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Research Paper

# Operational efficiency and recovery patterns of Turkish airports: A dynamic DEA and Malmquist index analysis

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**Abstract.** Airports are of strategic importance to national transport systems, facilitating passenger mobility, tourism, regional development, and economic connectivity. Therefore, airport efficiency is a critical issue for aviation management. The COVID-19 pandemic profoundly affected the air transport industry, highlighting the need to evaluate not only airport efficiency but also airport recovery patterns. This study analyzes the operational efficiency and recovery patterns of 10 major airports in Turkey between 2019 and 2024. Output-oriented Data Envelopment Analysis (DEA) with variable returns to scale and the Malmquist Productivity Index were applied to evaluate airport efficiency. Runway, terminal count, terminal area, and apron stand count were used as input variables, whereas aircraft movements, passenger traffic, and cargo traffic were used as output variables. The findings indicate variations in airport efficiency across the sample. İstanbul Airport, İstanbul Sabiha Gökçen, Ankara Esenboğa, Trabzon, and Muğla Milas-Bodrum airports remained on the efficiency frontier throughout the analysis period, whereas İzmir Adnan Menderes and Kayseri airports remained below the efficiency frontier. Furthermore, the Malmquist index indicates a significant decline in productivity during the initial phase of the pandemic; however, recovery patterns vary across airport types. This research contributes to the aviation management literature by examining airport efficiency and its dynamic patterns of productivity and recovery. From a practical perspective, it suggests that airport planning and policy should focus not only on traffic growth but also on infrastructure utilization and strategies tailored to each airport type.

**Keywords:** Airport efficiency, data envelopment analysis, Malmquist productivity index, airport recovery, Turkish airports.

Araştırma Makalesi

# Türk havalimanlarının operasyonel verimliliği ve toparlanma örüntüleri: Dinamik VZA ve Malmquist endeksi analizi

**Öz.** Havalimanları, yolcu hareketliliğini, turizmi, bölgesel kalkınmayı ve ekonomik bağlantısallığı destekleyen stratejik ulaşım altyapılarıdır. Bu nedenle havalimanı etkinliği, havacılık yönetimi açısından kritik öneme sahiptir. COVID-19 pandemisi hava taşımacılığı sektörünü derinden etkilemiş ve yalnızca havalimanı etkinliğinin değil, aynı zamanda toparlanma örüntülerinin de değerlendirilmesini gerekli kılmıştır. Bu çalışma, Türkiye'deki 10 büyük havalimanının 2019–2024 yılları arasındaki operasyonel etkinliğini ve toparlanma örüntüsünü analiz etmektedir. Araştırmada, değişken getiriye göre ölçek varsayımı altında çıktı odaklı Veri Zarflama Analizi (VZA) ile Malmquist Toplam Faktör Verimliliği Endeksi uygulanmıştır. Pist, terminal sayısı, terminal alanı ve apron park pozisyonu girdi; uçak hareketleri, yolcu trafiği ve kargo trafiği ise çıktı değişkenleri olarak kullanılmıştır. Bulgular, havalimanları arasında etkinlik farklılıkları bulunduğunu göstermektedir. İstanbul Havalimanı, İstanbul Sabiha Gökçen, Ankara Esenboğa, Trabzon ve Muğla Milas-Bodrum havalimanları analiz dönemi boyunca etkinlik sınırında yer alırken, İzmir Adnan Menderes ve Kayseri havalimanları etkinlik sınırının altında kalmıştır. Ayrıca, Malmquist endeksi pandeminin ilk aşamasında verimlilikte önemli bir düşüş yaşandığını, ancak toparlanma örüntülerinin havalimanı türüne göre farklılaştığını göstermektedir. Bu araştırma, havalimanı etkinliğini ve verimlilik ile toparlanma açısından dinamik örüntülerini inceleyerek havacılık yönetimi literatürüne katkı sağlamaktadır. Uygulama açısından ise, havalimanı planlaması ve politikalarının yalnızca trafik artışına değil, aynı zamanda altyapı kullanımına ve her havalimanı türüne özgü stratejilere odaklanması gerektiğini önermektedir.

**Anahtar Kelimeler:** Havalimanı verimliliği, veri zarflama analizi, Malmquist verimlilik endeksi, havalimanı toparlanması, Türk havalimanları.

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## 1. INTRODUCTION

Airports represent critical elements of national and international transport networks. In addition to being hubs of transport, they serve passengers, facilitate goods flows, enable tourism, foster business connections, integrate trade processes, and promote regional connectivity. Airport efficiency is a vital factor for aviation management. It is not enough to assess airport performance in terms of airport size and traffic volume; airports' performance needs to be evaluated in the context of resource utilization to produce operational outcomes.

This question is especially relevant to Türkiye, whose airport system consists of diverse airports. Istanbul Airport and Istanbul Sabiha Gökçen can be seen as hub airports for passenger operations. Antalya, Muğla Dalaman, and Muğla Milas-Bodrum are related to international tourism activities. Besides, Ankara Esenboğa, Trabzon, Gaziantep, and Kayseri airports play important roles in domestic accessibility. Therefore, one cannot measure the efficiency of these airports' operations in terms of traffic volumes due to differences in size, functions, and demand structures.

Thus, it is important to perform a comparative analysis of airport efficiency. A more efficient use of airport resources does not mean a more productive operation of the airport because of higher traffic volumes. Data Envelopment Analysis (DEA) is commonly used in airport performance assessment because this method measures efficiency based on multiple inputs and outputs rather than only on traffic sizes (Gillen & Lall, 1997; Wang et al., 2022). Moreover, the coronavirus disease pandemic has proved that the efficiency of airports should be measured not only in ordinary conditions but also in terms of recuperation and resilience. Recent studies indicate that operational efficiency and resilience represent related aspects of airport performance (Horton et al., 2025; Janić, 2021).

Despite many papers on airport efficiency at the international level, some problems exist in the field of airport efficiency in Türkiye. Thus, scholars have applied DEA, the Malmquist index, network DEA, and MCDM-based methods to evaluate airport performance in Türkiye (Ateş et al., 2018; Eren & Doğan, 2023; Akın, 2025; Pehlivanlı & Özsoy, 2025). There is, however, lack of research concerning airport efficiency changes and recovery performance. This is important since Turkish airports differ from each other by size, traffic structure, and functional importance, which might impact efficiency and recovery.

The proposed research aims to estimate the dynamic performance of airports in Türkiye based on Dynamic DEA and the Malmquist Productivity Index and explore the efficiency changes and recovery dynamics of major airports in the country from 2019 to 2024. The main research questions include estimating the effectiveness of Turkish airports in terms of converting infrastructure potential to traffic output, revealing efficiency trends in Turkish airports in 2019–2024, discovering airports with better recovery performance, and analyzing the sources of changes in airports' productivity dynamics.

The paper offers significant contributions to aviation management. First, the study is concentrated in Türkiye, where airport dynamic efficiency assessment remains understudied. Secondly, the study makes use of only secondary data and thus represents a transparent and reproducible empirical setting. Thirdly, the study uses not only static analysis of airport efficiency but also analyzes dynamic productivity of airports. Finally, the analysis of recovery trends is performed in relation to airports' efficiency assessment and airport functions.

## 2. LITERATURE REVIEW

### 2.1. Airport Efficiency in Aviation Management

Airport efficiency has become a vital topic in the aviation management field, considering that airports do not just serve as nodes within air transport systems but as sophisticated service systems involving infrastructure, operations, stakeholder coordination, and traffic outputs. In this respect, the term efficiency implies not simply a higher level of output with the same amount of input but also an ability of an airport to use runways, terminals, apron areas, and other processes related to the process efficiently, maintaining its efficiency regarding passengers, aircraft, and cargo. At the same time, this notion matches the definition of performance adopted in international aviation that implies a multidimensional concept of airport's productivity, service quality, safety, security, economic outcomes, and environmental responsibility (Airports Council International [ACI], n.d.).

A critical point related to airport efficiency is that airport performance and growth cannot be viewed as indicators of productive usage of airport infrastructure. In these conditions, the analysis of airport efficiency can serve as a strategic tool for aviation managers that allows determining whether the infrastructure capacity at their airports

is sufficient, insufficient, or excessive in order to make reasonable investment decisions. In particular, this point is essential due to the fact that the construction of additional terminal areas, aprons, or runways involves considerable expenses and high rigidity of infrastructure that makes short-term changes difficult. New airport capacity will bring managerial value only together with the stability of traffic volumes and efficient traffic usage. Thus, the measurement of efficiency will allow distinguishing between nominal capacity and effective capacity (ICAO, n.d.-a, n.d.-b; EUROCONTROL, n.d.-a).

In addition, airport efficiency is connected with the question of service quality and competitiveness. The inability to use airport infrastructure efficiently may be followed by congestion, traffic interruptions, passenger flow problems, problems with baggage handling, shortage of stands, and coordination issues between stakeholders. From this perspective, efficiency can be regarded as both a technical issue and an element of the sphere of services. The above idea is supported by the concept of operational readiness adopted in the industry since it is focused on integration, coordination, and readiness of the system (IATA, n.d.). Furthermore, airports currently compete with each other not only in terms of size but also regarding networks, transfer traffic, cargo operations, tourism flows, and revenue streams. In such competitive conditions, efficient airport infrastructure and reliable operations may provide an advantage to relatively smaller airports compared to inefficient large airports. Such approach is supported by the concept of total airport management that shifts attention to performance management rather than to the management of physical infrastructure (EUROCONTROL, n.d.-b).

Finally, the question of efficiency has been emphasized even further due to the consideration of sustainable and resilient airport infrastructure that has been discussed recently due to stakeholder requirements. At the current stage, airport efficiency implies not only increased throughput but also economically, environmentally, and operationally sound usage of infrastructure. As a result, the problem of airport efficiency has become an important strategic issue. From an academic perspective, airport efficiency remains one of the most popular concepts in research as it is related to infrastructure, resources, managerial decisions, and results achieved.

### 2.2. DEA Applications in Airport Studies

The DEA approach has gained prominence as a methodology used for analyzing performance of airports as organizations characterized by the utilization of a variety of inputs and producing multiple outputs. The resources used include runways, terminal capacity, apron, personnel and finances, and the produced outputs include traffic (passenger traffic, aircraft movements and cargo). Due to the impossibility of representing this organization model using just one ratio, DEA emerges as a useful technique for making comparisons among similar decision-making units (DMUs).

The application of DEA to study airports has a rich history. In fact, the first use of DEA for measuring airport productivity and efficiency is attributed to Gillen & Lall (1997). Thus, DEA provides an appropriate tool for measuring efficiency and productivity of airports because of its ability to accommodate organizational and operational diversity associated with various scales, functions, traffic compositions, and structural differences in organization. As Iyer & Jain (2019) observe in their review of applications of DEA in airport research, DEA is well suited for addressing airport-specific challenges because of its superior ability to handle organizational complexities and multiple outputs.

Apart from its use for measuring technical efficiency, DEA has been adapted for more sophisticated purposes in more recent airport studies. Specifically, in a recent study on airport capacity utilization in the US, Karanki & Bilotkach (2023) apply DEA to determine whether airports efficiently utilize their capacity. Likewise, in a related study, Wang et al. (2022) explore runway utilization and output targeting in international airports using DEA. DEA can also be integrated with other evaluation frameworks. For instance, in a study on airport performance assessment using prospect theory and evidential reasoning, Ganji et al. (2023) combine DEA with a prospect theory to make complex decision-making. Singh et al. (2024) use fuzzy DEA to measure airport efficiency in India. Taken together, DEA has been adapted to airport research to serve a wide range of purposes.

In addition to its use for static analysis, DEA can be used for dynamic studies. Indeed, the analysis of airport performance requires a longitudinal view, as efficiency changes over time as result of infrastructure development, varying demands, crises, and recovery efforts. Therefore, Liu & Qian (2024) use super-efficiency DEA to measure performance of major airports in China. They emphasize that a static approach cannot provide an adequate

representation of airports' current performance and should be replaced with a longitudinal approach. Taken together, the discussed examples indicate that DEA provides an effective tool for evaluating airport performance.

### 2.3. Dynamic DEA and the Malmquist Index

One of the ways to expand the capabilities of static DEA models is dynamic DEA. Unlike static DEA, which measures the efficiency level of DMUs at a particular point of time, the dynamic DEA technique allows evaluating whether efficiency increases, decreases, or stabilizes in a specific period. The need for such analysis is clearly demonstrated by many cases, including those involving transportation facilities such as airports, where performance may be subject to the impacts of resource allocation, demand conditions, investments, changes in policy, shocks, and recovery.

Another advantage of dynamic DEA is the possibility of conducting performance analysis for several years or even decades. It is especially useful when outputs change gradually or depend on some external factors that influence operational performance. Zhang et al. (2023) prove that dynamic DEA is effective for estimating both static and dynamic efficiency. At the same time, Liu et al. (2023) prove that DEA-based Malmquist productivity index can help in analyzing not only efficiency levels but also its changes and directions. Recently, several papers have also shown that dynamic DEA is highly relevant for complex performance assessment because performance tends to emerge at various stages. Chaoqun et al. (2024) demonstrate that dynamic network DEA is effective when assessing efficiency under uncertainty and risk, while Deng et al. (2025) apply dynamic network DEA to estimate innovation performance in the new energy vehicle industry. Therefore, the use of the mentioned tools emphasizes the significance of considering the time dimension of performance.

Malmquist productivity index represents one of the most important developments related to DEA because it helps to estimate whether productivity change happens due to movements towards the frontier or shifts of the frontier itself. In other words, it helps to decompose total factor productivity into efficiency changes and technological changes. It is essential because productivity improvement can happen due to internal improvements, development of technology, or both, while productivity decline happens because of poor efficiency or some changes in external conditions. Zhang et al. (2023), Liu et al. (2023), Jain et al. (2025), and Wang & Zhang (2025) emphasize that Malmquist productivity index has become one of the popular tools for DEA-based analysis of productivity changes.

When it comes to airport research, the use of dynamic DEA together with Malmquist index becomes even more relevant because the performance of airports strongly depends on the impacts of traffic volume, investments, crises, and recovery process. Although DEA can determine efficient airports in the current year, it fails to show whether these airports increase or decrease in efficiency or productivity. Therefore, dynamic DEA in conjunction with Malmquist index becomes an excellent tool for analyzing the evolution of airport efficiency and productivity.

### 2.4. Airport Resilience and Recovery After Disruptions

An increasingly important topic in aviation research is the concept of airport resilience. Indeed, airports operate in the environment that is full of uncertainty and disruption. Extreme weather events, systems breakdowns, pandemics, geopolitical tensions, and various kinds of shocks can affect airports. Thus, airport performance cannot be measured simply in terms of resource efficiency under normal conditions; the ability of airports to survive, sustain their operation, and recover from a disruption must also be evaluated. Hence, the literature on airport performance has shifted its focus from efficiency to such aspects of airport management as robustness, vulnerability, flexibility, and recoverability.

Indeed, Janić (2021) defines airport resilience in terms of the three dimensions: robustness, vulnerability, and recoverability. One can observe that airport resilience is multi-dimensional; for instance, even if an airport demonstrates resilience through robustness to disruptions, it could still be considered vulnerable if recovery was long or incomplete. In contrast, an airport that had experienced considerable disruption could still be viewed as resilient if recovery had been fast enough. Moreover, airport resilience research has recently become increasingly focused on developing quantitative measures of resilience. For example, Horton et al. (2025) focus on quantification and measurement of airport resilience through performance indicators. Another recent study – Wandelt et al. (2025) – proposes an airport index aimed at measuring airport resilience quantitatively in order to develop comparisons among airports. This is indicative of an emerging trend toward empirically based assessments of airport resilience.

Another relevant finding is that airport resilience varies depending on the type of event. For example, Zhou and Chen (2020) reveal that airport resilience during severe weather disruption depends not only on the disruption itself but also on the quality of response measures applied. Similarly, Lodiagin et al. (2026) investigate airport resilience during extreme events, emphasizing that the analysis of airport resilience should be made relative to disruption context. Finally, the coronavirus pandemic also highlighted the need for investigating airport resilience during global and structural disruptions: Hiney et al. (2025) analyze airport resilience under black-swan and VUCA events and emphasize the need for adaptation to new airport management conditions.

Overall, one can note that resilience and efficiency represent two distinct perspectives. While airports may demonstrate high levels of efficiency under certain conditions, their recoverability could still be limited. In other words, resilience represents the way airports cope with shocks and disruptors, whereas efficiency is performance under given conditions. An airport that has been highly optimized might turn out to be less flexible and resilient than a less-efficient airport when it comes to disruption because of traffic structure, organizational flexibility, and policies in place. Given this understanding of airport resilience, one can consider the post-pandemic environment where recovery has been achieved differently at different airports.

### 2.5. Literature Gap in the Turkish Context

The research on airport performance in the Turkish context has been developed over time, although it still lacks integration, as compared to the body of knowledge available in the field of international airport efficiency analysis. The existing literature concerning the performance of airports in Türkiye involves operational, sustainable, regulatory, process-related and costing aspects. However, most of these studies are static, and their scope is restricted to some airports, a certain timeframe of airport performance, and methodological application. As recent examples in the Turkish context of airport efficiency studies based on multicriteria decision-making can be referred Akın (2025), who measured airport operational performance using the MPSI-based MABAC technique, and Yüksel and Pırıl (2026), who conducted an evaluation of airport sustainability performance relying on the FAHP-IF-COPRAS methodology.

The studies based on the use of the DEA approach represent another area that deserves mention since they can be considered a valuable addition to the knowledge on Turkish airports' efficiency. Ateş et al. (2018) have utilized the DEA and Malmquist total factor productivity index for airport efficiency measurement, and H. Ulutaş (2018) has assessed airport efficiency paying specific attention to environmental dimensions. Network DEA was implemented by Eren and Doğan (2023) as well as two-stage DEA and common weights by Pehlivanli and Özsoy (2025) for the purposes of measuring Turkish airport performance. It should be stated that all these studies prove that the DEA method is appropriate to evaluate Turkish airports. However, only the aspects related to the assessment of airports' efficiency are discussed by researchers, while the recovery of airports' performance is neglected.

There is a lack of airport studies in the Turkish context considering both the airport performance and its recovery after disruption, which is another deficiency in this literature. The studies conducted by Keskin (2021), whose focus is on the evaluation of airports' efficiency from a regulatory standpoint, and by Ekici and Orhan (2026), whose focus is on the factors affecting unit costs at Turkish airports, can be regarded as an example of the valuable information provided to the literature, although the issue of recovery of airports after disruptive events is not addressed. Hence, there is no framework of longitudinal operational efficiency of Turkish airports available.

Finally, since the system of Turkish airports includes hub airports, tourism-oriented airports and regional airports, different reaction to crisis situations might be expected from them. For this reason, there is a need to conduct dynamic evaluation of Turkish airports in order to identify their efficiency and performance trends as well as to see whether they are recovering after a crisis event. Hence, research of this kind conducted over the 2019-2024 period by the means of DEA and Malmquist index is needed for addressing the identified gaps and to evaluate the use of infrastructure and the ability to recover after disruption.

## 3. METHODOLOGY

### 3.1. Research Design

This study follows a Quantitative Longitudinal Design based entirely on Secondary Data. Here, none of the data collection instruments such as surveys, interviews, or observations were used. Instead, airport-related data was collected from existing sources. The decision to use a Quantitative study based entirely on Secondary data is consistent

with the study's objective of evaluating the efficiency and productivity of selected Turkish airports. The Quantitative approach is particularly pertinent for this study's objective since the study aims to measure the relative efficiency of selected Turkish airports using objective measures of input-output relationships. Since the study is based on evaluating the efficiency of Turkish airports using variables that must be comparable across decision-making units and over time periods, the study's reliance on official data is more robust compared to using self-reported data.

From a methodological standpoint, the study follows a Quantitative approach using a Panel Design where airport performance is analyzed across multiple years. Using a Quantitative approach with a Panel Design enables the study to transcend cross-sectional analysis of airport efficiency to examine the dynamic nature of airport efficiency and productivity. As such, the study follows a Quantitative Longitudinal Design with an efficiency analysis using the Frontier approach. Figure 1 below provides an overview of the study's analytical approach where the study's design is explained in terms of the Quantitative approach using a Panel Design based entirely on Secondary data using the DEA approach and the Malmquist Productivity Index approach for evaluating airport efficiency and recovery in Türkiye for the period 2019 to 2024.

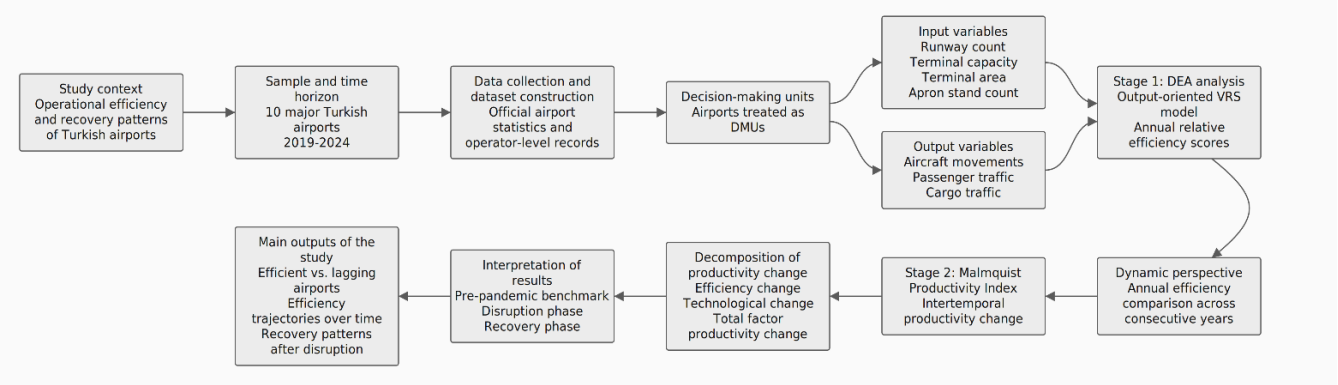



**Figure 1.** Analytical Framework of the Study

### 3.2. Sample

The sample for this study is comprised of 10 major airports in Türkiye. These airports have been purposively selected based on their operational importance in the Turkish aviation system, their traffic volumes, and their availability of comparable data for the study period. These airports have strategic importance in serving different aviation functions, ranging from primary hub operations to serving international tourism traffic and regionally important domestic traffic.

Airports in this study sample:

- İstanbul Airport
- İstanbul Sabiha Gökçen Airport
- Antalya Airport
- Ankara Esenboğa Airport
- İzmir Adnan Menderes Airport
- Muğla Dalaman Airport
- Muğla Milas-Bodrum Airport
- Trabzon Airport
- Gaziantep Airport
- Kayseri Airport

The selection of this sample is based on an attempt to develop a balanced sample for this study in order to analyze airport operations in Türkiye in a more meaningful way. By including İstanbul Airport and Sabiha Gökçen Airport in this sample, this study attempts to account for the metropolitan core of Turkish air transport systems. By including Antalya, Dalaman, and Milas-Bodrum airports in this study sample, this study attempts to account for the importance of tourism-oriented airport operations in Turkish aviation systems. By including Ankara Esenboğa and İzmir Adnan Menderes airports in this study sample, this study attempts to account for more airport operations in

Turkish aviation systems, which are strategically important for their operations and functions. By including Trabzon, Gaziantep, and Kayseri airports in this study sample, this study attempts to account for regionally important airports in Turkish aviation systems.

It is important to note that this study sample is not intended to account for all airports in Turkish aviation systems but to focus more on major airports with consistent and comparable data for this study period. In this regard, this study sample is appropriate for Dynamic DEA and Malmquist analysis since this analysis method requires a stable panel sample with comparable decision units.

### 3.3. Period of Analysis

The time frame covers the period between 2019-2024, chosen due to the appropriate scope that involves three different periods of performance. In particular, 2019 is considered to be the pre-pandemic period when airports operate without disruptions in operations. Next, 2020 and 2021 refer to the disruption period during which the airports experience certain changes in performance as a result of operational and demand issues. Finally, 2022-2024 refers to the recovery period that begins with the recovery of demands in air transport industry, reaching at times higher volumes than before the pandemic. Therefore, this six-year period appears to be an appropriate time frame to investigate not only operational efficiency but also productivity change in terms of disruption and recovery.

### 3.4. Data Sources

The secondary empirical data were gathered using only publicly available sources. Due to Dynamic DEA and the application of Malmquist Productivity Index, it was essential to have verifiable and comparable data. In this regard, three types of sources were utilized in the current study. Namely, the following groups of sources included DHMİ statistics/annual reports, airport/operator reports/institutional websites, and aviation sources (SHGM) in cases when it was required. First, DHMİ statistics were used as the first and primary source of data on yearly output of the airports, namely, passenger traffic volume, aircraft movements and cargo/yük traffic for each airport. Annual reports of DHMİ were also utilized to ensure consistency with respect to sectoral developments. Airport/operator reports and their institutional websites were mainly used to collect information about the infrastructure-related variables such as the number of runways, terminal capacity, terminal area and apron stands. In cases when this information was not available, it was necessary to use the operator information to complement the information about the traffic provided by DHMİ. Table 1 includes all sources used, types of information and its role in the data gathering process.

**Table 1.** Official Data Sources and Variable Coverage

| | **Main institution/source** | **Type of data obtained** | **Use in the study** |
|---|---|---|---|
| National Airport Statistics | DHMİ statistics | Passenger traffic, aircraft movements, cargo/yük traffic | Construction of annual output variables for each airport |
| Annual Institutional Reporting | DHMİ annual reports | Supplementary airport traffic data, annual sectoral information, contextual verification | Cross-checking annual figures and ensuring temporal consistency of the dataset |
| Airport/Operator Official Documents | Airport and operator official reports and webpages | Runway count, terminal capacity, terminal area, apron stand count, airport-specific operational details | Construction of airport infrastructure and capacity input variables |
| Official Aviation Regulatory and Technical Sources | SHGM and other official aviation sources | Aerodrome information, technical airport characteristics, infrastructure verification | Validation and completion of airport-level technical and infrastructure data |

Overall, the use of these official source groups was considered appropriate for the objectives of the study because it enabled the development of a structured and traceable airport-level panel dataset. Since the analysis requires both annual operational indicators and infrastructure-based input measures, reliance on a single source would not have been sufficient. By combining DHMİ statistics with operator-level documentation and official aviation verification records, the study establishes a data foundation that is compatible with the requirements of dynamic DEA and Malmquist productivity analysis.

### 3.5. Variables

The variables used in this study were selected in line with the operational structure of airports and the requirements of DEA-based efficiency analysis. Airports are treated as decision-making units that use physical and infrastructural capacity to generate operational traffic outcomes. Accordingly, the model includes four input variables and three output variables. The input variables are runway count, terminal capacity, terminal area, and apron stand count. These variables represent the infrastructural and physical capacity of airports. The output variables are aircraft movements, passenger traffic, and cargo/yük traffic, which reflect the realized operational performance of airports.

In this study, infrastructure-related variables are treated as capacity inputs, while traffic-related variables are treated as realized operational outputs. This distinction is appropriate because infrastructural variables generally remain stable or change slowly over time, whereas traffic variables vary according to operational conditions, demand fluctuations, and external shocks.

To clarify the variable structure of the model, Table 2 presents the inputs and outputs used in the analysis.

**Table 2.** Input and Output Variables Used in the Analysis

| Variable Category | Variable | Analytical Meaning |
|---|---|---|
| Input | Runway count | Airside operating capacity |
| Input | Terminal capacity | Passenger-handling potential |
| Input | Terminal area | Physical processing capacity |
| Input | Apron stand count | Aircraft parking and handling capacity |
| Output | Aircraft movements | Realized flight activity |
| Output | Passenger traffic | Realized passenger throughput |
| Output | Cargo traffic | Realized freight activity |

This variable structure allows the study to evaluate how well airports translate their physical capacity into actual traffic outcomes over time.

### 3.6. Data Analysis Methods

#### 3.6.1. Data envelopment analysis

Data Envelopment Analysis (DEA) is a non-parametric frontier method used to measure the relative efficiency of similar decision-making units using multiple inputs to produce multiple outputs. In this paper, DEA will be used to measure the effectiveness of each airport in using its infrastructure in generating traffic. DEA assumes nothing about the relationship between multiple inputs and multiple outputs; instead, it uses an empirical method of constructing a best practice frontier based on observations of the best-practice DMUs in the sample and then uses this frontier to evaluate each of the other DMUs (Gillen & Lall, 1997; Iyer & Jain, 2019).

The main objective of using DEA in this paper is to identify which of the airports are running efficiently compared to others in using their infrastructure in generating aircraft movements, passenger traffic, and cargo/yeük traffic. DEA analysis of airports is appropriate because it involves using multiple infrastructure-related inputs to generate multiple outputs. In such a case, productivity ratios based on a single factor are not appropriate in evaluating the performance of an airport, but DEA analysis will be appropriate in providing a systematic way of evaluating efficiency in a multiple input, multiple output case (Gillen & Lall, 1997; Wang et al., 2022).

Another rationale for using DEA as a technique for measuring efficiency is that it uses relative efficiency as opposed to absolute efficiency. An airport is considered to be efficient if, within a given sample of airports, it is not possible for another airport or a group of airports to achieve higher output levels with a given input or to achieve a given output with lower input levels. Hence, it can be seen that using DEA as a technique for measuring efficiency is highly applicable for benchmarking airports within a country's airport system. The technique has been widely used for measuring efficiency in airports. It remains to be one of the most widely used techniques for measuring efficiency in airports (Iyer & Jain, 2019; Karanki & Bilotkach, 2023).

In this research, DEA is considered to be a first step in measuring efficiency for selected airports in Turkey. The efficiency scores are calculated on an annual basis for selected airports. These efficiency scores are then considered for dynamic evaluation using the Malmquist index. The output-oriented Variable Returns to Scale (VRS) DEA model can be defined as follows (Coelli et al., 2005; Wang et al., 2022):

$$\max_{\phi,\lambda} \phi\,, \tag{1}$$

subject to

$$\begin{aligned} \sum_{j=1}^{n} \lambda_j\, x_{ij} &\le x_{io}, \qquad i = 1,2,\dots,m, \\ \sum_{j=1}^{n} \lambda_j\, y_{rj} &\ge \phi y_{ro}, \qquad r = 1,2,\dots,s, \\ \sum_{j=1}^{n} \lambda_j &= 1, \\ \lambda_j &\ge 0, j = 1,2,\dots,n, \end{aligned} \tag{2}$$

where $x_{ij}$ denotes input $i$ used by airport $j$, $y_{rj}$ denotes output $r$ produced by airport $j$, $\lambda_j$ represents the intensity variables, and $\phi$ is the proportional output expansion factor.

### 3.6.2. Dynamic perspective

In this research, airport efficiency is examined from a dynamic perspective by evaluating performance across consecutive years. This approach is important because efficiency is not a fixed condition; it may change due to shifts in demand, resource utilization, operational conditions, or managerial practices. While annual efficiency scores show the relative position of each airport in a specific year, they do not reveal whether efficiency is stable, improving, or declining over time (Zhang et al., 2023; Liu et al., 2023).

Therefore, the 2019–2024 period is used to capture changes in airport efficiency before, during, and after major disruption conditions. This longitudinal perspective makes it possible to identify whether airports-maintained efficiency, lost efficiency, or recovered their efficient position over time. It is particularly relevant for airports because traffic demand, infrastructure use, and recovery capacity may vary considerably across years.

### 3.6.3. Malmquist productivity index

To analyze the dynamic nature of airport performance, this research utilizes the Malmquist Productivity Index (MPI). Although the results of the Data Envelopment Analysis (DEA) indicate relative efficiency scores for each year, the MPI builds upon this by analyzing the productivity changes between each year. Thus, it is possible to move beyond the static nature of airport efficiency and analyze whether the airport performance is improving, declining, or static. This is particularly relevant when conducting a multi-year research study such as this one, where the aim is not only to identify efficient airports but also to analyze the dynamic nature of productivity between the pre-pandemic, pandemic disruption, and pandemic recovery phases.

The Malmquist index is particularly relevant when analyzing productivity because it breaks it down into different components. First, it analyzes the efficiency change, where it identifies whether a decision-making unit (DMU) is moving closer or further away from the best practice frontier. Second, it measures technological change, which captures the movement of the frontier itself across periods. This aspect encompasses changes in the production environment, which might include improvements in operating practices, the utilization of infrastructure, or

performance conditions. Third, the sum of these two aspects defines total factor productivity change. Essentially, it measures the direction and extent of productivity change from one period to another (Zhang et al., 2023; Liu et al., 2023; Jain et al., 2025).

Therefore, the MPI allows the study to not only identify whether there was any change in airport productivity from 2019 to 2024 but also establish the reasons for such productivity change. Thus, an increase in productivity might result from an improvement in relative efficiency or a positive change in the production frontier or both. Similarly, a reduction in productivity might result from a reduction in efficiency or unfavorable change in the production frontier or both. Thus, the Malmquist approach offers a more detailed understanding of airport performance across periods than the DEA scores for individual years.

Formally, the Malmquist total factor productivity index between period $t$ and period $t+1$ can be expressed as follows:

$$MPI = EC \times TC, \tag{3}$$

where

- $MPI$ = total factor productivity change,
- $EC$ = efficiency change,
- $TC$ = technological change.

An $MPI$ value greater than 1 indicates productivity improvement, a value less than 1 indicates productivity decline, and a value equal to 1 indicates no change in productivity. Within this framework, the Malmquist index serves as the principal tool for identifying the productivity trajectories of the sampled Turkish airports across the study period.

### 3.7. Model Orientation and Assumption

The study follows an output-oriented DEA approach with a Variable Returns to Scale assumption. This is consistent with the nature of airport operations and the nature of the dataset used for the study (Banker et al., 1984; Coelli et al., 2005). The output orientation is considered more pertinent for the study since airport operations cannot readily adjust input variables in the short term. Airport variables such as the number of runways, terminal capacity, terminal area, and apron stand count are relatively static or change at a slow pace. Conversely, there is considerable variability in the extent to which airport operations can convert these capacities into outputs such as aircraft movements, passenger traffic, and cargo/yük traffic. As such, the focus of the study is on the capacity for output expansion using existing resources rather than input minimization (Coelli et al., 2005; Wang et al., 2022). The Variable Returns to Scale assumption is equally pertinent for the study. The selected airports vary in terms of airport type, functional role, traffic composition, and operational scale. Some of these airports act as major hubs, whereas others act as tourism-oriented or regionally significant airports. Under these conditions, it is not tenable to assume that all these airports operate at an optimal scale or that input scale changes would result in corresponding output changes. As such, the VRS assumption is more pertinent for evaluating airport efficiency without imposing uniform scale effects across all selected airports (Banker et al., 1984; Iyer & Jain, 2019). As such, the output-oriented VRS DEA approach is methodologically pertinent for the study's objectives.

### 3.8. Validity and Limitations

The validity of the paper lies in the use of secondary information sources, which are easily obtainable. The use of documented data on the efficiency of airports of different levels also helps in transparency, traceability, and replicability of the results, as all variables of the model can be traced in the literature. The use of standardized variables in operational activities also helps in comparison, which is a requirement in DEA/Malmquist method-based analysis. However, a number of factors associated with the paper are acknowledged. Firstly, a number of variables, such as runway numbers, terminal area, and apron stand numbers, are considered to be stable in nature. This could be a drawback in terms of sensitivity to variations in efficiency between years. Secondly, a number of output variables, such as passenger traffic, aircraft movements, and cargo/throughput traffic, are not only a function of operational efficiency but also a function of a number of factors such as macroeconomic conditions, tourism activities, regulatory factors, and environmental factors. Hence, a change in output variables could be a result of a change in environmental factors rather than a change in operational efficiency. The third drawback of the paper is that it only includes a few

airports in Turkey. Hence, the paper does not include all the airports in Turkey. This means that the results of the paper are only applicable to a few of the airports in Turkey.

## 4. FINDINGS

### 4.1. Descriptive Statistics

Table 3 and Table 4 contain the descriptive information for the dataset used in the study. Table 3 aggregates the variables at the airport level by combining the fixed airport infrastructure inputs with the mean annual values of the output variables for the period from 2019 to 2024. Table 4 reports the variables for each year for the entire sample of ten airports. The justification for using these two forms of presentation is based on the fact that the input side of the airport model is heavily based on airport infrastructure, which is relatively stable.

The airport-level presentation of the dataset provides evidence of a highly differentiated structure for the sample of airports. İstanbul Airport is identified as the largest airport in terms of both physical capacity and output variables, followed by İstanbul Sabiha Gökçen Airport and Antalya Airport. Conversely, regional airports such as Kayseri Airport, Gaziantep Airport, and Trabzon Airport operate with much smaller airport infrastructure capacities. Tourism-oriented airports such as Antalya Airport, Muğla Dalaman Airport, and Muğla Milas-Bodrum Airport display highly differentiated output variables. The relevance of the dataset for empirical analysis is further emphasized by the fact that the sample includes hub airports, tourism-oriented airports, as well as regional airports with highly differentiated operational characteristics.

The year-level presentation of the dataset provides evidence of significant year-to-year variability in airport output variables for the entire period under examination. The aggregate output variables for the entire sample of ten airports display significant declines in 2020 compared to the output variables for 2019. Conversely, output variables increase steadily from 2021 onwards, with particularly strong increases in passenger and cargo output variables for the years 2023 and 2024. Conversely, airport infrastructure variables display stability for the entire period, which is consistent with the nature of airport input variables. The evidence presented above further supports the suitability of the dataset for Dynamic DEA and Malmquist analysis based on its representation of a highly differentiated structure with changing airport output variables over time.

**Table 3.** Descriptive Statistics by Airport (2019–2024 Average Outputs)

| Airport | Runway count | Terminal capacity (pax/year) | Terminal area (m²) | Apron stand count | Mean annual aircraft movements | Mean annual passengers | Mean annual cargo/yük (tons) |
|---|---|---|---|---|---|---|---|
| İstanbul Airport | 5 | 90,000,000 | 1,400,000 | 371 | 296,731 | 55,593,705 | 1,160,724 |
| İstanbul Sabiha Gökçen Airport | 1* | 41,000,000 | 320,000 | 24 | 211,925 | 30,748,731 | 50,482 |
| Antalya Airport | 2 | 82,000,000 | 191,000 | 202 | 172,618 | 24,728,251 | 8,358 |
| Ankara Esenboğa Airport | 2 | 10,000,000 | 182,000 | 21 | 83,100 | 9,331,734 | 11,866 |
| İzmir Adnan Menderes Airport | 2 | 35,000,000 | 310,978 | 72 | 87,649 | 9,003,673 | 24,677 |
| Muğla Dalaman Airport | 1 | 12,000,000 | 95,000 | 35 | 38,939 | 3,796,642 | 82 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Muğla Milas-Bodrum Airport | 1 | 5,000,000 | 95,683 | 47 | 35,767 | 3,027,538 | 165 |
| Trabzon Airport | 1 | 4,000,000 | 26,870 | 17 | 24,719 | 2,987,340 | 737 |
| Gaziantep Airport | 1 | 8,000,000 | 72,593 | 18 | 21,914 | 2,366,883 | 1,239 |
| Kayseri Airport | 1 | 8,000,000 | 37,500 | 13 | 16,894 | 1,845,185 | 774 |

*Runway count for İstanbul Sabiha Gökçen varies within the dataset because the second runway became operational during the study period.

**Table 4.** Descriptive Statistics by Year (Full Sample Totals)

| Year | Runway count | Terminal capacity (pax/year) | Terminal area (m²) | Apron stand count | Total aircraft movements | Total passengers | Total cargo/yük (tons) |
|---|---|---|---|---|---|---|---|
| 2019 | 17 | 295,000,000 | 2,731,624 | 820 | 1,215,873 | 173,904,127 | 689,726 |
| 2020 | 17 | 295,000,000 | 2,731,624 | 820 | 640,983 | 75,486,247 | 564,577 |
| 2021 | 17 | 295,000,000 | 2,731,624 | 820 | 852,482 | 115,509,953 | 882,032 |
| 2022 | 17 | 295,000,000 | 2,731,624 | 820 | 1,118,208 | 164,717,771 | 1,605,404 |
| 2023 | 17 | 295,000,000 | 2,731,624 | 820 | 1,205,476 | 190,230,229 | 1,657,543 |
| 2024 | 18 | 295,000,000 | 2,731,624 | 820 | 1,333,847 | 214,637,731 | 2,155,342 |

Overall, the descriptive statistics show that the dataset contains both substantial cross-sectional variation among airports and clear intertemporal variation across years. This structure provides an appropriate empirical basis for the subsequent efficiency and productivity analyses.

### 4.2. DEA Efficiency Scores

Table 5 below reports the annual DEA efficiency scores for the 10 selected airports. These efficiency scores were calculated on an output-oriented VRS DEA model, which is consistent with the methodological framework of this study. In this DEA framework, a score of 1.000 means that the airport is on the efficient frontier for a given year, while a score less than 1.000 means that the airport is relatively inefficient.

The results reveal that İstanbul Airport, İstanbul Sabiha Gökçen Airport, Ankara Esenboğa Airport, Trabzon Airport, and Muğla Milas-Bodrum Airport were efficient over the entire period from 2019 to 2024. Similarly, Antalya Airport was efficient from 2019 to 2020 and from 2021 to 2024, except for 2020 when there was a marginal decline in efficiency to 0.956. In contrast, İzmir Adnan Menderes Airport had the lowest efficiency scores over all years under consideration. Gaziantep, Kayseri, and Muğla Dalaman had lower efficiency scores, but these improved over time. In aggregate, the mean DEA efficiency scores for all airports varied from 0.773 to 0.925 annually. The highest mean efficiency score was recorded in 2024 when all eight airports were on the efficient frontier. This pattern reveals that, on average, there was stronger relative output performance in the later stages of the crisis period than during the disruption years.

**Table 5.** Yearly DEA Efficiency Scores of Turkish Airports (Output-Oriented VRS Model)

| Airport | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|---|
| İstanbul Airport | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| İstanbul Sabiha Gökçen Airport | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Antalya Airport | 1.000 | 0.956 | 1.000 | 1.000 | 1.000 | 1.000 |
| Ankara Esenboğa Airport | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| İzmir Adnan Menderes Airport | 0.399 | 0.412 | 0.388 | 0.392 | 0.356 | 0.364 |
| Muğla Dalaman Airport | 0.474 | 0.497 | 0.445 | 0.539 | 0.525 | 1.000 |
| Muğla Milas-Bodrum Airport | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Trabzon Airport | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Gaziantep Airport | 0.402 | 0.555 | 0.430 | 0.441 | 0.472 | 1.000 |
| Kayseri Airport | 0.450 | 0.510 | 0.513 | 0.551 | 0.495 | 0.885 |
| Mean Efficiency | 0.773 | 0.793 | 0.778 | 0.792 | 0.785 | 0.925 |
| Number of Efficient Airports | 6 | 5 | 6 | 6 | 6 | 8 |

These findings indicate that airport efficiency in the sample was not uniform across the period. Some airports-maintained frontier status consistently, while others showed persistent inefficiency or a delayed recovery pattern. This provides an important basis for the subsequent interpretation of productivity change and recovery dynamics.

Figure 2 displays the yearly evolution of average DEA efficiency scores and the number of airports located on the efficient frontier, providing a concise overview of system-level performance and the strength of recovery across the Turkish airport network during the 2019–2024 period.

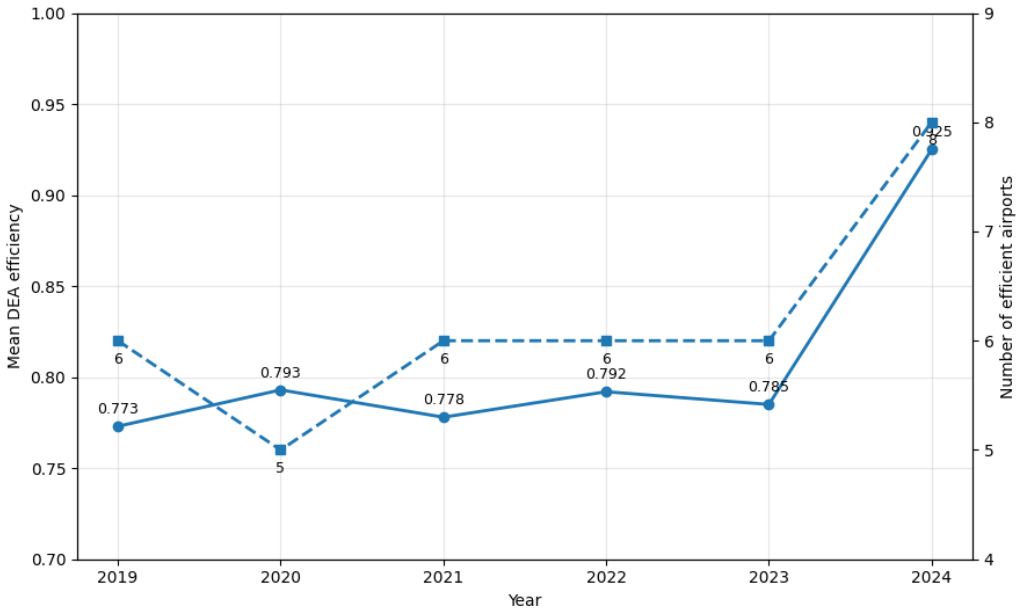



**Figure 2.** Mean Annual DEA Efficiency and Frontier Airport Count (2019–2024)

### 4.3. Efficient and Inefficient Airports

The DEA results allow for a clear discrimination between those airports which lie on the efficient frontier and those which are behind in terms of relative operational performance. In an output-oriented VRS model, those airports

which receive a DEA score of 1.000 are considered to be efficient, as they are producing the maximum output levels in comparison to all other sample airports. Those airports which receive a DEA score of less than 1.000 are considered to be relatively inefficient, as they potentially offer scope for increased operational output without requiring additional inputs.

The results clearly show that several of the airports in the model consistently operated on the efficient frontier throughout the analysis period. In particular, İstanbul Airport, İstanbul Sabiha Gökçen Airport, Ankara Esenboğa Airport, Muğla Milas-Bodrum Airport, and Trabzon Airport were all efficient in all years from 2019 to 2024. This indicates that these five airports maintained a stable frontier performance profile. A similar picture emerges for Antalya Airport, which was efficient in all years except 2020. This indicates that Antalya maintained a very high-performance profile throughout the analysis period, except for a slight blip in 2020 when it failed to achieve a frontier score.

On the contrary, there were several airports that remained below the efficient frontier for most or all of the time period under consideration. Among them, İzmir Adnan Menderes Airport had the lowest efficiency scores in every year of the sample, indicating relatively lower operational outputs compared to their potential based on their existing infrastructure capacity in the sample. Kayseri Airport, Gaziantep Airport, and Muğla Dalaman Airport also remained below the frontier for most years, though with different trends in their performances. Kayseri Airport showed persistent but relatively low inefficiency throughout the time period, whereas Gaziantep Airport and Muğla Dalaman Airport showed significant improvement in their performances in later years of the sample period. In particular, in 2024, Gaziantep Airport and Muğla Dalaman Airport reached the frontier, indicating a significant improvement in their relative output performances towards the end of the sample period.

It is also noteworthy that the airports that reached the frontier in different years did not necessarily do so uniformly across different types of airports. For example, airports such as İstanbul Airport and İstanbul Sabiha Gökçen Airport had high potential based on their existing infrastructure capacity in the sample but also showed high output performances, whereas airports such as Trabzon and Muğla Milas-Bodrum Airport had relatively small potential based on their existing capacity in the sample but also showed high output performances in reaching the frontier. In particular, this suggests that DEA efficiency is not necessarily based on the scale or size of airports but also on their potential in converting their existing capacity into actual aircraft, passengers, and cargo movements. In contrast, airports such as Kayseri Airport, Gaziantep Airport, and Muğla Dalaman Airport appear to have relatively low output performances compared to their existing capacity in the sample.

To summarize these distinctions, Table 6 classifies the airports according to their frontier position over the 2019–2024 period.

**Table 6.** Classification of Efficient and Inefficient Airports Based on DEA Results

| Airport | Efficiency status | Interpretation |
|---|---|---|
| İstanbul Airport | Efficient in all years | Stable frontier airport |
| İstanbul Sabiha Gökçen Airport | Efficient in all years | Stable frontier airport |
| Antalya Airport | Efficient in 5 of 6 years | Near-frontier / highly efficient |
| Ankara Esenboğa Airport | Efficient in all years | Stable frontier airport |
| İzmir Adnan Menderes Airport | Inefficient in all years | Persistent lagging airport |
| Muğla Dalaman Airport | Inefficient in 5 years, efficient in 2024 | Improving airport |
| Muğla Milas-Bodrum Airport | Efficient in all years | Stable frontier airport |
| Trabzon Airport | Efficient in all years | Stable frontier airport |
| Gaziantep Airport | Inefficient in 5 years, efficient in 2024 | Improving airport |
| Kayseri Airport | Inefficient in all years | Persistent lagging airport |

Overall, the results indicate that the sample contains three broad groups: stable frontier airports, near-frontier or improving airports, and persistent lagging airports. This distinction is analytically important because it provides the basis for interpreting subsequent productivity and recovery findings in a more structured way.

### 4.4. Malmquist Productivity Results

Table 7 displays the Malmquist Total Factor Productivity Change (TFPCH) results for each airport across successive periods. According to the Malmquist index, a TFPCH of more than 1.000 indicates productivity improvement, whereas a TFPCH of less than 1.000 indicates productivity decline, and a TFPCH of 1.000 indicates no change. As explained above, the Malmquist index decomposes productivity change into efficiency change and technological change; however, for better clarity, we report the overall results of TFPCH by airport and period.

The results indicate considerable variability in productivity change across the sample of airports. The most severe productivity decline was experienced between 2019 and 2020, when the sample average of TFPCH across airports declined to 0.538. This result is consistent with the severe disruption of airport activities at the beginning of the pandemic. A robust productivity growth spurt was experienced between 2020 and 2021, and between 2021 and 2022, when the sample average of TFPCH rose to 1.470 and 1.278, respectively. This growth spurt continued between 2022 and 2023, albeit at a slower rate. Between 2023 and 2024, the sample average of TFPCH declined slightly to 0.973, suggesting a more heterogeneous productivity growth spurt towards the end of the sample period.

In terms of airport-specific results, İstanbul Airport experienced the highest productivity growth spurt over the sample period, with a cumulative TFPCH of 2.084. Gaziantep, Muğla Milas-Bodrum, Muğla Dalaman, Kayseri, and Antalya airports also experienced productivity growth spurt between 2019 and 2024. Conversely, productivity declined slightly at İzmir Adnan Menderes and Trabzon airports, whereas the sharpest productivity decline was experienced at İstanbul Sabiha Gökçen airport. However, it is important to note that the infrastructure base of this airport changed within the sample period, which may influence intertemporal productivity results.

**Table 7.** Malmquist Total Factor Productivity Change (TFPCH) by Airport

| Airport | 2019–2020 | 2020–2021 | 2021–2022 | 2022–2023 | 2023–2024 | Cumulative 2019–2024 |
|---|---|---|---|---|---|---|
| İstanbul Airport | 0.649 | 1.761 | 1.317 | 1.113 | 1.258 | 2.084 |
| İstanbul Sabiha Gökçen Airport | 0.565 | 1.334 | 1.070 | 1.168 | 0.184 | 0.173 |
| Antalya Airport | 0.184 | 2.116 | 1.382 | 1.109 | 1.932 | 1.095 |
| Ankara Esenboğa Airport | 0.375 | 1.441 | 1.153 | 1.334 | 1.348 | 1.001 |
| İzmir Adnan Menderes Airport | 1.097 | 1.147 | 1.160 | 0.898 | 0.672 | 0.949 |
| Muğla Dalaman Airport | 0.843 | 0.918 | 1.583 | 1.063 | 0.871 | 1.132 |
| Muğla Milas-Bodrum Airport | 0.529 | 0.671 | 1.794 | 1.288 | 1.448 | 1.185 |
| Trabzon Airport | 0.709 | 1.244 | 1.008 | 0.951 | 0.923 | 0.981 |
| Gaziantep Airport | 1.383 | 0.851 | 1.942 | 1.263 | 0.429 | 1.203 |
| Kayseri Airport | 1.048 | 1.221 | 1.367 | 0.622 | 1.290 | 1.125 |
| Mean TFPCH | 0.538 | 1.470 | 1.278 | 1.121 | 0.973 | — |

Overall, the Malmquist results confirm that airport performance in the sample was shaped not only by differences in static efficiency, but also by substantial intertemporal variation in productivity. The findings suggest that the disruption period was followed by a strong but uneven recovery, with some airports achieving sustained productivity gains while others experienced volatility or late-period decline. These results provide an important basis for the next subsection, which interprets the airports in terms of broader recovery patterns.

### 4.5. Recovery Pattern Analysis

In order to further interpret the post-disruption trajectories of Turkish airports' DEA values, these airports have been classified on the basis of their annual DEA scores, stability and speed of recovery when compared with their corresponding DEA values in 2019. The classification is not limited to a mere efficient/in-efficient classification and determines whether these airports have managed stable performance, quick recovery, delayed recovery, or volatility with respect to tourism-oriented traffic patterns.

Four recovery patterns can be distinguished in terms of the classification mentioned above. The first pattern includes strong and stable performers, such as Istanbul Airport, Sabiha Gökçen International Airport, Ankara Esenboğa Airport, Trabzon Airport and Muğla Milas-Bodrum Airport. These airports managed to preserve frontier efficiency for most or all years in question. Istanbul Airport and Sabiha Gökçen International Airport preserved their frontier efficiency from 2019 to 2024 and also surpassed their 2019 passenger throughput by 2024. The second group is formed by airports that recovered quickly, which include Gaziantep Airport and Muğla Dalaman Airport. The airports had comparatively low DEA scores for most of the considered time period; however, reached frontier efficiency by 2024 and also surpassed their passenger traffic of 2019 in the process. The next group represents airports with slow recovery and includes İzmir Adnan Menderes Airport and Kayseri Airport. The airports either stayed behind frontier or recovered slower. İzmir registered the lowest average DEA score and failed to recover its passenger level of 2019 by 2024. At the same time, Kayseri managed to perform better during some years but did not reach frontier efficiency. Finally, the last group represents volatile tourism-oriented airports: Antalya, Muğla Dalaman and Muğla Milas-Bodrum. The airports experienced considerable decrease in traffic in 2020 but showed quick recovery in subsequent years. While Antalya Airport performed rather efficiently, Muğla Dalaman only became frontier-efficient in 2024 and Muğla Milas-Bodrum remained frontier-efficient all along despite volatility.

**Table 8.** Recovery Pattern Classification of Sampled Airports

| Airport | DEA Pattern (2019-2024) | 2024 Passengers/2019 Passengers | Recovery Category |
|---|---|---|---|
| İstanbul Airport | Efficient in all years | 1.546 | Strong and stable performer |
| İstanbul Sabiha Gökçen Airport | Efficient in all years | 1.170 | Strong and stable performer |
| Ankara Esenboğa Airport | Efficient in all years | 0.940 | Strong and stable performer |
| Trabzon Airport | Efficient in all years | 0.962 | Strong and stable performer |
| Muğla Milas-Bodrum Airport | Efficient in all years | 0.997 | Strong and stable performer / volatile tourism-dependent |
| Antalya Airport | Efficient in 5 of 6 years | 1.069 | Volatile tourism-dependent airport |
| Muğla Dalaman Airport | Inefficient in 2019–2023, efficient in 2024 | 1.149 | Rapid recovery airport / volatile tourism-dependent |
| Gaziantep Airport | Inefficient in 2019–2023, efficient in 2024 | 1.171 | Rapid recovery airport |
| İzmir Adnan Menderes Airport | Inefficient in all years | 0.931 | Delayed recovery airport |
| Kayseri Airport | Inefficient in all years | 1.119 | Delayed recovery airport |

A notable point is that some airports can reasonably belong to more than one interpretive category. For example, Muğla Milas-Bodrum was operationally efficient throughout the study period, yet its traffic pattern was still shaped by tourism-related volatility. Likewise, Muğla Dalaman can be interpreted both as a rapid-recovery airport and as a tourism-dependent airport. This overlap is substantively meaningful, since airport recovery is shaped by both relative efficiency and demand structure.

### 4.6. Comparative Interpretation

In general, the results show a definite difference between hub and regional airports, as well as between tourism-related and domestic-demand-oriented airports. Such a difference suggests that not only the size of infrastructure but also the role of airports within the transportation network and the character of underlying demand influences the level of airport performance.

First of all, according to the obtained results, both large hub airports (İstanbul Airport and İstanbul Sabiha Gökçen Airport) were able to achieve frontier performance throughout the whole examined period. In other words, large-scale airports are able to maintain efficient operations despite the complications associated with handling huge amounts of passengers and managing significant infrastructures. On the other hand, the findings prove that achieving frontier performance is possible without being an airport with a great deal of infrastructure. Namely, Trabzon Airport managed to stay at the frontier throughout all examined years in spite of the relatively low number of flights. Thus, it can be stated that efficiency depends on the effective utilization of airport infrastructure resources.

As for regional airports, they demonstrated various results. While some of them showed positive trends, others demonstrated persistently low efficiency. Specifically, Gaziantep Airport succeeded to achieve full efficiency during all investigated years, which means that this airport was highly successful in terms of its output performance. However, such airports as Kayseri Airport and İzmir Adnan Menderes Airport could not achieve frontier performance during the period under discussion. Therefore, it can be suggested that it would be incorrect to consider all regional airports equally, because efficiency depends on particular market circumstances.

Another major difference in the results is associated with the nature of underlying demand. As stated above, Antalya, Muğla Dalaman, and Muğla Milas-Bodrum airports have a more tourism-oriented profile. This resulted in more frequent changes in traffic volume and greater volatility. At the same time, it is necessary to state that tourism-oriented airports did not demonstrate poor performance. Thus, for example, Antalya Airport had efficient output performance throughout the whole period. Also, Muğla Milas-Bodrum airport maintained full efficiency. Finally, Muğla Dalaman airport was not quite efficient during the initial years but demonstrated considerable growth in 2024. Therefore, it can be concluded that tourism-related airports had lower stability in their performance, but they recovered faster after any shock or crisis period.

At the same time, airports with a more domestic demand, such as Ankara Esenboğa, Trabzon, Gaziantep, and Kayseri, demonstrated fewer changes in the volume of traffic. Despite the stability of demand, these airports were not efficient. Namely, Ankara Esenboğa Airport and Trabzon Airport maintained frontier efficiency throughout the whole period, while Kayseri Airport demonstrated inefficient operations during all investigated years. Finally, Gaziantep Airport reached the frontier only in the final year. Consequently, it is safe to claim that the airports characterized by domestic demand have more stable output performance, but they are not necessarily efficient.

Based on the presented analysis, it can be suggested that the performance of Turkish airports is influenced by many factors. First, each airport can be characterized by its specific functional role within the air transportation network, which affects the level of efficiency and output performance. Second, there is a significant difference in demand characteristics; some airports face greater fluctuations in passenger volume due to unstable demand profile, but some airports operate with stable demand. Third, there is a certain dependence between the utilization of available infrastructure resources and performance efficiency.

## 5. DISCUSSION

### 5.1. Interpretation of Efficiency Findings

Based on the findings, airport efficiency in Türkiye is dependent on the type of functions undertaken at each airport, demand structure, and use of available capacity, rather than just on the size of the infrastructure. Istanbul Airport and Istanbul Sabiha Gökçen Airport have been frontier-efficient throughout the period under consideration.

It means that even big airport hubs with lots of traffic are capable of efficiency in the long run. Also, the fact that Trabzon Airport is still efficient, despite being a much smaller airport, shows that efficiency is related to capacity utilization more than size.

For regional airports, the results are quite varied. Thus, Gaziantep Airport attained efficiency towards the latter half of the period, which shows success in adapting to their output performances. At the same time, Kayseri Airport and İzmir Adnan Menderes Airport failed to become frontier-efficient. Hence, regional airports should not be viewed as a homogenous category. Instead, their performance is determined by the level of local demand and ability to generate traffic within their capacities.

The same applies to demand structure since it determines how airports respond to pandemic-related issues and what recovery rates they exhibit. Tourism-driven airports like Antalya, Muğla Dalaman, and Muğla Milas-Bodrum were hit harder by the problems caused by the pandemic. Yet, Antalya was on or close to the frontier of efficiency, Milas-Bodrum sustained full efficiency in spite of some changes in demand, while Dalaman improved greatly by 2024. The airports relying mostly on domestic traffic like Ankara Esenboğa, Trabzon, Gaziantep, and Kayseri showed less traffic changes. Nonetheless, this did not guarantee greater efficiency.

### 5.2. Interpretation of Recovery Patterns

In terms of recovery patterns, one can observe that the post-disruption airport performance was influenced by traffic structure, tourism dependency, hubness, and regional demand dynamics. First, diversified airports had higher potentials for recovering from the disruptions since they had lower dependencies on specific passenger groups and route structures. Both Istanbul airports have a great number of network functions, diversified traffic, and high levels of integration with national and international airline networks. Second, tourism airports had a unique recovery pattern. For instance, Antalya, Dalaman, and Milas-Bodrum airports suffered greatly from the disruptive impacts of the global coronavirus pandemic because they depend mainly on tourism flows. However, even such airports can quickly restore their positions if demand returns and becomes stable. Indeed, despite the dependence on tourism demand, Antalya airport remained highly efficient, while Dalaman demonstrated some improvements in the latter half of the period under analysis. Third, hub airports are not just large and busy airports but play a critical role in the functioning of air transportation networks. The bridging nature of hub airports' functioning explains why both Istanbul airports showed a high efficiency level in all the years under consideration. In turn, regional airports had strong dependencies on regional demand dynamics. The differences between the recovery dynamics of Gaziantep and Trabzon airports suggest that economic development, internal mobility, and regional demand dynamics also play an important role in understanding the recovery patterns of airports.

### 5.3. Comparison with Previous Studies

The results support the literature on airport efficiency and reinforce the importance of using the DEA method for evaluating airports considering their complex multi-input and multi-output production process (Gillen & Lall, 1997; Iyer & Jain, 2019). Furthermore, they support the claim that airport efficiency cannot be inferred based on the airport size. Thus, large airports might be efficient, whereas smaller airports can become efficient if the available infrastructure is used effectively.

The results of the current study are consistent with research focusing on capacity utilization and output targeting. While Wang et al. (2022) argue that output targeting is important for airport efficiency, Karanki and Bilotkach (2023) emphasize capacity utilization. Similarly, the current findings show that some airports operate below the efficiency frontier not because of a lack of infrastructure but due to insufficient conversion of the capacity into traffic outputs.

Furthermore, the research results are consistent with previous DEA-based airport efficiency analyses carried out for Turkey (Ateş et al., 2018; Eren & Doğan, 2023; Pehlivanlı & Özsoy, 2025). The study contributes to the literature by incorporating the dynamic aspects of productivity and efficiency measurement into airport efficiency analysis and providing annual evaluations during the period 2019–2024. In addition, it provides an interpretation of the results through the lens of disruptions and recoveries, addressing the gap in the Turkish literature on airport efficiency and post-crisis recovery.

Finally, the results are consistent with the literature on resilience. According to Janić (2021), the concept of resilience should be viewed in terms of robustness, vulnerability, and recoverability. Similarly, Horton et al. (2025)

and Wandelt et al. (2025) underline the need for explicit performance metrics to evaluate airport resilience. The current study supports this idea and shows that efficiency and recovery are interconnected but different phenomena. Some airports were efficient at all times, while others showed gradual improvement and became more resilient towards the end.

### 5.4. Aviation Management Implications

Consequences of the research findings can be considered from various perspectives. Firstly, airport planning should consider not only the expected traffic growth or amount of infrastructure available to an airport. The fact that some airports possessing well-developed infrastructure did not appear efficient according to the results of this research means that planners must place the emphasis on capacity diagnosis and output generation. Secondly, airport operators should make sure that airport capacity is being effectively used. Due to the fact that airport infrastructure is expensive and rigid, lack of airport capacity utilization may lead to decreased efficiency of operations. Therefore, the results concerning İzmir Adnan Menderes and Kayseri airports indicate the necessity to estimate how efficient the airport capacity allocation matches traffic development plans. Thirdly, investments must be made differently depending on the particular characteristics of each airport. Efficient airports may need flexible investments, whereas non-efficient airports may require improvement in operations, traffic development, or process optimization rather than infrastructure investments. In other words, investments must be based on efficiency analysis rather than simply growth expectations. Fourthly, crisis preparedness must vary depending on the particular purpose of the airport. Disruption and recovery processes differ in tourism airports, hub airports, and regional airports, and a common crisis strategy will not provide sufficient protection for any of these categories. Therefore, special attention should be paid to developing different crisis strategies for different types of airports. Finally, this research indicates that there is a need for implementing differentiated regional airport policies in Türkiye. Regional airports cannot be treated as a homogeneous group because their efficiency and recovery patterns are quite heterogeneous, which means that some may require network development, role reassignment, or specialization, while others may require traffic diversification and cost control.

## 6. CONCLUSION

This study evaluates the efficiency and recovery dynamics of ten largest airports of Türkiye over the period from 2019 to 2024 using the Output Oriented Variable Returns to Scale Data Envelopment Analysis model and Malmquist Productivity Index. Airport efficiency has been found to vary depending on each airport and time. Istanbul Airport, Istanbul Sabiha Gökçen Airport, Ankara Esenboğa Airport, Trabzon Airport, and Muğla Milas-Bodrum had dominated the efficient frontier, while Izmir Adnan Menderes and Kayseri did not reach the frontier. In addition, the results imply that the post-disruption recovery pattern among airports cannot be explained by the level of traffic volumes alone, but rather by such factors as infrastructure utilization and airport and demand type.

In terms of contributions to aviation management, this study explores the relationship between efficiency and recovery after disruption for Turkish airports, which has not been well-studied yet. While previous research has investigated airport efficiency in Türkiye, studies evaluating multi-year recovery of airports in terms of efficiency are scarce. Thus, the contribution of the paper consists in providing evidence that the efficiency of airports should be analyzed together with their post-disruption recovery.

First and foremost, it is evident that airport performance evaluation requires considering not only traffic growth trends but also efficiency, i.e., the ability of an airport to utilize its existing infrastructure. If the capacity of an airport exceeds traffic volume output, then an airport remains inefficient even though it is quite capable of serving a high number of customers. This implies that increasing the efficiency of the airport before investing in new infrastructure should remain one of priorities. Second, airports of different types face different demand and functional requirements, thus policymakers should refrain from developing standard strategies for all airports. Strategies should be developed based on empirical efficiency findings.

Limitations of the study should also be mentioned. Primarily, airport selection implies that only ten airports were considered. Even though these airports constitute key players of the Turkish airport market, their number remains insufficient to evaluate the whole set of airports of Türkiye. Second, only publicly available secondary sources have been used, which allowed evaluating a narrow set of variables and made this study transparent. Moreover, some infrastructural variables can have time-related impact due to the implementation of new expansions over the study

period. Future research can use a broader sample of airports to evaluate their performance. In addition, other factors can be considered in the analysis, for example, environment, finance, service quality, and others. Finally, the methodology can be expanded through such techniques as Bootstrapping and Network DEA.

## ETHICAL STATEMENT & GENERAL STATEMENTS

This article meets the standards of research and publication ethics.

## ARTIFICIAL INTELLIGENCE USE DISCLOSURE

During the preparation of this manuscript, some Artificial Intelligence (AI) tools were used solely to improve grammar, spelling, punctuation, and/or linguistic fluency. AI was not used to generate the scientific content of the study. All AI-assisted suggestions were reviewed and verified by the author(s).

## AUTHORS' CONTRIBUTIONS

The authors have read and approved the final manuscript.

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## COMPETING INTERESTS

The authors declare that they have no competing interests.

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