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Digital Twin Integration for Sustainable Management in the Aerospace Industry.

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Abstract: This paper investigates the application of digital twins as strategic tools for achieving operational and environmental goals in the aerospace industry. A bibliometric review was conducted between November 2024 and April 2025, using Boolean operators and targeted keywords across databases such as Google Scholar and ScienceDirect. The review focused on publications from 2020 onward, complemented by foundational studies. Results indicate that digital twins enhance sustainability in airport operations by enabling scenario simulation, risk forecasting, and data-driven decision-making. The findings highlight the potential of digital twins to support smart infrastructure and accelerate the transition toward low-carbon aviation.

Keywords: Digital Twin, Sustainability, Aerospace Industry, Smart Airports, Environmental Management, Predictive Maintenance, Operational Efficiency.

Introduction

The aerospace sector faces growing operational and environmental challenges, further intensified by the COVID-19 pandemic (Rebouças & Abrahão, 2023; Grundström & Ferrari, 2022; Ritchie, 2024). As a result, the aviation industry has undergone necessary adaptations to ensure operational safety and service quality for stakeholders (Bh Airport, 2023; Marques, 2022). Within this context, digital twins have emerged as Industry 4.0 solutions capable of simulating, monitoring, and predicting operations in real time. Their implementation in airports enables data-driven decision-making, contributing to greater efficiency, safety, and sustainability (Sahu & Upadhyay, 2024; Grundström & Ferrari, 2022). However, a research gap remains concerning the strategic use of this technology in airport planning and governance (Viscardi Filho, Rebouças, & Pássaro, 2024; Rebouças & Abrahão, 2023).

Research Aim and Research Questions

The objective of this research was to present a bibliometric review on Digital Twins to assist researchers with the stratetgies to apply this technic in airports and make these airports know as sustainables and smarts. A bibliometric review was conducted between November 2024 and April 2025 using the databases Google Scholar, ScienceDirect, and Google, applying Boolean operators and specific keywords. Structures such as the following were entered into the search engines: "Digital Twin" AND "Airport" AND ("Sustainability" OR "Sustainable airport"). Relevant studies published since 2020 were selected and supplemented by foundational theoretical works to support the discussion on digital twins and sustainable airports.

Research Results

The digital twin (DT), also referred to as digital avatar, digital shadow, or digital master (Yao et al., 2023), was originally developed by National Aeronautics and Space Administration (Tao et al., 2022). It has evolved from a 3D simulation tool into a dynamic system that integrates sensors and big data to simulate, predict, control, monitor, and optimize real-world processes using historical records and operational data (Yao et al., 2023; Wanasinghe et al., 2020; Grundström & Ferrari, 2022). This functionality enhances safety for physical plant operators, reduces operational costs and time in airport environments, and enables staff training in the context of occupational safety. Based on data from physical facilities, DTs can be used for training and emergency evacuation simulations (Wanasinghe et al., 2020).

Currently, the applicability of digital twins has extended to sectors such as self-care, healthcare, logistics, energy, and communications, particularly in relation to efficiency and sustainability. The Internet of Things (IoT) is responsible for enabling interaction between the physical and virtual environments. In the environmental domain, DTs can reduce carbon footprints, mitigate greenhouse gas (GHG) emissions, and improve conscious energy use (Farsi, Daneshkhah & Jahankhani, 2020).

These capabilities emphasize the relevance of DTs in the aerospace sector for minimizing environmental impacts.

In airports, digital twins are also used for predictive maintenance, environmental control, and decision support, aligning with the Strategic Plan of the Brazilian Air Force (FAB) (Brasil, 2018) and the United Nations Sustainable Development Goals (Undp, N.D.; Bh Airport, 2023). These functions are especially relevant in the context of aviation disaster prevention. Technological and social disasters in aviation do not occur suddenly; early signs and information often alert decision-makers about potential risks. Such disasters are typically the result of technical, institutional, social, or administrative failures, which may act independently or in combination (Gonçalves Filho et al., 2021).

According to Brazil's Ministry of Health (DataSUS), 2,882 fatalities related to air accidents were recorded between 1996 and 2023. In December 2024, the crash of a small aircraft en route to southern Brazil resulted in 17 injuries and 10 fatalities after colliding with commercial buildings during Christmas festivities (Ornell *et al*., 2025). To reduce fatalities in Brazilian airspace and mitigate operational failures at airports, DTs can be strategically employed. Their functionalities are applicable to both civil and military aviation. In fact, the digital twin aligns with the Brazilian Air Force's Strategic Military Plan (PEMAER 2018–2027), as its use in scenario virtualization and simulation helps reduce risk probabilities and operational deficiencies, enabling efficient, effective, and impactful decision-making (Brasil, 2018).

Countries such as Canada, Norway, China, Italy, Brazil, the United Kingdom, Germany, Saudi Arabia, and the Netherlands have adopted digital twin policies in the oil and gas sector (WANASINGHE *et al*., 2020; YAO *et al*., 2023). In the airport sector, DTs contribute to risk reduction, logistics improvement, increased energy efficiency, and the integration of operational data—supporting lower emissions of CO_2, NO_x, and particulate matter while improving responsiveness to extreme events.

In the civil aviation landscape, the implementation of digital twins is crucial to enhancing the competitiveness of private aerospace companies. These firms allocate up to 20% of aircraft operational costs to maintenance (REBOUÇAS & ABRAHÃO, 2023). Beyond maintenance and airport operations, environmental concerns remain critical. According to Brazil's Ministry of Infrastructure (Brasil, 2022) and the International Civil Aviation Organization (Icao, 2014), key environmental impacts of airports include noise, GHG emissions, fuel consumption, and air quality degradation. Among these, noise generated by operations and airport expansion is considered the most significant.

Conclusions

The digital twin emerges as a key tool for enhancing the efficiency, safety, and sustainability of airport operations. Its application goes beyond operational simulation, enabling integrated management of risks and environmental impacts. The adoption of this technology is strategic for meeting regulatory and environmental requirements, while positioning the aerospace sector as a leading force in the transition toward a low-carbon economy.

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