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USING DIGITAL TWIN IN SIMULATING AIRPORT LANDSIDE OPERATIONS

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Rezumat. *Operațiunile din zona landside a aeroporturilor, inclusiv check-in, parcări și zone comerciale, necesită o gestionare eficientă pentru a gestiona fluxurile dinamice de pasageri. Tehnologia Digital Twin (DT) oferă o soluție prin crearea unei replici virtuale a acestor zone, actualizată în timp real prin senzori IoT și inteligență artificială. Modelele DT permit simulări predictive, identificarea punctelor critice și optimizarea operațiunilor—cum ar fi gestionarea cozilor și dirijarea pasagerilor—înainte de implementare. O abordare modulară de implementare permite integrarea progresivă, îmbunătățind procesul decizional și experiența pasagerilor, reducând totodată riscurile. Odată cu avansul tehnologiilor IoT și analiticii de date, modelele DT reprezintă un instrument rentabil pentru o gestionare mai inteligentă a aeroporturilor.*

Această lucrare propune integrarea tehnologiei Gemenilor Digitali (DT) ca o soluție transformatoare. Se dezvoltă un cadru conceptual multi-nivel pentru un Geamăn Digital Aeroportuar Landside (GDAL), care structurează sistemul în patru straturi interconectate: achiziția de date din surse eterogene, managementul și comunicarea datelor, modelarea și analiza avansată, și vizualizarea interactivă. Articolul analizează beneficiile strategice și operaționale ale acestui cadru. În același timp, sunt evaluate critic provocările majore de implementare, cu un accent special pe dilema fundamentală dintre utilitatea derivată din analiza detaliată a datelor despre pasageri și imperativele de securitate cibernetică și confidențialitate, conform reglementărilor precum GDPR.

Abstract. *Airport landside operations, including check-in, parking, and retail areas, require efficient management to handle dynamic passenger flows. Digital Twin (DT) technology offers a solution by creating a virtual replica of these areas, updated in real time by IoT sensors and artificial intelligence. DT models enable predictive simulations, critical points identification, and operations optimization, such as queue management and passenger routing—before implementation. A modular implementation approach allows for progressive integration, improving decision-making and passenger experience while reducing risks. With the advancement of IoT and data analytics technologies, DT models are a cost-effective tool for efficient airport management.*

This paper proposes the integration of Digital Twin (DT) technology as a transformative solution. A multi-level conceptual framework for a Landside Airport Digital Twin (LADT) is developed, structuring the system into four interconnected layers: data acquisition from heterogeneous sources, data management and communication, advanced modeling

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and analysis, and interactive visualization. The article analyzes the strategic and operational benefits of this framework. Major implementation challenges are evaluated, with a focus on the fundamental dilemma between the utility derived from detailed analysis of passenger data and the imperatives of cybersecurity and privacy, as per regulations such as GDPR.

Keywords: Digital Twin, airport management, landside operations, Passenger Flow Simulation.

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1. Introduction

The airside section of the airport contains, along with the landside section, populated by vehicle parking, entry and exit roadways, ticketing agents, luggage check-in locations, security screening stations, and shopping outlets, a sophisticatedly complex operating system [1]. However, this phenomenon does not only apply to a physical structure. An airport is a socio-technical system in which the flow of passengers intersects with other staff, all operational pieces, and levels of activity that fluctuate based on demand [2]. Therefore, it is imperative to assess such systems to ensure optimal performance for passenger satisfaction, company profits and airport function safety. Therefore, the most urgent issues to resolve are traffic flow and overcrowding, issues of decreased wait times and resource distribution needs that are most effective despite unpredictable surges in demand—compounded, at times, by unforeseen incidents or delayed flights [1]. Human behavior is stochastic; all people have different needs and itineraries projecting different associations and complications; therefore, a strictly quantitative approach will be applicable [3].

Traditionally, landside operations management has relied on static planning, manual coordination, and siloed IT systems [1]. Decisions are often reactive, made in response to problems that have already arisen, such as long security queues or congestion at check-in counters. This approach relies on historical data and operator experience but lacks the ability to anticipate and adapt solutions to dynamic airport conditions in real time. The result is suboptimal resource allocation, increased operating costs, long wait times for passengers, and an overall unsatisfactory experience, which can negatively impact non-aeronautical revenues [4].

In this context, Digital Twins (DT) technology emerges as a fundamental paradigm shift. A Digital Twin is a virtual, dynamic representation of a physical system that is continuously updated with real-time data from the sensors and operational systems of its physical counterpart [1]. Unlike a simulation, which analyzes an isolated process, a DT is defined by bidirectional data flow: data from the physical world updates the virtual model, and analyses and predictions from the virtual model inform decisions and actions in the physical world [5]. This feedback loop transforms static infrastructure into a reactive system capable of monitoring, analysis, predictive ("what-if") simulation, and continuous optimization in a risk-free environment [1].

The objective of this paper is to propose a holistic conceptual framework for implementing a Digital Twin in the landside area of an airport (LADT). The paper presents the architecture structure of such a system, along with an analysis of its strategic and operational impact and a critical assessment of the key implementation challenges.

2. Conceptual framework for a landside airport digital twin (LADT)

To structure the complexity of an airport DT, a conceptual framework is proposed that integrates theoretical foundations with practical technological components, providing a coherent vision for design and implementation.

At the heart of any Digital Twin lies the conceptual model proposed by Grieves, which defines three essential components: the physical entity in the real world, its virtual model, and a bidirectional data connection linking them [5], [6]. This fundamental triad ensures that the virtual model is not a static representation, but a digital tool that evolves in sync with its physical twin.

Building on this foundation, we propose a four-level functional architecture inspired by standards such as ISO 23247 [7] and practical implementations such as cloud-based architectures [8]. This modular structure allows for a systematic approach to development.

Level 1: Physical Interface and Data Acquisition

This level represents the interface with the physical system and is responsible for collecting raw data. Data sources are heterogeneous and include:

- Dynamic data sources are considered real-time data streams from a dense network of IoT (Internet of Things) sensors that monitor space occupancy, vibrations in baggage handling systems (BHS), people counters at entrances and checkpoints, smart cameras for passenger flow and crowd density analysis, Wi-Fi or RFID-based location systems, and aggregated data from passenger mobile applications[1].
- Static and semi-static data sources are represented by fundamental geometric and semantic data that provide the 3D spatial context. These come from BIM

(Building Information Modeling) models, GIS (Geographic Information Systems) and CAD (Computer-Aided Design) plans of terminals and adjacent infrastructure.[9]

- Operational data sources consist of critical information from existing airport systems, such as the Airport Operational Database (AODB), flight information display systems (FIDS), and resource management systems.[8]

Level 2: Data Management and Communication

This level acts as a centralized DT resource management system, operating data flow, storage, and processing. Its key components are:

- **Data Ingestion and Processing:** Using cloud platforms and edge computing network nodes to collect, aggregate, and process data volumes. Edge computing is vital for applications that require low latency, such as real-time video analysis ( ) for rapid detection of queues or dangerous congestion[1].
- **Data Storage:** Implementation of dedicated databases for the efficient management of time-series data from sensors, along with structured (from AODB) and unstructured (video, text) data. Technologies such as NoSQL (not only SQL) databases or those optimized for time-series are essential[10].
- **Interoperability:** Creating an integration platform based on standardized APIs (Application Programming Interfaces) is crucial to breaking down data silos between disparate systems (e.g., security, BHS, building management) and creating a unified digital environment [11].

Level 3: Modeling and Analysis

This component handles the entire internal management of DT, where raw data is transformed into usable information. The simulation engine is used to accurately model landside operations, requiring a hybrid approach. Discrete Event Simulation (DES) is suitable for modeling sequential processes, such as check-in and security control flows[12]. This must be complemented by Agent-Based Modeling (ABM), which can simulate the emergent and stochastic behavior of thousands of individual passengers, each with their own decisions and trajectories[3].

AI/ML integration refers to artificial intelligence (AI) and machine learning (ML) algorithms (ML) algorithms are applied to historical and real-time data sets to perform predictive analytics (e.g., forecasting queue lengths, anticipating congestion in case of delays) and to detect operational anomalies (e.g., an impending equipment failure)[1].

Level 4: Applications and Visualization

This level represents the interface with human users (operations managers, security personnel, planners). Operational dashboards provide a unified interface ("single pane of glass") that offers an interactive, real-time 3D/4D visualization of the entire landside area. This provides managers with complete situational awareness, allowing them to monitor KPIs (Key Performance Indicators) and identify problems instantly[1]. What-if scenario analysis, where a risk-free virtual sandbox environment is provided in which management can test hypotheses and plan interventions, is suitable for actively testing different types of scenarios. For example, you can simulate the impact of adding new self-check-in kiosks, reconfiguring waiting lanes, or planning optimal evacuation routes in case of an emergency.

Implementing such a complex framework involves a fundamental strategic decision related to the trade-off between data accuracy and cost. The effectiveness of Level 3 predictive analytics depends directly on the granularity and accuracy of the data collected in Level 1. For example, high-resolution tracking of passengers through smart cameras[1] and LiDAR scanners [13] enables much more accurate flow simulations. However, the implementation and maintenance of such a dense network of sensors and the necessary network and computing infrastructure represents a significant capital expenditure (CAPEX) and operating expenditure (OPEX)[1]. Therefore, the decision on the level of data fidelity is not purely technical, but a strategic management choice. Effective implementation must be guided by specific use cases: high fidelity is justified for real-time security queue management, while lower fidelity may be sufficient for long-term capacity planning, thus optimizing return on investment (ROI).

3.Strategic and operational impact analysis

Implementing the proposed LADT framework generates added value on multiple levels, from operational efficiency to economic justification, but it also involves significant challenges that must be managed strategically.

Maximizing operational efficiency by simulating and optimizing passenger flows, LADT enables significant reductions in waiting times and congestion at critical points such as check-in and security screening. Dynamic allocation of resources—staff, counters, boarding gates—based on real-time demand forecasts prevents both underutilization and overcrowding, leading to much more efficient use of airport assets.

Improving the passenger experience is one of the main advantages of the proposed system. There is a direct correlation between reduced waiting times, clear information provided through dynamic signage, and high passenger satisfaction [1]. A smooth and stress-free experience can increase the time passengers spend in commercial areas, thereby boosting non-aeronautical revenues, which are vital to the business model of modern airports[4].

Cost reduction and economic justification (ROI) through the following methods: cost reductions come from several sources: optimisation of the number of staff required, predictive maintenance of landside assets (BHS systems, HVAC, escalators) which reduces downtime and unplanned repair costs, and efficient energy consumption management[1]. Although the initial investment is considerable, industry analyses suggest that DT optimizations can generate 20-30% increases in operational and capital efficiency, providing a solid basis for a positive ROI in the medium to long term[14].

Increasing safety and security through the use of DT-specific virtual spaces is an essential element in the development of the digital platform. The ability to simulate emergency scenarios (evacuations, security breaches, fires) in a realistic virtual environment and train staff for these situations exponentially improves preparedness and crisis response effectiveness[1].

To summarize these benefits, Table 1 correlates the technical characteristics of LADT with operational and business results.

Table 1: Landside Digital Twin Benefits Matrix

DT Capability	Operational Area	Primary Benefit
Passenger Flow Simulation & Queue Analysis	Check-in Counters, Security Control	Reduced waiting times, increased throughput
Dynamic Resource Allocation	Counters, Staff, Gates	Optimization of personnel costs, efficient use of assets
Predictive Maintenance (IoT sensors)	BHS, HVAC, Escalator Systems	Reduced downtime, lower maintenance costs
Emergency Scenario Simulation	Entire Terminal	Increased safety, efficient evacuation planning
Heatmap Analysis	Commercial Spaces, Restaurants	Layout optimization, increased non-aeronautical revenue

High costs and economic feasibility are covered in the following scenarios: Significant initial investment in hardware (sensors, cameras, servers), software (DT platforms, simulation engines), and systems integration is a major barrier, especially for medium-sized or small airports. A pragmatic strategy to overcome this obstacle is a phased implementation, starting with high-impact use cases and demonstrable ROI, allowing for the justification of future investments[14].

Data integration and lack of standardization can be an obstacle to centralizing raw data. The difficulty of integrating heterogeneous data from legacy, isolated systems with data from modern IoT devices is a fundamental technical challenge[1]. The lack of industry-accepted data ontologies, and standards for airport DT complicates interoperability and increases integration costs[15].

Cybersecurity and data privacy is the most complex and critical challenge. A DT centralizes a huge volume of sensitive operational data, becoming a high-value target and expanding the airport's cyber attack surface. A successful attack on the DT could have direct physical consequences, from disrupting operations to compromising safety[16]. Furthermore, the collection and analysis of granular data on passenger movement and behavior falls under strict data protection regulations, such as the GDPR[1].

These issues highlight a central strategic dilemma: the conflict between utility and privacy. On the one hand, the value of a LADT lies precisely in its ability to understand and predict passenger behavior in detail in order to optimize flows and services. This requires the collection of granular, potentially identifiable data. On the other hand, legal and ethical frameworks, such as the GDPR, impose strict principles of data minimization, informed consent, and privacy protection[17]. This conflict cannot be resolved by adding security features later on. It requires an architecture fundamentally designed on the principle of "privacy-by-design," where protection mechanisms, such as anonymization, pseudonymization of data, and advanced technologies, are integrated into the core of the system. The above implementation solutions and mitigation strategies are summarized in Table 2.

Table 2: Implementation Challenges and Mitigation Strategies

Challenge	**Description**	**Mitigation Strategy**
High Initial Costs	Significant investments in sensors, software, cloud/edge infrastructure, and skilled personnel.	Phased approach focused on ROI, DT-as-a-Service models, starting with existing data.

Heterogeneous Data Integration	Difficulty in unifying data from isolated systems (silos) with different formats and protocols.	Adopt open platforms, develop standardized data ontologies, use middleware.
Compliance GDPR/Privacy	Risk of violating regulations on personal data by collecting flow and behavioral data.	Privacy-by-Design architecture, anonymization/pseudonymization, encryption, Federated Learning (FL).
Cybersecurity	Extended attack surface; risk of a digital attack having physical consequences.	Defense-in-depth architecture, network segmentation, strict access management, vulnerability testing on DT.

4.Strategic and operational impact analysis

Validating the conceptual framework and overcoming the challenges mentioned depend on integrating solutions from practical implementations and adopting advanced technologies.

Analysis of DT projects implemented in airports provides concrete evidence for the viability and benefits of the proposed framework. At Amsterdam Schiphol Airport, the implementation of a Common Data Environment to integrate data from BIM and GIS sources validates the importance of a robust Level 2 (Data Management) for interoperability and predictive maintenance [18]. The Vancouver International Airport project demonstrates the power of Level 4 (Visualization), where a real-time 3D replica of the terminal and airfield provides operational staff with exceptional situational awareness to manage resources and respond to incidents [13].At Brussels Airport, the development of a DT based on physical models (Level 3) to simulate energy consumption and CO2 emissions directly supports strategic decarbonization objectives [19]. The Dallas/Fort Worth (DFW) project highlights the need for clear digital governance and the integration of a wide range of systems (BIM, GIS, EAM - Enterprise Asset Management) to create a unified vision [20].

Among the solutions for managing and correlating raw data into clear and robust information are federated learning and generative artificial intelligence. Federated learning (FL) is an emerging technology that offers an elegant solution to the "utility vs. privacy" dilemma. FL enables cooperative training of machine learning models on distributed data without requiring the centralization of sensitive raw data. Each stakeholder (airport, airline, retailer) can train its model locally on its own data, sharing only model updates (gradients), not the data itself [21]. This not only ensures GDPR compliance, but can unlock the potential of a truly holistic DT.

The airport is an ecosystem of competing and collaborating business entities. A major barrier to integrated DT is the reluctance of these entities to share proprietary data for commercial and legal reasons. This is a socio-technical problem, not just a technical one. Federated learning offers a technical solution to this socio-technical problem by creating a governance framework for collaboration that respects data sovereignty. Thus, FL becomes a strategic enabler that makes the vision of a digital "system of systems" politically and commercially feasible.

Generative artificial intelligence (GenAI) can play a crucial role in Level 3 (Modeling and Analysis). GenAI models can create "what-if" scenarios that are much more complex and unpredictable than rule-based simulations. This is particularly valuable for stress testing cyber defenses and emergency response plans by simulating new and unexpected attack tactics or cascades of disruptive events [22].

The long-term vision is the convergence of LADT with the Digital Twins of other airport domains. Integration with airside operations [12], baggage handling systems [23], and even urban and regional transport networks could create a holistic, seamless digital replica of the entire passenger journey, from home to the boarding gate.

5. Conclusions

The integration of Digital Twin solutions into airport landside operations is more than just a technological upgrade; it is a fundamental paradigm shift in critical infrastructure management. This paper demonstrates that the transition from a reactive, isolated systems-based approach to a proactive, predictive, and holistic one is not only possible but necessary to cope with the increasing complexity of air transport.

The main contribution of this article is the proposal of a multi-level conceptual framework (LADT) that logically structures the components of such a system, from data acquisition to interactive visualization. This framework serves as a guide for systematic design and implementation, ensuring that all aspects—technical, operational, and strategic—are taken into account.

From a managerial and strategic perspective, the fundamental conclusion is that a Digital Twin project should not be viewed as a simple IT acquisition, but as a business transformation initiative. Its success depends on robust data governance, the adoption of a "privacy-by-design" concept from the conception phase, a rigorous analysis of the return on investment, and strong leadership capable of overcoming organizational barriers and promoting collaboration between departments. The dilemma between data utility and privacy must be addressed head-on, as a central strategic challenge, not as a secondary technical issue.

Ultimately, Digital Twin is emerging as a fundamental pillar for the airport of the future—an airport that is more robust, more efficient, safer, and ultimately more focused on the passenger experience. They are the key to unlocking the immense value hidden in the massive volumes of data that an airport generates every day, transforming that data into actionable intelligence and sustainable competitive advantage.

A stochastic model using the theory of probability is developed and employed for the prediction of the relationship between the workforce resources and job availability. The study shows that the stochastic modeling is a powerful tool that can be used successfully in the prediction of the dynamics of human resources while establishing a correlation with the job availability. The stochastic modeling of the human resources dynamics is a promising predictive approach that can help in enhancing the management of human resources and thus, minimizing the risk of skilled work force.

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