consequently, the model placed it in the last position. Investigating Table 8 for the variables associated with the dominant airline of the top-ranking airports, it is evident that most of these airports are categorized as 5 in terms of CARRIERDEST, CARRIERFLIGHTS, and INTERCONTDEST, and at least as category 4 in CODESHARE. This implies that a hub in the EURMEAF region is one where its primary carrier offers more than 100 destinations at its facilities, including more than 30 intercontinental destinations, and where the sum of the four longest flights exceeds 25000 nautical miles. In addition, the airline must have code-share agreements with more than 10 other carriers operating at that airport. Hence, it can be inferred that the main hubs in EURMEAF are more focused on the role of global connectors than the main hubs in AMERICAS.

Comparing the ranking containing weights from worldwide with the ranking encompassing region-specific weights, three changes in positions among the alternatives were noted. In the EURMEAF ranking, AMS surpassed LHR, thus taking the third position. Both have similar GACI scores, but the former exhibits a higher percentage of passengers in connection, while the dominant airline of the latter has more code-share agreements. Another change observed is that considering the region-specific weights, CAI dropped from sixth to eighth place, while AUH gained two positions, ranking sixth, and the seventh position remained with FRA. Although both are not determined as hubs by the index, CAI has a slightly higher GACI value than AUH, however, the latter boasts a transfer rate of around 70%, while the former does not reach 20%. Lastly, MUC surpassed DOH in the EURMEAF ranking, finishing ninth. DOH obtains better values than MUC for GACI, transfer rate, and characteristics of the dominant airline. However, it is noted that the normalized values for both airports are very close in both rankings, and any subtle variation in weights could result in changes in their positions. Similar to what occurred in AMERICAS group, it was inferred that both rankings accurately portrayed the hub selection process in Europe, the Middle East, and Africa, as the top positions were filled by airports with high GACI values, a considerable transfer rate, and their dominant airline included in at least category 4 of the variables investigated by the study. In two of the three changes observed, the weight of the EURMEAF region placed more importance on the airports' transfer rates than their global connectivity, while in the worldwide weight, the opposite occurred.

#### 4.3.3. North, South and Southeast Asia and Oceania

Table 9 presents the rankings obtained using worldwide weights and ASIAPACIFIC group weights for the fifteen alternatives located in the Asia-Pacific region. Regarding the first ranking, it was observed that when examining the GACI scores of the compared alternatives, the last positions were those where the airports have a GACI value less than 2 and, therefore, are not considered hubs. With the exception of KUL, in all of the first eleven positions, the respective airports have a GACI score greater than 2, and in the cases of SIN and CAN, third and fifth positions respectively, greater than 2.4. Regarding the transfer passenger rate, this world region presents the lowest values for its major airports. The only airports that boast a transfer passenger rate greater than 25% are SIN and HKG. The former is included in the top 3 of the ranking, but the latter ended up in the twelfth position. However, it is worth noting that HKG has a GACI score less than 2 and, consequently, is not determined as a hub by the index. Examining the cases where the transfer rate is less than 10%, KIX, GMP, and MAA were placed at the bottom positions, meanwhile CGK and HND were placed in median positions due to their significant values for GACI and the variables of the dominant airline.

Regarding the categorical variables, many of the top-ranked airports worldwide cover at least category 3 for CARRIERDEST and INTERCONTDEST, and at least category 4 for CARRIERFLIGHTS and CODESHARE. A hub airport in the Asia-Pacific region is therefore one that has its main carrier offering a range of over 50 destinations departing from its facility, including at least 6 intercontinental ones, and where the sum of its four longest flights exceeds 15,000 nautical miles. Additionally, this airline needs to have more than 10 code-share agreements with partner airlines at this airport. Hence, it can be concluded that of the three regions studied, ASIAPACIFIC is the one in which dominant airlines tend to have a network with a smaller number of destinations departing from their hubs. This situation aligns with the low estimated rates of transfer passengers for airports in this region.

The ASIAPACIFIC ranking, among the rankings of specific groups, is the one that most modifies positions between alternatives when compared to the worldwide ranking, largely due to the fact that the Asia-Pacific region assigns greater weights to aspects of the airport region than to infrastructure aspects, contrary to the global landscape of hub selection. The most pronounced changes were the loss of three positions for ICN, PEK, CAN, and KUL, and the gain of six positions for HND and NRT. These latter two airports belong to Tokyo, a city with high levels of globalization, abundant population, and considerable GDP per capita. HND went from eighth place to second, although it has a low transfer passenger rate, this airport exhibits a good GACI score, and its dominant airline performs well in terms of extending longer flights and code-share agreements. NRT, which achieved the fourth position, has a higher percentage of connecting passengers, a similar behavior of its main carrier, excluding the variable of the number of destinations offered which falls below category 3, and its GACI score is lower than HND. These two airports serve as international gateways to Japan. Examining the airports that dropped the most positions in the specific ranking analysis, except for CAN, the other three have GACI levels very close to or below the hub cutoff score, and therefore, their connectivity is not as strong as that of the other major airports in this group. Their transfer rates are in the range of 10–20%, which can be considered moderate to high compared to alternatives in the region. The characteristics of the dominant airlines align with the categories marked as hubs in this group, except for KUL, which has intercontinental destinations below expectations. In summary, it can be said that both rankings successfully identified the airports most likely to serve as hubs in the Asia-Pacific region. While the global weights placed more emphasis on the transfer passenger rate and the characteristics of the dominant airline, the specific weights placed airports located in cities with strong economic indicators at the top of the ranking, at the expense of airports with weaker connectivity.

## 5. Conclusions and suggestions

Many studies in the field of air transport mention hub airports, but few of these have sought to understand how the selection of a hub by an airline works and which aspects are most important in this process. This paper aimed to fill this gap in the literature by formulating a new two-stage model using the combined SEM-AHP technique, in which the first stage served to define priorities among characteristics of airport infrastructure and characteristics of the region where the airport is located, and the second stage verified whether this ordering of importance reflects the choice of airports associated with the hub function containing elements determined by previous studies. The SEM-AHP approach proposed in this paper can be very useful in studying characteristics present in other modes of transport as well as in other fields of science. Since the multicriteria analysis of the model does not depend on interviews with experts, this reduces subjectivity when judging weights between criteria and sub criteria. Moreover, it eliminates the obstacle of gathering a large number of experts who are often involved in the industry rather than academia, making access difficult for researchers. The findings of this paper can help airlines define criteria priorities when seeking to establish a new hub within their networks. Similarly, it assists airport operators in stipulating new investments in their infrastructures, in order of importance, to attract the attention of carriers to use their facilities as a hub.

In the first stage of the model presented in this study, SEM helped to understand how aspects associated with airport infrastructure, the socioeconomic factors of the city where the airport is located, and the activity of the dominant airline at that facility are related. This is a pioneering approach to understanding the relationships of these three elements in the context of air transport, as similar studies have been conducted for maritime transport (Deng et al., 2013; Munim and Schramm, 2018). The two research hypotheses formulated were tested and supported. It was found that intrinsic characteristics of airports and external characteristics of their surroundings and region have a positive effect on characteristics of the main carrier. In other words, the more abundant the infrastructure of the facility, the greater its airport capacity and, consequently, the chances of the dominant airline at the location turning it into a passenger and destination connecting center. Likewise, airports in cities with significant economic indices and good global attractiveness become notable candidates to be chosen as hubs by these carriers.

Analyzing the results of the SEM, it was possible to verify that airport characteristics have a greater influence on hub selection than region characteristics. Within the AIRPORT construct, a property was discovered that may be studied further, in which elements of the passenger terminal (TERMINALAREA and GATES) are more important than elements of the airport airside (RWYLENGTH and AIRPORTAREA) when an airline chooses a hub. This information can be crucial for carrier network definitions. Within the REGION construct, it was found that the city's globalization index (CITYGLOB) is a key component in hub selection, while population and GDP per capita are, of all observed variables, the least important in this decision-making process. The model also proposed fragmented study groups referring to world zones in order to find peculiarities among these regions. In AMERICAS and EURMEAF groups, it was possible to notice that the influence of AIRPORT is even more pronounced over REGION. Meanwhile, the ASIAPACIFIC group presented a tendency contrary to the pattern found in the worldwide analysis, in which characteristics of the airport region are more important than infrastructure characteristics.

In the second stage of the research tool, the SEM findings were tested in the AHP in order to use the loading factors and regression coefficients found in the first phase of the model to determine the weight judgments between criteria and sub criteria. Three sets of airports were analyzed related to each of the established zones in the study, and the AHP rankings containing weights for the worldwide group from the SEM and weights from the respective specific groups were compared. To verify if

these results were consistent with the research objective, i.e., to find only airports suitable for becoming hubs in the top positions, estimates of transfer passenger rates and global connectivity indices proposed by previous studies were used (Maertens et al., 2020; Cheung et al., 2020; Maertens and Grimme, 2015).

The airports in the AMERICAS group with a higher percentage of connecting passengers appear to serve more as regional hubs than global hubs and are located in medium-sized cities, while airports with better connectivity according to the GACI are located in the most populous cities and serve as international gateways. This particularity in the region may explain why population and GDP per capita have much less influence than the globalization index during the hub selection process. Airports that combine these two characteristics, such as DFW and ORD, appeared at the top positions in the rankings. On the other hand, the airports in the EURMEAF group with higher transfer rates are located in the Middle East and primarily serve as global hubs, while European airports have higher connectivity but lower transfer rates, serving as both connectors within the continent and international gateways for their countries. The latter obtained the best positions in both rankings, with the exception of DXB, positioned in the top 5, which has high connectivity and also a considerable transfer rate. Upon examining aspects related to alternatives located in the top positions, it was concluded that both the worldwide ranking and the specific groups ranking succeeded in selecting the airports most likely to function as hubs. While the former prioritizes aspects related to connectivity and the activity of the dominant airline to proceed with its classification, the latter acts as a correction factor by processing some position changes among airports with similar GACI scores in order to favor those with a higher transfer rate.

The ASIAPACIFIC group is characterized by having the major hubs with the lowest percentages of connecting passengers, where no alternative has a transfer rate exceeding 30%, except for SIN. This may indicate that these airports primarily serve as international gateways for passengers and, to a lesser extent, redistribute these passengers within their countries. The transfer rates among alternatives show little variation, and therefore, the main factors to be considered in this regional analysis are related to connectivity and the dominant airline. Airports with higher connectivity and the main carrier offering intercontinental destinations are those located in the most populous cities. Thus, this circumstance is highly correlated with the fact that socioeconomic characteristics exert a greater influence on airport infrastructure in the selection of hubs within the Asia-Pacific region. When examining the two rankings, it was found that both accurately described the decision-making process in this region by assuming the top positions for airports that combine high values in connectivity, transfer rate, and carrier activity. It is worth noting that the weights of the ASIAPACIFIC ranking emphasized the most populous cities with good global connectivity, better reflecting the context of this world area.

After completing the two stages of the combined SEM-AHP technique, it was found that the priorities among the observed variables considered by the model for the worldwide group can be used to assist decision-makers in choosing to establish a hub at a given airport regardless of the world region. However, it is also valid to calibrate these results using the specific weights of each region in order to align with the air transport scenario of each airline's locality. Furthermore, future studies could enhance the model proposed in this paper, such as by including other aspects in the SEM related to both airport infrastructure and socioeconomic factors of the region. Similarly, an estimation containing the transfer passenger rate of most airports in this study could contribute to better explaining the behavior of hubs along with variables of dominant airline activity. One of the limitations faced in this paper was finding more indicators for which data were available for all airports and cities in the sample.

## CRedit authorship contribution statement

**Gabriel Bordeaux:** Writing – original draft, Methodology, Data curation, Conceptualization, Investigation. **António Couto:** Writing – review & editing, Supervision, Methodology. **Edgar Jimenez:** Writing – review & editing, Methodology.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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## Appendix A. Database Airports

| Database Airports                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| North America, Latin America and the Caribbean (AMERICAS)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |  |
| Albuquerque (ABQ), Anchorage (ANC), Atlanta (ATL), Austin (AUS), Baltimore (BWI), Belo Horizonte (CNF), Bogota (BOG), Boise (BOI), Boston (BOS), Brasilia (BSB), Buenos Aires (AEP), Buenos Aires (EZE), Burbank (BUR), Cancun (CUN), Calgary (YYC), Charleston (CHS), Charlotte (CLT), Chicago (MDW), Chicago (ORD), Cincinnati (CVG), Cleveland (CLE), Columbus (CMH), Curitiba (CWB), Dallas (DAL), Dallas/Fort Worth (DFW), Denver (DEN), Detroit (DTW), Edmonton (YEG), Fort Lauderdale (FLL), Fort Myers (RSW), Fortaleza (FOR), Guadalajara (GDL), Hartford (BDL), Honolulu (HNL), Houston (HOU), Houston (IAH), Indianapolis (IND), Jacksonville (JAX), Kahului (OGG), Kansas City (MCI), Las Vegas (LAS), Lima (LIM), Los Angeles (LAX), Medellin (MDE), Memphis (MEM), Mexico City (MEX), Miami (MIA), Milwaukee (MKE), Minneapolis/St Paul (MSP), Monterrey (MTY), Montreal (YUL), Nashville (BNA), New Orleans (MSY), New York (JFK), New York (LGA), Newark (EWR), Oakland (OAK), Omaha (OMA), Ontario (ONT), Orlando (MCO), Palm Beach (PBI), Panama City (PTY), Philadelphia (PHL), Phoenix (PHX), Pittsburgh (PIT), Portland (PDX), Porto Alegre (POA), Punta Cana (PUJ), Raleigh/Durham (RDU), Recife (REC), Rio De Janeiro (GIG), Rio De Janeiro (SDU), Sacramento (SMF), Salt Lake City (SLC), Salvador (SSA), San Antonio (SAT), San Diego (SAN), San Francisco (SFO), San Jose (SJC), San Juan (SJU), Santa Ana (SNA), Santiago (SCL), Sao Paulo (CGH), Sao Paulo (GRU), Sao Paulo/Campinas (VCP), Seattle/Tacoma (SEA), St Louis (STL), Tampa (TPA), Tijuana (TIJ), Toronto (YYZ), Vancouver (YVR), Washington (DCA), Washington (IAD)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  |
| Europe, the Middle East and Africa (EURMEAF)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  |
| Abu Dhabi (AUH), Abuja (ABV), Addis Ababa (ADD), Alicante (ALC), Algiers (ALG), Amman (AMM), Amsterdam (AMS), Ankara (ESB), Antalya (AYT), Athens (ATH), Bahrain (BAH), Barcelona (BCN), Basel/Mulhouse (BSL), Belfast (BFS), Belgrade (BEG), Bergen (BGO), Berlin (BER), Bilbao (BIO), Birmingham (BHX), Bari (BRI), Bologna (BLQ), Bordeaux (BOD), Bristol (BRS), Brussels (BRU), Brussels/Charleroi (CRL), Budapest (BUD), Bucharest (OTP), Cairo (CAI), Cagliari (CAG), Cape Town (CPT), Casablanca (CMN), Catania (CTA), Cologne (CGN), Copenhagen (CPH), Cyprus/Larnaca (LCA), Dammam (DMM), Dubai (DXB), Dubai/Sharjah (SHJ), Dublin (DUB), Dusseldorf (DUS), Durban (DUR), Edinburgh (EDI), Eindhoven (EIN), Faro (FAO), Frankfurt (FRA), Geneva (GVA), Gdansk (GDN), Glasgow (GLA), Gothenburg (GOT), Gran Canaria (LPA), Hamburg (HAM), Helsinki (HEL), Heraklion (HER), Hurghada (HRG), Ibiza (IBZ), Istanbul (IST), Istanbul (SAW), Izmir (ADB), Jeddah (JED), Johannesburg (JNB), Katowice (KTW), Kuwait (KWI), Krakow (KRK), Lagos (LOS), Lisbon (LIS), London (LGW), London (LHR), London/Luton (LTN), London/Stansted (STN), Luxembourg (LUX), Lyon (LYS), Madrid (MAD), Malaga (AGP), Malta (MLA), Manchester (MAN), Marrakesh (RAK), Marseille (MRS), Milan (LIN), Milan (MXP), Milan/Bergamo (BGY), Munich (MUC), Moscow (DME), Moscow (SVO), Moscow (VKO), Muscat (MCT), Nairobi (NBO), Nantes (NTE), Naples (NAP), Nice (NCE), Oslo (OSL), Palermo (PMO), Palma de Mallorca (PMI), Paris (CDG), Paris (ORY), Paris/Beauvais (BVA), Pisa (PSA), Porto (OPO), Prague (PRG), Reykjavik (KEF), Rhodes (RHO), Riga (RIX), Riyadh (RUH), Rome (FCO), Saint Petersburg (LED), Salt Lake City (SLC), San Diego (SAN), San Francisco (SFO), San Jose (SJC), Santa Ana (SNA), Santiago (SCL), Sao Paulo (CGH), Sao Paulo (GRU), Sao Paulo/Campinas (VCP), Seattle/Tacoma (SEA), Sevilla (SVQ), Sofia (SOF), Stockholm (ARN), Stuttgart (STR), Tel Aviv (TLV), Tenerife (TFS), Thessaloniki (SKG), Tirana (TIA), Toulouse (TLS), Tunis (TUN), Valencia (VLC), Vancouver (YVR), Venice (VCE), Vienna (VIE), Warsaw (WAW), Zurich (ZRH) |  |
| South/Southeast/Far East Asia and Oceania (ASIAPACIFIC)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |
| Adelaide (ADL), Ahmedabad (AMD), Auckland (AKL), Bangalore (BLR), Bangkok (BKK), Bangkok (DMK), Beijing (PEK), Beijing (PKX), Brisbane (BNE), Busan (PUS), Cebu (CEB), Changchun (CGQ), Changsha (CSX), Chengdu (CTU), Chengdu (TFU), Chennai (MAA), Chiang Mai (CNX), Christchurch (CHC), Chongqing (CKG), Kochi (COK), Dalian (DLC), Da Nang (DAD), Denpasar (DPS), Fukuoka (FUK), Fuzhou (FOC), Gold Coast (OOL), Goa (GOI), Guangzhou (CAN), Guiyang (KWE), Haikou (HAK), Hanoi (HAN), Hangzhou (HGH), Harbin (HRB), Hefei (HFE), Ho Chi Minh City (SGN), Hohhot (HET), Hong Kong (HKG), Hyderabad (HYD), Jakarta (CGK), Jeju (CJU), Jinan (TNA), Kolkata (CCU), Kuala Lumpur (KUL), Kunming (KMG), Lanzhou (LHW), Manila (MNL), Makassar (UPG), Melbourne (MEL), Medan (KNO), Mumbai (BOM), Nagoya (NGO), Nanjing (NKG), Nanchang (KHN), Nanning (NNG), New Delhi (DEL), Ningbo (NGB), Osaka (ITM), Osaka (KIX), Okinawa (OKA), Perth (PER), Phuket (HKT), Pune (PNQ), Qingdao (TAO), Sanya (SYX), Seoul (GMP), Seoul (ICN), Shanghai (PVG), Shanghai (SHA), Shenyang (SHE), Shenzhen (SZX), Shijiazhuang (SJW), Singapore (SIN), Sapporo (CTS), Sydney (SYD), Surabaya (SUB), Taipei (TPE), Taiyuan/Jinzhong (TYN), Tianjin (TSN), Tokyo (HND), Tokyo (NRT), Urumqi (URC), Wenzhou (WNZ), Wuhan (WUH), Xiamen (XMN), Xi'an/Xianyang (XIY), Zhengzhou (CGO)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  |

## Appendix B. Descriptive Statistics and Data Sources

| Variable       | Min   | Max    | Mean    | Standard Deviation | Sources                                                                                                                                                                                                                                         |
|----------------|-------|--------|---------|--------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| RWYLENGTH      | 1738  | 24507  | 6890,59 | 3846,06            | <a href="http://www.gcmap.com/">http://www.gcmap.com/</a><br>Own Calculations via Google Earth<br>Own Calculations via Google Earth<br>Own Calculations via Google Earth<br>World Bank (2023), OECD (2023)<br>Demographia (2023)<br>GaWC (2020) |
| TERMINALAREA   | 2     | 180    | 33,21   | 32,53              |                                                                                                                                                                                                                                                 |
| GATES          | 0     | 195    | 40,99   | 39,43              |                                                                                                                                                                                                                                                 |
| AIRPORTAREA    | 75    | 4230   | 878,52  | 741,47             |                                                                                                                                                                                                                                                 |
| GDPPERCAPITA   | 2,27  | 204,61 | 44,53   | 27,18              |                                                                                                                                                                                                                                                 |
| POPULATION     | 0,054 | 37,73  | 6,04    | 6,99               | <a href="http://flightconnections.com/">http://flightconnections.com/</a> based on market figures from November 2023                                                                                                                            |
| CITYGLOB       | 0     | 12     | 5,39    | 3,71               |                                                                                                                                                                                                                                                 |
| CARRIERDEST    | 1     | 5      | 2,64    | 1,31               |                                                                                                                                                                                                                                                 |
| CARRIERFLIGHTS | 1     | 5      | 2,63    | 1,21               |                                                                                                                                                                                                                                                 |
| INTERCONTEST   | 1     | 5      | 1,77    | 1,11               |                                                                                                                                                                                                                                                 |
| CODESHARE      | 1     | 5      | 2,00    | 1,16               |                                                                                                                                                                                                                                                 |

### Appendix C. Description of the Variables

|                                  |                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------------------|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Airport Characteristics          | RWYLENGTH      | Total length of all runways in meters.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|                                  | TERMINALAREA   | Approximate area, in hectares, of operational passenger terminal buildings for scheduled aviation (i.e., excluding decommissioned or under-construction terminals in 2023) and their respective apron spaces for parking with airbridges, estimated through polygon calculations of aerial views verified by the authors using Google Earth. This measurement reflects the ground footprint of these facilities relative to the total airport site area and does not consider the floor area of multiple levels within terminal buildings, if applicable.                                                                                                                                                                                                                                                                                                                                                                                                                            |
|                                  | GATES          | Number of gates equipped with airbridges.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|                                  | AIRPORTAREA    | Approximate total area of the airport site, in hectares, estimated through polygon calculations of aerial views verified by the authors using Google Earth. Wherever possible, the measurement considered the boundaries of the airport's perimeter fence, including runways, taxiways, aprons, terminals (commercial, general aviation, and cargo), hangars, support buildings, and also vehicle parking areas located near terminal access curbs.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Region Characteristics           | GDPPERCAPITA   | GDP per capita values expressed in thousands of current international dollars (USD) and adjusted by Purchasing Power Parity (PPP), based on 2019 data for the region where the airport is located. The year 2019 was selected to exclude potential economic distortions caused by COVID-19. Regions corresponds to TL2 (Territorial Level 2) as defined by the Organisation for Economic Co-operation and Development (OECD), covering subnational divisions such as U.S. states, Chinese provinces, Spanish autonomous communities, and so on. When regional GDP data was unavailable, national values from the World Bank database were used.                                                                                                                                                                                                                                                                                                                                      |
|                                  | POPULATION     | Estimated population for the year 2023 of the metropolitan area served by the airport, in millions of inhabitants. In cases where airports are part of multi-airport systems, the primary city of the system was chosen as the reference. For example, the population of Miami metropolitan area was used for Fort Lauderdale Airport, the population of Milan metropolitan area was used for Bergamo Airport, and so on.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|                                  | CITYGLOB       | Classification based on the GaWC 2020 (Globalization and World Cities Research Network); a think tank established by the Department of Geography at Loughborough University in the United Kingdom. This index categorizes global cities into tiers known as alpha, beta, gamma, and sufficient, along with their respective subcategories. GaWC assesses cities worldwide based on inter- and intra-relations of offices located in their territories, focusing on accounting, advertising, banking/finance, and law. Consequently, this variable is represented by an ordinal value ranging from 0 to 12, where 0 pertains to cities not listed by GaWC, and 12 represents cities in the Alpha group, highly integrated into the world economy, in the alpha++ subcategory, the highest within this group. The criteria for selecting the reference city for each airport within multi-airport systems followed the same approach previously described for the variable POPULATION. |
| Dominant Airline Characteristics | CARRIERDEST    | Number of destinations offered by the dominant airline operating at the airport.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|                                  | CARRIERFLIGHTS | Sum of the longest flights by the dominant airline departing from the airport in the northeast, northwest, southeast, and southwest directions to detect the centrality of this facility within the carrier's network and potential market orientations.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|                                  | INTERCONTDEST  | Number of intercontinental destinations (i.e., those surpassing the International Air Transport Association (IATA) Traffic Conference Zone in which the airport is situated. IATA divides the world into three zones, namely: Zone 1 – Americas, Zone 2 – Europe, Africa, and the Middle East, and Zone 3 – Asia-Pacific), offered by the dominant airline operating at the airport.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|                                  | CODESHARE      | Number of codeshare agreements held by the main carrier operating at the airport with other carriers also operating at this airport, based on global alliances and information available on the website of the dominant airline.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |

### Appendix D. Categories of Dominant Airline Characteristics

| Variable       | Units of Measurement      | Categories |       |       |        |      |
|----------------|---------------------------|------------|-------|-------|--------|------|
|                |                           | 1          | 2     | 3     | 4      | 5    |
| CARRIERDEST    | destinations              | 0–25       | 26–50 | 51–75 | 76–100 | 100+ |
| CARRIERFLIGHTS | nautical miles (thousand) | 0–5        | 6–10  | 11–15 | 16–25  | 25+  |
| INTERCONTDEST  | destinations              | 0          | 1–5   | 6–15  | 16–30  | 30+  |
| CODESHARE      | agreements                | 0          | 1–5   | 6–10  | 11–20  | 20+  |

### Appendix E. Pairwise Comparison Matrices of Criteria and Sub Criteria

| WORLDWIDE   |         |            |               | REGION       |               |            |
|-------------|---------|------------|---------------|--------------|---------------|------------|
| AIRPORT     |         |            |               | ← 2,306      |               |            |
| AIRPORT     | GATES   | RWY LENGHT | TERMINAL AREA | REGION       | GDP PERCAPITA | POPULATION |
| AIRPORTAREA | ↑ 1,232 | ← 1,017    | ↑ 1,332       | CITYGLOB     | ← 2,247       | ← 1,387    |
| GATES       |         | ← 1,253    | ↑ 1,081       | GDPPERCAPITA |               | ↑ 1,620    |
| RWYLENGHT   |         |            | ↑ 1,354       |              |               |            |
| AMERICAS    |         |            |               | REGION       |               |            |
| AIRPORT     |         |            |               | ← 3,969      |               |            |
| AIRPORT     | GATES   | RWY LENGHT | TERMINAL AREA | REGION       | GDP PERCAPITA | POPULATION |
| AIRPORTAREA | ↑ 1,530 | ↑ 1,280    | ↑ 1,552       | CITYGLOB     | ← 5,520       | ← 1,609    |
| GATES       |         | ← 1,195    | ↑ 1,014       | GDPPERCAPITA |               | ↑ 3,431    |
| RWYLENGHT   |         |            | ↑ 1,213       |              |               |            |
| EURMEAF     |         |            |               | REGION       |               |            |
| AIRPORT     |         |            |               | ← 5,157      |               |            |
| AIRPORT     | GATES   | RWY LENGHT | TERMINAL AREA | REGION       | GDP PERCAPITA | POPULATION |
| AIRPORTAREA | ↑ 1,329 | ↑ 1,045    | ↑ 1,402       | CITYGLOB     | ← 1,720       | ← 1,551    |
| GATES       |         | ← 1,272    | ↑ 1,055       | GDPPERCAPITA |               | ↑ 1,109    |
| RWYLENGHT   |         |            | ↑ 1,342       |              |               |            |
| ASIAPACIFIC |         |            |               | REGION       |               |            |
| AIRPORT     |         |            |               | ↑ 1,396      |               |            |
| AIRPORT     | GATES   | RWY LENGHT | TERMINAL AREA | REGION       | GDP PERCAPITA | POPULATION |
| AIRPORTAREA | ↑ 1,110 | ← 1,110    | ↑ 1,141       | CITYGLOB     | ← 1,606       | ← 1,218    |
| GATES       |         | ← 1,233    | ↑ 1,028       | GDPPERCAPITA |               | ↑ 1,319    |
| RWYLENGHT   |         |            | ↑ 1,267       |              |               |            |

The arrow points to the most important factor of the comparison, meaning that for the worldwide group, the AIRPORT criterion is 2.306 times more important than the REGION criterion, and so on.

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## **A combined approach using structural equation modeling and analytic hierarchy process in hub airports selection**

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