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Usage Of Digital Twin Technologies In Airports: The Case Of Istanbul Airport*

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Abstract

This study investigates the application potential of digital twin technology in airport management through the case of Istanbul Airport. Digital twin is an innovative technology that aims to enhance operational efficiency and strengthen decision-making processes by creating digital representations of physical systems. Adopting a qualitative research approach, the study collected data through literature review, document analysis, and semi-structured interviews. The findings indicate that digital twin applications at Istanbul Airport are primarily utilized in infrastructure monitoring, maintenance planning, and operational simulation. However, structural challenges such as data compatibility, human resources, and cybersecurity emerge during the integration process. The study identifies that digital twin systems contribute to airport management particularly in areas such as scenario analysis and predictive maintenance. It concludes that digital twin technology can be considered a strategic tool in airport management and offers practical recommendations for its implementation in the aviation sector.

Keywords: Digital Twin, Istanbul Airport, Airport Management, Digital Transformation.

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1. Introduction

Digitalization in the aviation sector plays a significant role in increasing operational efficiency, ensuring safety, and improving service quality. Digital twin technology, which is based on the principle of modeling physical systems in a virtual environment and integrating them with real-time data, has become a major transformation tool in airport management. Digital twins stand out as a technology developed to monitor, simulate, and optimize complex systems, large-scale operations, and physical assets. Their ability to simultaneously perform multiple functions such as continuous system performance monitoring, predictive maintenance applications, scenario-based analysis, and decision support offers effective utilization in dynamic environments such as airports [1; 2; 3].

Digital twin technology contributes to the more efficient management of operations in various areas, ranging from cargo and baggage handling systems to ground services, passenger information boards, and building automation systems [4]. By combining real-time data flow with simulations, it enables improvements in resource management, operational decision-making processes, and service quality [5; 6]. Nacak (2023) has shown that digital twin applications reduce costs in production and operational processes, facilitate fault detection, and shorten operation durations. Similarly, Yıldırım (2023) stated that digital twins

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positively impact areas such as efficiency, maintenance processes, and resource utilization in airport management [7]. A review of implementation examples reveals that digital twin technology is used for various purposes in different airports. At Singapore Changi Airport, it is actively employed for the dynamic management of passenger flows and efficient use of terminal capacity; at London Heathrow Airport, for optimizing aircraft parking positions and air traffic flows; and at Amsterdam Schiphol Airport, for infrastructure planning and enhancing energy efficiency. These examples demonstrate that the technology contributes not only to daily operations but also to long-term strategic planning [8; 9; 10]. Digital twin systems also offer significant advantages in terms of security management. By spatially monitoring hazards, simulating emergency scenarios, and optimizing command operations, they strengthen safety processes [10]. In this regard, digital twins contribute not only to operational but also to structural decision-making mechanisms.

However, the integration process of digital twin technology also brings various challenges, such as high cost, data security, system interoperability, and stakeholders' willingness to adapt to digitalization [3; 7]. With all these strengths and weaknesses, digital twins are expected to play a decisive role in the future of airport management.

This study examines the integration of digital twin technology into the operational processes of Istanbul Airport and aims to analyze the contributions of the technology to airport management as well as the challenges encountered during its implementation.

2. Airport Concept and Airport Operations

Airports are specially organized areas designed to enable the landing and takeoff of aircraft, equipped with infrastructure for flight preparation and buildings required for managing passenger traffic [11]. At the same time, airports are multifunctional commercial facilities constructed for the transportation of passengers and cargo, serving as gateways that establish a country's international connectivity. By facilitating transitions between air and ground transportation, airports possess physical, social, and economic infrastructure that brings all stakeholders together [12]. As one of the core components of the air transport system, airports today are not only transportation hubs but also integrated systems that develop technological infrastructure and prioritize sustainable practices [13]. Global economic, technological, socio-cultural, and political changes have affected the structure of airports, leading to a redefinition of these structures [12].

The activities carried out in airports have diversified in line with these developments and have evolved into a multi-stakeholder service network. Airport activities are generally grouped under two main headings: "aviation services" and "non-aviation services" [14].

Aviation services include fundamental airport operations such as air traffic control, meteorology, security, firefighting, and runway-apron maintenance [15; 16], as well as ground handling services like passenger services, ramp operations, cargo transportation, basic aircraft maintenance, and catering [17]. Non-aviation services, on the other hand, encompass commercial activities such as restaurants, duty-free shops, banks, and car rentals, which both diversify revenues and contribute to passenger satisfaction [12]. The effectiveness of these services is largely linked to resource management, technical capacity, facility infrastructure, and adaptation to digital technologies. Airports are evolving alongside technological advances and growing passenger traffic, being equipped with innovative systems that increase efficiency and safety. These developments not only enhance speed and effectiveness in operational processes but also elevate service quality aimed at improving passenger experience. In the literature, such technological transformation is often addressed under topics like airport digitalization, Industry 4.0 in airports, or smart airports [18].

The integration of digitalization and automation systems lays the foundation for the restructuring of today's airports within the framework of the smart airport concept. Due to their dynamic nature, airports are systems that continuously evolve in both physical and managerial processes. Emerging digital technologies are making this system more agile, flexible, and data-driven, thereby spreading the smart airport concept. Advanced digital applications are used in many processes, from check-in and baggage tracking to security and passenger guidance. Terminal navigation via mobile devices, biometric identification systems, facial recognition technology, IP-based security solutions, data mining, and AI-powered operational systems are among the core components of smart airports [19]. Particularly, self check-in kiosks and AI-assisted procedures are among the most visible examples of this transformation [42].

Smart airport applications offer multiple benefits such as increasing passenger satisfaction, improving resource efficiency, and enhancing the competitive advantage of airport operators. These digital solutions are not merely technological innovations but are also considered instruments of transformation for a holistic approach to airport management and service delivery.

2.1. Smart Airports and the Use of Smart Technologies in Airports

A smart airport is defined as a modern airport model that enhances operational efficiency, improves passenger experience, and supports sustainability through the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics. Also referred to as "Airport 4.0," this concept is described in various ways in the literature and is continually evolving. The concept has developed in relation to other digitalization-focused structures such as "smart buildings," "smart cities," and "smart factories," and is positioned as a system that aims to integrate urban life with flight operations.

These structures aim to optimize operational processes and increase customer satisfaction by accelerating the flow of information between urban transportation, air traffic control, and airline companies [20]. These airports not only meet passenger needs but also aim to generate new solutions through systems equipped with advanced technologies. Thanks to technologies such as big data, IoT, and mobile networks, human-machine integration is achieved, operational processes are restructured, and many systems can be remotely controlled [9].

These technologies increase efficiency in service processes through applications such as real-time data analysis, biometric security systems, and automated baggage management, while also offering safer and more comfortable environments for passengers and staff. The interaction of smart devices enables the integrated and efficient management of operations and allows for rapid intervention in case of malfunctions. In smart airports, numerous applications such as self-service kiosks, autonomous vehicles, digital voucher processing, RFID tagging, automated baggage delivery, and personnel planning and scheduling are implemented within this scope [21].

These systems not only accelerate passenger flows, automate security procedures, and reduce touchpoints, but are also aligned with strategic goals such as sustainability and resource conservation. Today, airports have transformed into multifunctional centers with digital information flow, and business processes have fundamentally changed thanks to automation systems. This digital environment, which offers passengers more comfortable services, transforms airports from mere transportation hubs into digital platforms.

This transformation is not merely a technological innovation but also a strategic step toward increasing passenger satisfaction and strengthening operational decision-support mechanisms. Advanced digital solutions—such as facial recognition, RFID-based baggage tracking, IoT-supported security systems, and automated control processes—are transforming the traditional structure of airports. The use of these technologies in airports provides benefits such as managing terminal congestion, accelerating screening processes, and improving time management [22]. However, the success of this transformation is not only related to technical infrastructure but also directly dependent on passengers' level of technological adaptation. For example, while self-service baggage drop-off systems increase passenger satisfaction, the varying usage tendencies across age groups necessitate user profile-sensitive system design [23].

At this point, "digital twin" systems, which represent a more advanced level of digital technologies used in smart airports, come to the forefront. These systems, which create digital representations of physical systems, offer significant innovation in areas such as modeling operational scenarios, infrastructure monitoring, and predictive maintenance.

2.2. Digital Twin and Its Use in Airports

A digital twin is a virtual representation of physical assets created in a digital environment and continuously fed by real-time data. This structure contributes to processes such as monitoring, analysis, simulation, and optimization by maintaining constant data exchange with the physical system [1;27]. At its core, this technology is the digital representation of a physical object, system, or process, providing a real-time data flow between the physical and digital entities and allowing for dynamic management throughout the asset's lifecycle [6; 24]. The architecture of a digital twin consists of a physical asset, a digital model, and the connection that ensures uninterrupted data flow between the two. This technology is widely used in sectors such as manufacturing, healthcare, energy, defense, automotive, construction, and smart cities to enhance operational efficiency [7].

The aviation industry is one of the sectors where digital twin technology finds the most application. Through digital twins, areas such as aircraft engines, in-cabin systems, maintenance processes, and flight operation simulations can be improved in terms of both safety and efficiency. For instance, the digital twins of Rolls-Royce engines allow for real-time monitoring of engine performance and predictive maintenance. Similarly, General Electric utilizes digital twins to monitor the temperature levels of aircraft components and identify potential failures in advance [25; 26]. Enhancing flight safety, reducing carbon emissions, optimizing fuel consumption, and conducting pilot training through more realistic scenarios are among the key contributions of digital twins in aviation. A summary of key studies focusing on digital twins in the aviation sector is presented in Table 1.

Table 1. Digital Twin Studies in the Field of Aviation

Author(s) / Year	Topic	Objective	Findings
Nacak (2024) [6]	Digital Twin Applications in Aviation	This study addresses the basic concepts of digital twin technology and its applications in the aviation sector.	The use of digital twins in design processes offers advantages such as cost reduction, shortening of processes, and early error detection before production.
Siddiqui & Mead (2024) [8]	Digital Twin ConOps as a Platform for Airport Master Planning	To evaluate infrastructure scalability and asset utilization capacity using digital twin technology as a concept of operations (ConOps) platform for airport master planning.	The DT system, with its augmented reality (AR) and extended reality (XR) features, optimizes airport planning and enhances decision-making processes.
Soyer & Duman (2024) [37]	A Qualitative Study on Passenger Experiences Regarding the Future of Artificial Intelligence in Airports	The aim of this study is to examine how AI technologies are used in airports in developing countries and their impact on passenger experiences.	The study found a strong correlation between participants' distrust in AI and low technological literacy, while also revealing the potential of AI to improve passenger experience.
Weinberg (2024) [38]	The Role and Applications of Airport Digital Twin in Cyberattack	To investigate how digital twins can be used to protect airports from cyberattacks and how their integration with Generative AI (GenAI) provides a defense mechanism.	Digital twins offer proactive defense in airport cybersecurity through threat modeling, anomaly detection, and simulation; GenAI enhances security measures by simulating cyberattack scenarios.
Chen et al. (2024) [39]	Tangible Digital Twin with Shared Visualization for Collaborative Air Traffic Management Operations	To explore the visualization and interaction design of a mixed reality (MR)-based digital twin prototype to support ground control tasks of air traffic controllers (ATCOs).	User studies showed that the system's visual and interactive design was acceptable and that ATCOs developed a high level of shared situational awareness.
Li et al. (2022) [40]	Digital Twin in Aerospace Industry: A Gentle Introduction	To introduce the applications and potential of digital twin technology in the aerospace industry and eliminate misconceptions about its proper implementation.	The study highlights the transformative impact of digital twins in areas such as product development, design optimization, performance improvement, and predictive maintenance. It also suggests future directions including interaction, standardization, and cognitive dimensions.
Negri et al. (2019) [41]	Biometric Technologies in Airport Self Check-In Applications	To examine the applicability of biometric check-in systems in airports.	It was found that widespread adoption will take time due to high investment costs and privacy concerns; analyzing user perceptions was recommended.
Kovynyov & Mikut (2019) [42]	IoT, RFID, and Biometric Solutions in Airport Operations	To evaluate digital solutions such as RFID, IoT, and biometric technologies in airport operations.	Due to the low technological maturity level, some solutions were found to require further testing before implementation.
Zaharia & Pie (2018) [45]	Digital Transformation Processes and Challenges in Airports	To analyze the digital transformation processes at Henri Coanda International Airport.	The study identified challenges faced during digital transformation in airports and offered suggestions for improving technology and process integration.
Cam & Durmaz (2018) [43]	Digital Aviation: Future Passenger Experiences Through Current Practices	To examine the digitalization processes of airport and airline operations and their impact on passenger experience.	It was determined that digitalization enables airports to transform from mere transit points into destinations offering more personalized and proactive experiences for passengers.
Erturan & Ergin (2018) [44]	Digital Audit and Digital Twin Method	To explore the use of digital twin technology in accounting and auditing processes.	The study concluded that digital twins accelerate data analysis in auditing, facilitate error detection, and optimize internal audit processes.

Applications of digital twin technology in airports have rapidly expanded in recent years. Table 2 presents examples of digital twin implementations at selected airports.

Digital twins have been created for numerous physical components such as airport terminals, runways, ground service vehicles, passenger flows, and energy infrastructures to enable real-time monitoring and management of operations. At major international hubs such as Istanbul Airport, Frankfurt, Schiphol, and Changi, digital twin systems are used in a wide range of critical functions including passenger navigation, maintenance planning, infrastructure monitoring, delay diagnosis, energy optimization, and security control [27; 28].

These implementations enhance passenger experience, enable more accurate resource planning, reduce environmental impacts, and accelerate decision-making processes. For instance, at Schiphol Airport, aircraft parking positions are managed through digital twins to optimize apron traffic; at Frankfurt Airport, energy consumption is analyzed to reduce the carbon footprint. At Istanbul Airport, digital twin applications are effectively used under the F1RST Project to optimize passenger flow and resource utilization.

Table 2. Comparative Analysis of Selected Airports Utilizing Digital Twin Technology

Airport	Digital Twin Application	Area of Use	Advantages	Challenges
Aberdeen International Airport (UK)	Amorph Systems Digital Twin (Digital twin of turnaround operations)	Management of turnaround operations	Reduction of delays, increased operational efficiency	Real-time data integration, system complexity
Londrina Airport (Brazil)	Infraero Smart Airport Twin (Digital twin of existing facilities)	Facility management and asset tracking	Improved passenger experience, optimized asset management	Ensuring data integrity, system integration
Hartsfield-Jackson Atlanta & LAX (USA)	Siemens Real-Time Twin & Bentley iTwin (Enhanced passenger experience and security)	Passenger experience, maintenance, and security optimization	Operational efficiency, passenger satisfaction, reduced maintenance costs	Complexity of data integration, high installation costs
São Paulo-Guarulhos Airport (Brazil)	Dassault Systèmes 3DEXPERIENCE Twin (Operational digital twin)	Passenger services and monitoring of general operations	Improved efficiency, enhanced passenger service	Data accuracy, system compatibility, security risks
Vancouver International Airport (Canada)	Real-time interactive digital twin	Operational efficiency, sustainability	Real-time monitoring, operational efficiency, sustainability	Data collection and integration challenges, high costs
Soekarno-Hatta International Airport (Indonesia)	IBM Maximo Application Suite (Digital twin of baggage handling and lighting systems)	Baggage handling and aerodynamic lighting management	Operational efficiency, improved maintenance processes	Data security, system integration, high initial costs
London Heathrow Airport (UK)	NATS Demand Capacity Balancer (DCB)	Emission management, air traffic optimization	CO_2 emission reduction, operational efficiency	Real-time data integration, system complexity
Amsterdam Airport Schiphol (Netherlands)	Common Data Environment (CDE) & Hysopt Digital Twin	HVAC systems, infrastructure simulations	Energy savings, operational scenario testing, improved asset management, enhanced data quality, strengthened inter-team collaboration	Data integration complexity, high installation costs
Frankfurt Airport (Germany)	AI@FRA Digital Twin Platform	Passenger experience, infrastructure management	Operational efficiency, passenger satisfaction	Data integration complexity, high installation costs
Singapore Changi Airport (Singapore)	Vouse Digital Twin & TwinMatrix SpatialVerse	Passenger experience simulations, digital product development, metaverse integration	Increased passenger engagement, operational efficiency	High technology investment, data security and privacy concerns
Hamad International Airport (Doha, Qatar)	SITA Digital Twin Platform	Real-time operations monitoring, asset management	Operational efficiency, resource optimization	Data integration complexity, high installation costs
Brussels Airport (Belgium)	IES Digital Twin Technology	Building energy management, sustainability planning	Carbon emission reduction, energy savings	Data accuracy, system compatibility
Istanbul Airport (Turkey)	F1RST Project, A-SMGCS System	Operations management, resource optimization, passenger flow monitoring	Real-time decision-making, increased efficiency, sustainability	Managing high data volumes, system integration

Digital twins also provide managerial benefits in operational details such as planning the routes of ground service vehicles, monitoring baggage handling systems, optimizing runway usage based on weather conditions, and identifying congestion points within terminals. Real-time data analytics and simulation capabilities enable proactive and scenario-based decision support systems in airport management [25; 29; 30]. Thus, digital twin technology offers strategic contributions to the management of airports in a more sustainable, safe, efficient, and passenger-oriented manner.

3. Methodology

3.1. Research Problem

Airports are characterized by complex operational processes due to their large-scale infrastructure systems, high passenger volumes, and multi-actor structures. Traditional management methods often fall short in coping with increasing traffic volumes and dynamic conditions, necessitating more flexible, data-driven, and integrated solutions. Digital twin technology holds the potential to make airport management more transparent, traceable, and efficient. However, the tangible effects of this technology on airport operations, its current level of implementation, and the challenges encountered remain under-researched areas.

This study aims to reveal the extent to which digital twin technology contributes to airport management, how it transforms operational processes, and what difficulties arise during its implementation. The analyses, conducted through the case of Istanbul Airport, are intended to evaluate the current state and future potential of the technology.

3.2. Research Method and Limitations

A qualitative research method was adopted in this study. Qualitative research allows for an in-depth examination of a phenomenon within its natural context and is based on interpretive approaches. Within this framework, document analysis and semi-structured interview techniques were used as data collection tools. Official documents, activity and sustainability reports, project presentations, corporate websites, and media content related to Istanbul Airport were reviewed and analyzed using content analysis methods. As a result of this process, a comprehensive conceptual framework was developed regarding the application areas, objectives, and current status of the technology at the airport.

Subsequently, a semi-structured interview method was employed to gather expert opinions. This technique is a flexible interview approach conducted within a framework of pre-determined open-ended questions, allowing participants to freely express their views. In this context, interviews were conducted with three Building Information Modeling (BIM) engineers and two Big Data analysts who were directly involved in the digital twin applications at Istanbul Airport.

This research has certain limitations. First, the study is limited to the case of Istanbul Airport, and the findings may not be directly generalizable to other airports. Additionally, the study focuses on the operational and managerial impacts of digital twin technology rather than its technical infrastructure components. The data are based on secondary sources and a limited number of expert opinions. Some information may not have been accessible due to corporate confidentiality policies. Moreover, while the long-term effects of digital twin technology are discussed in a predictive manner based on available data, no definitive conclusions are drawn about the future.

3.3. Case Study of Istanbul Airport

Istanbul Airport was constructed to strengthen Turkey's role in global air transportation and officially opened on October 29, 2018. Spanning an area of 76.5 million square meters, its main terminal building covers 1.4 million square meters, making it one of the world's largest single-roof terminal structures. Once operating at full capacity, the airport is planned to serve 200 million passengers annually and currently offers flights to more than 320 destinations while hosting over 100 airline companies. With the commissioning of a third independent runway on June 18, 2020, the airport has increased its simultaneous takeoff and landing capacity, thereby enhancing operational efficiency [31].

This section analyzes the application of digital twin technology in the context of airport operations through the case of Istanbul Airport. With its advanced technological infrastructure, high capacity, and comprehensive digital transformation vision, Istanbul Airport represents one of Turkey's most digitally advanced airports and provides a suitable case for evaluating the applicability of digital twin systems at the airport scale.

The research assessed the current state of Istanbul Airport's digital twin infrastructure through document analysis of technical reports, strategic documents, and media content, and semi-structured interviews with experts. Based on the data collected, the system's usage purposes, operational units, contributions to decision-making processes, encountered challenges, and achieved benefits were examined.

4. Findings

4.1. Document Analysis Findings

At Istanbul Airport, digital assistant services designed to enhance the passenger experience from start to finish are supported by artificial intelligence and advanced chatbot technologies. Through continuously evolving AI-powered platforms, passengers receive personalized support

throughout the entire journey—from departure from home to arrival at the boarding gate.
Under the "Phygital Experience" strategy, which integrates the physical and digital worlds, Istanbul Airport operates with the vision of providing every passenger with a personalized digital travel companion. The use of QR codes enables navigation and supports a seamless digital travel experience from locating the baggage carousel to completing parking payments [32].
At İGA Istanbul Airport, digital twin applications are developed under the institutional digital transformation strategy known as the "F1RST" project. "F1RST" stands for "Future-Focused, Innovative, Resilient, Sustainable, and Technological," and aims to fully digitize airport operations. Accordingly, the digital twin infrastructure has been integrated with wireless IoT sensors, AI algorithms, and big data analytics [33].
Developed under the F1RST project code by IST Systems, the Smart Dashboard and Digital Twin solutions—intended specifically for İGA and its stakeholders—operate seamlessly with all digital systems 24/7 and provide real-time, multi-dimensional AI support. The F1RST application offers multifunctional usage from a single screen, making it the first of its kind and unique in the aviation industry [34].
Furthermore, according to İGA officials, AI-enhanced image processing solutions have become increasingly competent. Especially in congestion monitoring and management, camera images contribute to more efficient passenger processing. Density monitoring systems positioned at critical transition points such as entrances, security checkpoints, check-in, and passport control analyze passenger density and provide real-time alerts to relevant units via AI-based mechanisms. These systems aim to enhance operational efficiency by making decision-making processes more dynamic and data-driven.
Another key component of the project is the Smart Dashboard, an advanced decision support system that digitally monitors and manages İGA's physical processes. This interface acts as both the visual representation and data analysis center of the digital twin infrastructure. With real-time data flow, the system monitors terminal operations—such as passenger density, energy consumption, and baggage system performance—via digital replicas, enabling rapid decision-making, resource optimization, and scenario simulations [35].
One of the most striking features of digital twin technology is its contribution to sustainability goals. İGA leverages digital twin systems to improve energy efficiency and reduce greenhouse gas emissions and has obtained ISO 50001 and ISO 14064 certifications. According to 2022 data, İGA achieved a 13% reduction in emissions compared to the previous year, significantly improving its environmental performance. Looking ahead, İGA plans to further integrate the digital twin infrastructure with artificial intelligence and machine learning technologies. This integration is expected to support a smarter, more flexible, and more sustainable airport management system [33; 35].
The success of the digital twin system relies heavily on a robust data collection and processing infrastructure. At Istanbul Airport, this system is supported by an advanced IoT network consisting of 107 LoRaWAN gateways and more than 6,000 edge devices. These sensors collect real-time data on energy use, temperature, humidity, waste management, and cleaning operations and transmit it to the digital twin platform via integration with SCADA control systems. The data is analyzed using AI-based algorithms, supporting processes such as predictive maintenance, congestion management, and operational planning. Supported by image processing systems, these applications monitor passenger density at entry gates, security checkpoints, check-in areas, and passport control points, enabling the prediction of potential disruptions in advance. Thus, the digital twin infrastructure functions not only as an operational tool but also as a strategic asset for safety and crisis management [36].
Additionally, Istanbul Airport has developed 3D planning systems and virtual tower applications that enable real-time tracking of aircraft movements. Supported by Dallmeier Panomera® multi-focus sensor cameras and SeMSy® video management software, these systems offer high monitoring efficiency over large areas.
Digital twin technology has also been actively used during the construction and infrastructure development phases of the airport. Building Information Modeling (BIM) and Lean Construction approaches were applied simultaneously. During the design phase, more than 600,000 conflicts were prevented, and approximately €2.5 billion in potential cost and time losses were avoided. This integrated approach reveals that digitalization plays a crucial role not only in operations but also in infrastructure development processes.
İGA's digital transformation efforts stand out not only for their technological sophistication but also for international recognition. The organization was awarded the "Digital Transformation Award" by ACI Europe and also earned the title of "Europe's Best Digital Airport," reinforcing its leadership in this field [31].
A prominent element of Istanbul Airport's digital transformation strategy is the use of wireless communication technologies. LPWAN (Low Power Wide Area Network)-based infrastructure systems allow for wide-area data transmission with low energy consumption, thus enhancing the sustainability contributions of digital twin technology. This system offers advantages in remotely monitoring energy consumption, environmental parameters, and maintenance needs, while also improving operational efficiency [35].
Moreover, the digital systems implemented at Istanbul Airport are not limited to technological infrastructure but are supported by holistic solutions focused on user experience. For instance, personalized digital assistants provide real-time support in areas such as flight information, terminal navigation, parking, and baggage tracking, thereby realizing the goal of an "end-to-end digital travel experience" [32].

As reported by AeroTime (2023), Istanbul Airport's digital transformation vision not only aims to optimize current processes but also focuses on building a flexible and resilient technology infrastructure adaptable to future needs [33]. The systems developed within this scope aim to ensure integrated management of airport operations across all stakeholders and serve as a pioneering model for digitalization in the aviation sector.

4.2. Interview Findings

The qualitative data obtained from the interviews were analyzed using thematic analysis, and the role, benefits, and challenges of digital twin technology during its implementation were categorized under several themes.

Purpose and Scope of Digital Twin Technology:
According to the participants, the initial aim of implementing digital twin technology was to improve maintenance processes, optimize fault management, and monitor infrastructure systems more effectively. Over time, the system has been integrated into areas such as flight operations, passenger mobility, situational awareness, and long-term planning.

Operational Efficiency and Decision Support Processes:
It was emphasized that the digital twin system accelerates decision-making processes by consolidating multiple data sources, enabling managers to make quicker and more accurate decisions. Moreover, automating manual reporting processes has led to significant increases in personnel efficiency, reportedly saving approximately 2 million Euros.

Integration and Data Management:
Participants noted that the system is integrated with different infrastructures (e.g., AMS, SAP, SCADA, radar, sensors) through big data technologies. Data is transmitted in real-time via message-routing systems like Kafka and used integrally on a unified platform.

User Adaptation and Organizational Culture:
The success of the system's implementation depends not only on technical competence but also on users' ability to adapt to the system. In this regard, data literacy training, analytical skill development, and the establishment of organizational structures to strengthen internal communication have been prioritized.

Challenges and Solutions:
The most common challenges included performance issues, users' unfamiliarity with the technology, and technical difficulties in system integration. To address these, simplified user interfaces, performance-friendly models, and training-supported usage strategies were developed.

Future Potential and Dissemination Strategies:
Participants stated that the successful implementation of digital twin technology at Istanbul Airport could serve as a model for other major airports in Turkey. The integration of AI, crisis management, safety, and occupational health were identified as future areas where this technology is expected to expand. Strategic planning, inter-institutional collaboration, and reinforcement of technical and legal infrastructures were deemed essential.

Planning and Implementation Process:
Interviewees emphasized that implementing digital twin technology in large-scale, multidisciplinary infrastructure projects like Istanbul Airport requires a long-term, meticulous, and well-planned BIM process. Initiating BIM applications in the early stages of construction played a critical role in forming the information infrastructure that would later evolve into a digital twin. Detecting technical conflicts through digital models in advance significantly reduced project timelines and costs, especially by preventing potential clashes in the field.

Application and Areas of Use:
Participants noted that digital twin technology is actively used at Istanbul Airport, particularly in technical and operational areas such as monitoring mechanical, electrical, and infrastructure systems, planning maintenance processes, and optimizing energy management. Thanks to integration with systems such as IoT sensors, SCADA, BMS, and ERP, real-time event and task management can be performed. These models are also effectively used in user orientation and training processes. On the other hand, digital twin applications are reportedly used at a more limited level in multi-stakeholder areas where data privacy is critical, such as passenger flow, apron traffic, and security systems.

Integration and Collaborations:
Participants emphasized that the success of digital twin technology depends on the integration of various systems and interdisciplinary collaboration. They noted that integrating departments using different software platforms such as SAP, Honeywell, and Siemens into the digital twin infrastructure requires intensive coordination. Workflow matrices and user-centered training documents were developed to ensure transparent and efficient processes. Additionally, it was unanimously agreed that establishing effective collaboration models among engineering teams, software developers, and managers is essential for the sustainable management of BIM and digital twin systems.

Benefits and Efficiency:
Participants highlighted that digital twin applications significantly contribute to long-term facility management and operational efficiency. Monitoring fault detection and maintenance processes through digital models allows related personnel to respond quickly using mobile devices. Beyond financial benefits such as managing leasable areas and technical infrastructure via digital models, the alignment of BIM models with physical site conditions also supports the creation of institutional memory and facilitates access to information.

Sustainability and Future Outlook:
There was a shared opinion among interviewees that digital twin technology will be used more extensively and in more advanced forms in the future. They particularly emphasized that AI-based systems will enhance the predictive and analytical capacity of digital twin applications. However, ensuring the sustainability of

digital twin infrastructures requires regular training, ongoing support for technical staff, and continuous managerial commitment. Istanbul Airport's pioneering role in this field has enabled the transfer of accumulated knowledge and experience to other major infrastructure projects in Turkey.

5. Conclusion

This study aims to evaluate how digital twin technology is implemented in airport management, what operational and managerial benefits it provides, and what challenges are encountered during the implementation process, using Istanbul Airport as a case study. In today's context, digitalization has evolved beyond a mere data collection process into a strategic transformation tool through the interpretation, analysis, and integration of data into decision-making processes. In this regard, digital twin technology is not only a technical modeling tool for large-scale infrastructures but also a strategic management instrument with capabilities such as real-time monitoring, scenario simulation, and predictive decision-making.

The successful integration of digital twin applications in a high-capacity and complex aviation structure like Istanbul Airport demonstrates that the technology supports not only operational benefits but also organizational transformation. The digitalization process, which began with a Building Information Modeling (BIM) infrastructure, has evolved into a multilayered and dynamic digital architecture integrated with IoT devices, SCADA, BMS, and SAP systems. This holistic structure enables the real-time digital representation of physical assets, remote monitoring of airport operations, and proactive decision-making through scenario-based simulations.

Findings from the field indicate that this architecture has transformed many internal processes within the institution. Significant gains have been achieved in areas such as making maintenance activities more predictable, optimizing energy management, accelerating fault detection, and improving resource planning. As one participant stated, "even organizational reflexes have changed over time," indicating that digital twin systems initiate not only a technological but also a cultural transformation. Additionally, using these technologies as tools to transfer institutional knowledge during the orientation of new employees provides significant value in terms of organizational sustainability.

However, several challenges were also identified during the implementation process. Technical incompatibilities in integrating different software systems, delays in obtaining data from external firms, users' lack of familiarity with the systems, and the non-user-friendly design of certain interfaces occasionally limited the effective use of the system. One participant's remark— "without training, the system's potential remains limited"—clearly highlights the need for simultaneous investments in human capital and institutional capacity alongside technological investments.

Based on these findings, it is recommended that digital twin technology be integrated not only into the processes of technical teams but also those of planning, security, operations, marketing, finance, and passenger experience departments. To enable such integration, institutions should establish non-hierarchical, horizontally interactive digital management committees in which different disciplines can collaborate. The development of user-friendly and simplified interfaces, the design of customizable dashboards for different user profiles, and the use of simplified data modeling tools will support widespread use. In addition, continuous training programs should be implemented to enhance data literacy, digital model interpretation, system interaction, and analytical skills, and these programs should be regularly updated.

User experience should be monitored through internal feedback systems, and system designs should be dynamically updated based on these insights. Furthermore, the integration of digital twin systems with AI-supported decision-making mechanisms will generate added value in areas such as predictive maintenance, anomaly detection, scenario-based simulations, and end-to-end resource management. Such integration will make airport management more predictable while increasing the flexibility and sustainability of systems.

By analyzing the digital twin applications of a large and complex infrastructure system like Istanbul Airport through field-based data, this study addresses a significant gap in the existing literature regarding case studies. At the same time, the application demonstrates how the concept of Airport 4.0 materializes in practice, thereby translating theoretical approaches in the literature into concrete examples.

Nonetheless, some gaps remain in the literature. In particular, there is a lack of applied research on the integration of digital twins with advanced technologies such as artificial intelligence, big data analytics, augmented reality (AR), and extended reality (XR). Future studies should explore these integrations in detail. Additionally, the concept of Airport 4.0 should be defined in a comprehensive, systematic, and measurable framework, and its impact on operational processes should be examined both theoretically and practically.

Another recommendation for future research is to conduct comparative analyses of how digital twin applications are structured in airports in different countries. This would reveal contextual differences in implementation more clearly.

Digital twin technology is not merely a tool for digitalization in airport management; it is a strategic transformation process that enables a transition to a data-driven, sustainable, and holistic management culture. For this transformation to succeed, investments must be made not only in technology but also in human resources, institutional capacity, and organizational culture. Istanbul Airport is one of the few examples at the national level that carries out the digital transformation process in both technical and strategic dimensions and offers a valuable case for international comparative evaluations.

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