Digitally Transforming Airports to Enhance Sustainability – A Technology Selection Framework

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Abstract

Airports' contribution is significant in the growth of business and economies of nations. Airports are complex infrastructure entities that include equipment and systems that generate greenhouse gas (GHG) emissions, affect communities, and have a huge impact on sustainability. The measures to improve airport sustainability are being recommended by various civil aviation bodies, IATA, ICAO, and ACI are prominent among them. The literature on the research studies about the methods to improve sustainability at airports is available. However, the literature on the application of digital transformation of airports is scares, and more so is the literature on the impact of airport digital transformation on sustainability. The main purpose of this article is to enumerate digital transformation applications to airport operations, systems, equipment, and infrastructure with a sustainability perspective. It also discusses their impact on sustainability in light of the Triple Bottom Line approach. The 'Digital Technology Selection Framework for Impact on Airport Sustainability' is proposed which could assist airports to assess the sustainability impact of the digital transformation initiative they proposed to deploy.

Keywords: Digital Transformation, Airport Sustainability, Airport Environmental Burden, Digital Technology Selection Triple Bottom Line Approach

1. Introduction

Airports, as part of aviation infrastructure, are critical to economic growth. Global air travel growth is expected to continue in developed and developing economies. This entails the building of new greenfield airports and also the expansion of existing airports. Airports significantly contribute to economic growth and employ a large number of people. Airports enhance regional and international connectivity while also facilitating trade. Airports are intricate entities with numerous stakeholders, such as airlines, airport operators, regulators, and concessionaires who provide a variety of services. The operation of an airport involves numerous systems and equipment, all of which result in environmental costs and impacts.

Airport operators strive for an operational environment that is financially viable, provides adequate returns to investors, promotes passenger happiness and safety, and contributes positively to the environment. The operation of the airport has a direct influence on the expansion of the economy as well as investment.(Sellner & Nagl, n.d.) The economic impact of airports is classified under four different heads direct, indirect, induced, and catalytic. (*VIRGINIA AIRPORT SYSTEM ECONOMIC IMPACT STUDY EXECUTIVE SUMMARY*, n.d.). Indirect effects include the economic activity performed by suppliers such as the activities of Food and Beverages suppliers to the airport concessionaires are classified as merchants. Catalytic advantages are what we refer to as a combination of tourism, trade, and investment in the region, and they are made possible by the airports. (Airport Council International, n.d.)

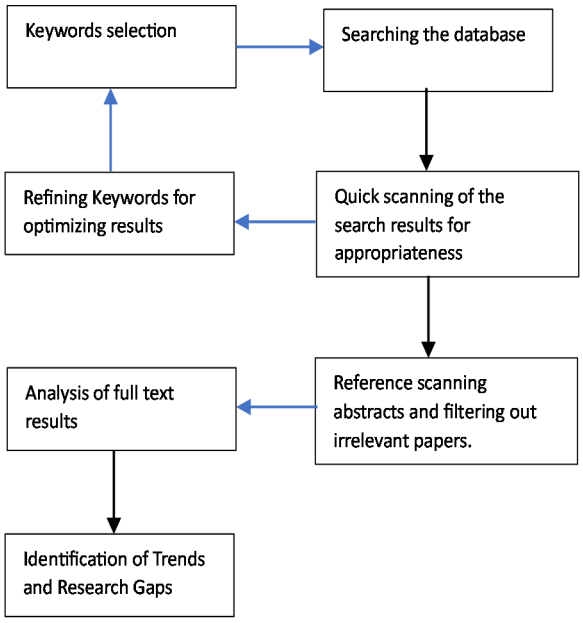
Environmental and sustainable development issues associated with airport operations include GHG emissions, noise reduction, and energy consumption. Developing a well-balanced airport expansion strategy to increase airport capacity and cater to future growth opportunities, while minimizing the associated negative environmental impacts is a challenge that airport authorities have to deal with (Maha Mousavi Sameh & Scavuzzi, n.d.) Digital transformation is rapidly changing the way business is being done. The airports are digitalizing their operations and automating processes. The focus is on optimization, revenue enhancement, and leveraging existing capacities. Myriad digital technologies are available which could be deployed at the airport. Passenger flow-related processes such as security, check-in, baggage drop and retrieval, boarding, and border control could be enhanced by Digitalization. On the other hand, equipment and systems such as baggage belts, escalators, HVAC, illumination, security baggage screening, etc., could be automated, increasing their efficiency and availability. Digital transformation of airports leads to enhancement in capacity utilization, reduction in energy and water usage, and improvement in economic sustainability. Digitalization also causes a reduction in emissions due to greenhouse gases, reduction in carbon footprint, and contributes to environmental sustainability. However, the selection of appropriate digital technologies with sustainability impact is a daunting task since there are no guidelines available for such a selection. This article presents a tool *'Digital Technology Selection Framework for Impact on Airport Sustainability' that will assist airport in sustainability assessment of digital technologies.*

2. Methodology, Literature Review

Literature review was conducted using a step-by-step approach (see Figure 1). The keywords were selected to obtain the research papers relevant for studies on digital transformation and its correlation with airport sustainability. A quick scan of the search results was carried out and the keyword used were refined to improve the search results. The database search with revised keywords was carried out which fetched better search results. In this study, the selected keywords were "sustainability", "digital transformation", "and "airports". The reference scan of the abstracts for the searched research articles was conducted and the irrelevant papers were filtered out. The remaining research papers formed the basis for the observations and the study undertaken in this paper. The keyword search was conducted in the EBSCO and Google Scholar databases. The literature review included The shortlisted literature was analysed to identify current research trends in the research published for a period of 15 years since 2009 up to 2024. The rationale for selection of this period is that the digital technologies are being harnessed for industrial and business applications only for last 15 years.

The first search yielded 17000 results; these were further refined. The publications which were, not relevant to the subject, not research articles, were citations, were then screened out. The articles not relevant to the research topic, were then excluded which yielded a final

Figure 1: Literature Review Process Flow Diagram
Source: Authors



count of 34 articles for evaluation. The low article number can be attributed to two reasons: First, Digital transformation at airports is comparatively a recent phenomenon. Second, Studies on digital transformation's impact on sustainability at airports are rare.

The studied articles have been classified into four broad topics (see Table 1). It can be seen that there are 17 articles on airport sustainability, nine articles on airport digitalization/digital transformation, and there are only two articles on the relationship between digital transformation and sustainability.

3. Airport Environmental Burden

An airport consists of airside infrastructure such as runways, aprons, and terminal buildings for effective operation of airlines. Emissions from aircraft, both while they are in the air and on the ground, generate a variety of negative impacts on air quality and climate, contributing to the depletion of the ozone layer. Aircraft engine emissions containing gases such as NOx, HC, Sox, CO, and other particles can cause harmful effects from the ground level as well as at different flight levels and higher altitudes. Ground support equipment, and airport ground-service vehicles also contribute to environmental pollution at the airport.

Any unpleasant sound, defined as noise, can have serious consequences for the physical and mental health of human beings, and their overall well-being. Noise pollution due to the generation of excessive aircraft noise is one of the most critical environmental issues at airports.

Table 1: Subject wise Literature Classification *Source: Authors*

Subject	Author / References	Number of Articles
Sustainability	(*UNITED NATIONS General Assembly*, 1997) (ELKINGTON, 2018) (Kuhlman & Farrington, 2010)	3
Airport Sustainability	(Lu et al., 2018), (Baxter et al., 2014), (Thomas et al., 2001) (Eid et al., 2022), (Greer et al., 2020) , (Dimitriou & Karagkouni, 2022) , (Kilkiş & Kilkiş, 2016), (Heyes et al., 2023) , (Maha Mousavi Sameh & Scavuzzi, n.d.) (Budd et al., 2015) ; (Monsalud et al., 2015) (IATA, 2022) , (Di Mascio et al., 2022), (Elhmoud & Kutty, n.d.) , (Sreenath et al., 2021), (SAGA, 2009) , (*VIRGINIA AIRPORT SYSTEM ECONOMIC IMPACT STUDY EXECUTIVE SUMMARY*, n.d.)	17
Airport Digitalization	(Rajapaksha & Jayasuriya, 2020) (Peters, 2022) (STROME TREVOR, 2023) (Biancardo et al., 2020) (Di Vaio & Varriale, 2020), (Chourasia et al., 2021) (Pinto, 2021) ,(Rawlings, 2022)	9
Digital Transformation and Sustainability	(Kamra, 2021) , (Morse, 2019)	2

The acquisition of land to construct airports and the infrastructure related to them results in the relocation of people, the loss of livelihoods, and social unrest. When land is utilised efficiently and operations are optimised,

capacity can be increased without the requirement of additional land. Airport operations generate waste, which includes waste from passenger amenities, airfield operations, maintenance activities, and construction required for expansion or renovation. Airside activities at an airport such as airfield de-icing and anti-icing using chemicals, aircraft refuelling, maintenance, and cleaning of aircraft and vehicles, generate chemical pollutants that are discharged into the water bodies adjacent to airports adversely impacting the lives of species living in water and human beings (Maha Mousavi Sameh & Scavuzzi, n.d.).

Sustainability can include many different aspects in a complex system like an airport, such as water preservation, design and building approaches, and emission reduction. Because sustainability can affect various aspects of an

airport's architecture, maintainability, and operational efficiency, it’s a challenge to prepare the best plan for sustainability. Currently, the airports are being built with a focus on growth and efficiency. (Boons et al., 2010)

What Is Sustainability?

A broad definition of sustainability is ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (Brundtland Harlem, 1987)[1]. The multifaceted goal of development is to raise everyone's standard of living. The three aspects of sustainable development, economic, social, and environmental protection are interconnected and mutually supportive.

(*UNITED NATIONS General Assembly*, 1997) As a challenge to business leaders to rethink capitalism, the *"triple bottom line" approach* prompts deeper thought about capitalism and its future. It encourages "businesses to track and manage economic, social, and environmental value added or destroyed". (ELKINGTON, 2018)

Airports require a plan that considers the importance of sustainability to meet current demands without jeopardizing future resource base. However, cutting operational costs while reducing the impact on the environment and providing excellent customer service is a herculean task that airports must face.

4. Airport Sustainability

Environmental protection, including the preservation of natural resources, social advancement that takes into account the needs of all stakeholders, and maintaining high and steady rates of economic growth are all included in airport sustainability practices. The "Triple Bottom Line" of economic expansion, social accountability, and environmental management is widely acknowledged as central components of sustainability. Sustainability definitions and initiatives frequently incorporate the Triple Bottom Line principles. (ELKINGTON, 2018)

In the context of airport management, sustainability refers to an all-encompassing strategy that aims to protect the airport making them economically viable, operationally efficient, conserving natural resources, and socially responsible (EONS).

Many airport managers are aware of the numerous advantages that starting and implementing a sustainability program can provide the airport. Increased asset utilisation, reduced environmental impact, technology optimization, better technologies, reduction in asset development cost, enhanced bond ratings, improved community benefits, increased productivity due to an improved work environment, and decreased health, safety, and environmental risks are all ways to increase competitiveness. (SAGA, 2009)

Sustainable aviation refers to an ecosystem that enables an effective and environmentally friendly operating environment. The aviation ecosystem must have at its core strategy, three fundamentals, environment, economy, and social. These must be based on a strong structure encompassing stakeholder cooperation, regulatory requirements, and new innovative technologies. Airports are an integral part of this aviation ecosystem. Awareness and importance of sustainability are growing in airports and sustainability initiatives are progressing at different levels. The thrust of these efforts is on improving the efficiency of terminal and airside operations with the ultimate aim of reducing greenhouse gas emissions. (*Airport Sustainability Frost Sullivan*, 2022)

Airports are also concentrating their efforts on optimizing energy usage while improving their greenhouse gas emissions and noise levels. Increased adoption of electric ground equipment to handle aircraft operations decreases the effects of carbon emissions. Increased usage of resource planning tools to optimize the resources required for airside operations, Automated & electric transporters at landside (car parking) and airside (terminal to aircraft) reduce emissions and noise. Increased limitations on inefficient aircraft with higher fuel burns, emissions, and noise levels contribute to reducing adverse impacts on communities at and around the airport (*Airport Sustainability Frost Sullivan*, 2022)

The sustainability practices are influenced by airport location, size and number of passengers flying through, economic strength, etc. The airport stakeholder groups include employees working at the airports, suppliers and contractors, business partners, government and regulators, passengers & visitors, and the community (Greer et al., 2020)

The airport planning process should include sustainability while studying different options for development. This must include existing functional infrastructure and retrofitting and improving existing processes making them efficient. Depending on whether existing airport facilities need to be retrofitted or new infrastructure needs to be built in accordance with net zero carbon regulations, the investments can be significant. Therefore, activities related to sustainability ought to be prioritised according to what will produce the maximum probable reduction in the overall carbon footprint of the airport in the most efficient manner.

4.1. Airport Sustainability Initiatives

The capacity, location, business potential, and regional conditions of each airport determine the investments in sustainability. The following rules and methods can be applied to sustainability:

- Utilizing technology to make airport operations more efficient and less harmful to the environment.
- Implementing sustainable building practices will reduce energy wastage, conserve resources, and reduce CO2 releases from the infrastructure development cycle.

These systems need substantial investment and are ideal for large airports which need quick aircraft turnarounds due to a large number of flights. (Sreenath et al., 2021)

Since sustainability involves various parameters in the design, master planning, operations, and maintenance of airport systems, evaluating sustainability at an airport is a crucial planning step. A crucial first step toward effective sustainable planning is the creation of a set of guidelines for sustainability evaluation. The impact of airport terminal buildings, airfield lighting, and service vehicles on a variety of environmental impact categories, is examined employing a structured, multilayered influence matrix. (Monsalud et al., 2015)

4.2. Implementing Sustainability at Airports

The carbon footprint of airports can be reduced in a variety of ways. There are many ways to reduce energy wastage, shifting to renewable energy sources, getting hybrid, electric, or CNG-powered vehicles, promoting the use of public transportation among staff, clients, and visitors, working with airlines and air traffic control to reduce runway taxiing times, and implementing green landing techniques. Sustainability practices can be broadly categorised into three types, environmental, social, and economic environmental practices They have the potential to reduce the use of natural resources (such as fossil fuels), reduce emissions, minimize waste generation, and water pollution, and alleviate flooding, reducing water consumption in airports.

4.3. Energy Management

The energy used to operate the airport, whether generated on-site or purchased off-site, is a substantial source of CO2 emissions. The environmental impact will be affected by the combination of type of energy sources and the implementation of energy-saving measures. Airports are increasing their use of renewable energy sources. Renewable energy generation has substantially increased, due to falling costs driven by technology advancements. Delhi airport operates an onsite solar power plant of 13.14 MW capacity substantially reducing

its carbon footprint (*Green Energy*, 2022) whereas Hyderabad airport operator has enhanced its solar power capacity to 10 MW with a plant spread over an area of 45 acres having more than 30 thousand solar panels, bringing them savings of about USD150000 a year and reducing carbon footprint. (*Solar Power*, 2021)

Airside Operations involve airlines, airports, and ground-handling agencies as stakeholders. The sustainability actions on the airside is their shared responsibility. Usage of electricity driven equipment can be considered to reduce emissions and noise. Electricity driven Ground Power and Pre-Conditioned Air systems at aircraft stands can replace the use of ATF powered aircraft APU and diesel-powered ground power units that generate significant levels of emissions. These systems have high energy efficiency and low noise emissions. Heathrow Airport has deployed an IoT solution that alerts the airport and in turn, the airline that the aircraft APU is being used causing emissions and advises them to use electric powered units. Other equipment that can shift to electrical energy are Ground Handling Equipment, Fuel Hydrant Systems, and Assisted taxiing by hybrid or electric towing vehicles to reduce carbon emissions. (IATA, n.d.) (Mariani et al., 2019)

The most fuel is saved by air traffic management systems that permit more direct routes and the use of more productive optimal altitude and speed. Route optimization can significantly lower CO2 emissions.(Maha Mousavi Sameh & Scavuzzi, n.d.). A considerable amount of energy is required to meet the airport's operational requirements. Electricity is used mainly for lighting and air conditioning loads in the terminal building, apron, parking, and street lighting in open areas

Technology upgradation – Modern light-emitting diode (LED) technology replaces old traditional lighting on aprons, streets, parking areas, and exterior lighting using sodium-vapor bulbs, which reduces energy consumption by about 50% and has 1.5 times longer lifespan. Reducing energy consumption by replacing obsolete lighting and HVAC systems with more efficient technologies. Depending upon the weather conditions use of skylights and natural ventilation can also save energy. (IATA, n.d.). These requirements are fulfilled by the airports by purchasing electricity based on the consumption of fossil fuels such as diesel, natural gas, or aviation fuel. Additionally, emergency generators, boilers, and ground support vehicles also make use of fossil fuels. (de Rubeis et al., 2016)

4.4. Sustainable Water Management

Water is used in a variety of indoor and outdoor operations at airports, including toilet flushing, food preparation, and the operation of (HVAC) systems. Airports also use water for irrigation, as well as for cleaning and maintaining aircraft and infrastructure. In terms of consumption, major airport's use is comparable to the amount of water used by small and medium-sized cities. Tracking water use, utilizing water-saving fixtures and fittings, reducing irrigation demand, and using alternative water sources are some of the recommended water conservation measures for airports. (Greer et al., 2020)
Sustainable Water Management Initiatives that Airports use include:

- The 3R model, which stands for Reduce, Reuse, and Recharge water, can help airports use less fresh water. To achieve zero discharge and lower water usage, airport operators must treat and repurpose the wastewater. The demand for freshwater can be reduced and optimised by using treated wastewater for landscaping, toilet flushing, and HVAC maintenance.
- Rainwater harvesting.
- Reduced water consumption (Sreenath et al., 2021) (Liao et al., 2021)

4.5. Solid Waste Management

Airport operations result in a significant amount of solid waste generation. The airport's solid waste is produced by operations involving passengers, offices in airport buildings, restaurants, bathrooms, cargo operations, maintenance facilities, and landscaping. The majority of the waste produced in an airport is from the airlines, retailers, and cafeterias. When managing hazardous waste, airports adhere closely to the rules. They manage waste through licensed waste contractors, and hazardous items including asbestos, radioisotopes, and lubricants are collected, separated, and safely disposed of. (Sreenath et al., 2021)

4.6. Social Practices

A company's social practices are thought to include the effects of its operations on its workers, suppliers, investors, customers, and communities both locally and globally. Reducing noise, developing employees, and improving safety practices are also included in these.

The development of human capital is critical in an airport. Employees must grow personally and professionally to improve the airport experience and maintain good administration. Airports have the potential to significantly improve the life of local communities. Some airports support local communities and regions by purchasing local goods and hiring local workers (Sreenath et al., 2021) The relationship between airport administrators and the local community will be strengthened by this investment in the community's well-being. Hyderabad Airport supports sustainable growth and empowers local communities through grassroots-level initiatives in education, health, and vocational training. (Eid et al., 2022) (Varalakshmi Foundation, 2023)

4.7. Local Impacts

The airport's operations have repercussions for the surrounding communities, the most notable of which are the disturbances caused by the noise produced by aircraft landing and taking off, the contamination of the water supply, and the transportation options. The mitigation measures that airports can employ are:

Airport airside layout that minimizes aircraft noise and the impact of emissions.

- Use of approved noise reduction operational procedures consistent with regulatory guidelines.
- Building "sound walls" or "ground profiling" to lessen the noise effect for nearby residents.
- Protection of soil and water resources from stormwater overflow and harmful liquids(IATA, n.d.). Mumbai airport monitors and controls decibel levels through noise monitoring terminals installed along the landing and take-off paths to meet the civil aviation requirements prescribed by the regulator. (*Environment Management*, 2023)

Landside Access - Transportation

Communities living around the vicinity of the airports are adversely impacted by the surface traffic originating to and from the airport. Airports must therefore examine ways to alleviate the environmental effects of landside access of passengers, personnel, commodities, and cargo in and out of the airport, some of the options are:

- Encouraging efficient, dependable, and economical transport alternatives that limit automobile emissions and congestion.
- Convenient connections to regional, local, and high-speed rail services, as well as public transportation.
- A terminal layout that makes it simple to access a highway network.
- Integration of hotel shuttle services and off-airport car rental businesses.
- Electric Vehicle charging points.
- CNG, Hydrogen, and electric-powered vehicle deployment reduces GHG emissions Kansai International Airport uses hydrogen-powered buses and forklifts to reduce emissions (IATA, n.d.)

4.8. Economic practices

Airports strive for a financially viable operating model that provides appropriate returns to investors while also providing a high degree of passenger satisfaction and safety, all of which contribute to the development of the nation**.** (Eid et al., 2022)

Sustainability Options

Infrastructure- When it comes to airports, one of the negative effects of emissions from aircraft and ground support equipment is a deterioration in air quality, which can have a direct impact on human health.

Green Building – LEED Certification- Airports must implement sustainable building standards and design techniques to optimize energy use, conserve resources, and reduce carbon emissions throughout the infrastructure's entire lifecycle. US Green Buildings Council rates buildings for their environmental impact. The Mumbai Airport Terminal 2 and Delhi airports have been awarded a Platinum rating by the Indian Green Buildings Council. (Sustainability Report, 2020)

4.9. Sustainability Evaluation, Ranking and Reporting

‘International Air Transport Association (IATA)’ and ‘Airports Council International (ACI)’ evaluate or rank airports based on the implementation and performance of their sustainability efforts. The ‘Committee on Aviation Environmental Protection (CAEP)’ is a technical committee of the ICAO (‘International Civil Aviation Organization’). CAEP assists the Council in policy formulation and adopting guidelines related to aircraft noise and emissions, and their impact on the environment. (CAEP, 2023)

Airports Council International - (ACI) using its ‘Airport Carbon Accreditation Program’, ACI certifies airports for their environmental initiatives. It supports the ‘Paris Agreement's’ goals of limiting the rise in the average global temperature to 2°C above pre-industrial levels and aiming to stay below 1.5°C.
The program allows airports to participate at one of the four main, progressively more demanding levels of accreditation: Mapping, reduction, optimization, and transformation are the first four steps. In addition, level 3 and level 4 airports have the option of offsetting their residual emissions. In order to meet rising public and stakeholder expectations, ACI encourages airports to reduce their emissions following the most recent scientific and political developments. (Airport Carbon Accreditation 28/9/2023) . The program offers a one-of-a-kind framework and tool for active carbon management at airports, with measurable outcomes. It focuses on the operational activities that have the greatest impact on carbon emissions. It aids in guiding and supporting airports through a process of continuous improvement and collaboration with stakeholders.

Sustainability Ranking - It is an index that evaluates the performance of airports based on various dimensions in comparison with one another. 'It is a composite index consisting of 25 different indicators and five dimensions. Airport services and quality, energy consumption, renewable energy usage, CO2 emissions and mitigation plan, sustainability initiatives, and low-emission transport are the dimensions.' (Kilkiş & Kilkiş, 2016). The IATA Environmental Assessment (IEnvA) program assesses the commitment of aviation entities toward sustainability. (IEnva, 2023). Sustainability reports are prepared and published as per the guidelines set by the 'Global Reporting Initiative (GRI)', (Global Reporting Initiative, 2020) (Sreenath et al., 2021)

5. Digital Transformation and Its Impact on Airport Sustainability

The implementation of digitalization tools at airports provides a streamlined and trouble-free experience for their patrons. Digital transformation helps to: streamline ground handling processes to achieve better efficiency, reduce operational risks due to potential delays or incidents, optimize space usage, improve retail revenues by increasing relevance and ensuring practicality of offers, optimize the use of valuable space at the airports by flow management, provides real-time travel information to passengers on boarding time, and optimizes preventive maintenance leading to cost savings. It provides opportunities to maximize the amount of time spent in airport shops and lounges by reducing the amount of time spent waiting in line to drop off bags and obtain boarding passes. (GARDY, 2016)

Digital integration of 'Airport Collaborative Decision Making (A-CDM)' helps collaboration between airlines, airport operations, ground handlers, and air traffic controllers (ATCs). This cooperation leads to the better on-time performance of flights, reduced fuel consumption leading to reduction in carbon footprint, and improved efficiency. The airlines aim to minimize Total Off Block Time (TOBT), meaning the time the aircraft spends at the airport. Digitally integrated ADSB (Automatic Dependence Surveillance Broadcast) with ground operations, passenger boarding, etc., reduces TOBT. (Schultz et al., 2022). Mobile Technologies, Facial Recognition, Smart Video Surveillance, Radio Frequency Identification (RFID), and Customer Relationship Management. Artificial Intelligence, Internet of Things (IoT), Robotic Process Automation, Predictive Maintenance, Blockchain Technologies, and Cloud Computing are the digital technologies being considered for airport deployment in passenger engagement and process automation.

Digital transformation can reduce airport capacity constraints, improve airport operation management, optimize passenger flow, and improve relationships among airport stakeholders (Halpern, Budd, et al., 2021) (Zaharia & Pietreanu, 2018). Digital transformation streamlines customer-centric management, work processes, and forecast difficulties. The application of Augmented reality and biometric processes leads to the creation of smooth passenger flows. Self-driving electric vehicles and drone inspections of airfields to monitor activity are all possibilities with digitalization. (Pinto, 2021)

Efficiency improvements, resource optimization, reduction in energy consumption, and process improvements in customer engagement processes lead to improvement in sustainability. Removal of constraints in infrastructure capacity improves capacity utilization reducing the need for investment in infrastructure and saving precious resources. Airport digital transformation initiatives have a positive impact on sustainability, which can be classified into three major practices economic practices, social practices, and environmental practices

Economic practices

Digitalization of airports aims at improving operational efficiencies, maximization of capacity utilization, and excellence in passenger satisfaction. Airport digitalization processes have been broadly categorized into passenger-related processes, infrastructure and asset management, airside operations, and ground handling. (Halpern, Mwesiumo, et al., 2021)

Ground Operations -Airport ground operations, encompass all of the services that are necessary for an airline between the landing and take-off of an aircraft. These services include passenger boarding and disembarkation, refuelling, cabin cleaning, catering, baggage handling, aircraft maintenance, and aviation security services. (Kovynyov & Mikut, 2018)

Passenger Processes- The identification of passengers and verification of travel documents including boarding passes have now been digitally enabled. The passenger carries his/her boarding pass on mobile phone and produces the identification documents to get entry into the airport premises. The process has gone through a further digital transformation using augmented reality, big data analytics, blockchain technology, and cloud services. Airports in India have embarked upon the digitalization of passenger identification and airport entry processes. In a one-time registration process, passengers can register their biometric data, with identification on a *DigiYatra* portal. For all subsequent journeys, the passenger updates the flight details at home. On arrival at the airport, the passenger can quickly pass through the check-in process without the need for any verification by producing his/her mobile phone updates, and personal identification is uploaded. 'DigiYatra is an industry-led initiative in India that uses facial recognition technology for seamless terminal entry & security clearance at the airports a hassle-free, and paperless process. It is a decentralized mobile-based platform where air travellers can save their IDs and travel documents.' Digiyatra has already been implemented at Delhi, Bangalore, Pune, Varanasi, Vijayawada, Kolkata and Mumbai airports. (*"DIGI YATRA" REIMAGINING AIR TRAVEL IN INDIA*, n.d.)

Smart video surveillance and mobile technologies are being utilized to track congested areas in real-time and smooth out passenger movements. The positive side effect of this efficient check-in, self-baggage drops, and crowd control operations is that they increase passenger satisfaction and free up time for shopping, leading to increased retail and F&B sales.

Digital IoT sensors installation in appropriate places at airports can make navigation of passenger amenities, shopping areas, help desks, etc. easier for passengers. Information on flight updates, public transport, waiting time at counters, etc. can be shared with passengers on their mobile phones using geolocation technologies. The efficiency of the terminal's operations is increased by process automation, monitoring and managing passenger flow, and customer involvement. Digitalization of passenger processes can increase the terminal capacity by up to 20% (Blondel et al., 2015) (Halpern, Budd, et al., 2021)

Ground Handling - IoT can be implemented for the asset tracking of ground support equipment (GSE) such as buses, belt loaders, passenger steps, baggage trolleys & tugs. Automation of GSE scheduling minimizes the total number of GSE equipment and vehicles required to handle flights reducing the requirement of ground handling equipment, and improving capacity utilization resulting in direct savings of capital expenditure. (Kovynyov & Mikut, 2018) (Rawlings, 2020) Digitalization of the ground handling processes both within the terminal and airside has a tremendous impact on the economic aspect of sustainability. Improvement in operational efficiency increases capacity utilization, saves precious economic and natural resources, and also increases passenger satisfaction. Major airports all over the world, including London, Tokyo, and Singapore, have begun testing out various forms of autonomous technology, including autonomous vehicles, automated

baggage handling and transport systems, and even aerobridges that automatically align themselves to the doors of planes. Additionally, it utilizes artificial intelligence technology to read the faces of passengers as well as their emotions, such as screams. At the Tokyo airport, a pilot project is currently being undertaken to monitor aircraft movement on the runway using digital infrared (IR) camera technology. Immigration clearance of passengers can be done very quickly with e-passport readers and facial recognition technology. (Sreenath et al., 2021)

ACDM enables the optimization of all activities under air traffic management through the continuous sharing of real-time data among the operators concerned. Since real-time operational information is available, the platform optimizes the utilization of the infrastructure. It also decreases congestion and reduces difficulties in ground handling. The platform encourages the efficient use of ground-handling resources. It improves the efficiency of on-ground aircraft traffic allowing flexibility in pre-departure planning reducing wastage of slots and consequently taxiway congestion. It enhances process predictability and delivers real-time network updates. Finally, in terms of the effects on airlines, the platform provides for improved on-time performance and speedier turnaround. A-CDM is a blockchain technology application that improves the operating efficiency of an airport through supply chain improvement. (Di Vaio & Varriale, 2020). The A-CDM implementation has improved operational efficiency at Mumbai International Airport. (Sustainability Report, 2020)

Digitalization of airside operations could increase the runway capacity by up to 10%. (Blondel et al., 2015) . (IATA, n.d.). An increase in runway capacity coupled with terminal efficiency improvement could increase the airport's capacity in terms of handling flights eventually leading to an increase in profitability. Implementation of the e-Freight initiative for air cargo has the potential to eliminate more than 7800 tonnes of paper documents annually and contribute to sustainability (Ordieres-Meré et al., 2020)

Energy Consumption Management - Monitoring airport systems such as escalators, baggage carousals, lighting systems, etc., when not in use by using IoT and switching them off, reduces power consumption substantially, eventually reducing carbon footprint, and improving sustainability.

Digitalization positively impacts economic sustainability and knowledge pillars of TBL approach to sustainability of the airports (T Prieto Remón, 2021)

Predictive Maintenance

Airport operations encompass complex systems such as baggage handling, baggage screening, HVAC, waste management, and others. These systems involve the continuous operation of a large number of equipment for the smooth operation of airports. The failure of any of the systems results in flight delays and crowding of airports which cascades into tremendous strain on airport capacity and utilities. The equipment and systems breakdown can be avoided by digital transformation. Internet of Things using sensors coupled with proactive, insightful data, and artificial intelligence alerts, the operators of the ensuing breakdown well in advance, which can be used to avoid systems breakdown. Digital twins are being used in critical equipment and systems monitoring and predictive maintenance A digital twin as a unified, real-time information base provides accurate understandings for both strategic decision-making and streamlining airport infrastructure management processes. The digital transformation thus extends the useful life of equipment and systems and contributes to sustainability. Airfield ground lighting (AGL) is critical for aircraft take-off and landing. AGL health is continuously monitored using digitalization tools, which provide mobile phone alerts and help maintain or replace the AGL component before its breakdown.

Digital Transformation technologies such as IoT, Artificial Intelligence, Cloud technologies, the Internet, Information Technology, Mobile Communications, Machine learning, Sensors, RFID, and their combination offer innumerable opportunities to improve operational efficiency, reduce energy consumption, and avoid breakdown, the possibilities are numerous.

6. Digital Technology Selection Framework for Impact on Airport Sustainability

Digital transformation technology solutions being offered by technology companies to the airports are focussed on efficiency improvements, process optimization, and customer satisfaction. While this is desirable these solutions do not highlight or quantify the sustainability impact it will have on airports. The airports which are planning to invest in digital transformation and who want to improve sustainability do not have any mechanism to assess the sustainability impact of the digital technologies they want to deploy. Digital transformation of an organization need substantial investments and also commitment to continuous upgradation and maintenance. Sustainability impact assessment therefore is a critical issue that is facing airports embarking on digital transformation journey. The 'Digital Technology Selection Framework for Impact on Airport Sustainability' is a tool that gives airports the ability to predict the impact of proposed digital transformation measures before making a decision to invest in digital technologies. It is believed that the proposed 'Digital Technology Selection Framework for Impact on Airport Sustainability' (see Table 2) will serve as an effective tool for airports to select a particular technology based on its predicted sustainability impact.

6.1. Results & Discussion

The study of articles in the literature has been classified into four broad topics (see Table 1). It can be seen that there are 17 articles on airport sustainability, nine articles on airport digitalization/digital transformation, and there are only two articles on the relationship between digital transformation and sustainability. There is no literature relating airport digital transformation to sustainability. Therefore, there is a need to pursue research to ascertain the relationship between airport digital transformation and sustainability. This paper establishes the relationship between airport digital transformation and sustainability.

Digital Transformation technologies such as IoT, Artificial Intelligence, Cloud technologies, the Internet, Information Technology, Mobile Communications, Machine learning, Sensors, RFID, and their combination offer innumerable opportunities to improve operational efficiency, reduce energy consumption, and avoid equipment breakdown, the possibilities are numerous. Since the technologies are evolving simultaneously there are immense opportunities for innovation in the airports and other industries. The airport functional areas in which digital transformation can be implemented and the type of impact it will have in terms of their impact on sustainability are summarized in the 'Digital Technology Selection Framework for Impact on Airport Sustainability' (see Table. 2)

6.2. Significance and Future Implications of the Study

The twin objectives of reducing sustainability impact and improving profitability can be met with the digital transformation of airports. However, selecting an appropriate bouquet

of digital transformation technologies is a challenging task. The proposed 'Digital Technology Selection Framework for Impact on Airport Sustainability' is a useful tool for airports to assess the sustainability impact of a particular digital transformation technology on sustainability. This study makes a significant contribution to the body of knowledge since the literature on the relationship between digital transformation and sustainability is rare. There is a limitation to the generalization of the proposed assessment framework since it is based on a literature review and is at a conceptual stage. Future

Table 2: Digital Technology Selection Framework for Impact on Airport Sustainability

Functional Area	**Impact on Sustainability**			
	Environmental	**Operations**	**Social**	**Economic**
Airside Operations				
Airport Collaborative Decision Making (ACDM)	⬌	★	✦	★
Passenger				
Biometric Identification	✖	★	✦	✦
Passenger Flow Management	✖	✦	✦	✦
Passenger facilitation				
Self-Baggage Drop, Self-Check-In	✖	✦	✦	⬌
Retail Sales	✖	✦	✦	⬌
Energy Consumption Management				
Airside Lighting	⬌	✦	✖	★
Open areas and Parking lighting	✦	✦	▬	✦
Terminal lighting	✦	★	⬌	✦
Predictive Maintenance				
Utility Systems	✦	✦	✖	★
Equipment (Assets)				
HVAC Systems	✦	★	⬌	★
Water and Waste Management	★	★	✦	✦
Ground Handling				
Ground Support Equipment	✦	★	✦	★
Terminal Equipment				
Baggage Handling System	⬌	★	★	✦
Escalators, Travellators, Elevators	✖	★	★	✦

Source: Authors

Legend: High Impact - ★ Medium Impact - ✦

Low Impact - ⬌ No Impact - ✖

research could be based on case studies and empirical research in this upcoming area of technology application and its relationship with sustainability.

6.3. Conclusion

Airports play an important role in the economic development of a nation. Airports need numerous equipment and systems for successfully meeting their operational requirements of handling aircraft and passengers. This equipment generates substantial quantities of greenhouse gas (GHG) emissions, affect communities, and have a huge impact on sustainability. As responsible business entities airports have a responsibility to minimize sustainability impact. Digital transformation of airports has become a necessity to improve operational efficiency, increase capacity utilization, enhance passenger satisfaction, and meet business goals. The twin objectives of reducing sustainability impact and improving profitability can be met with the digital transformation of airports. However, selecting an appropriate bouquet of digital transformation technologies is a challenging task. The proposed 'Digital Technology Selection Framework for Impact on Airport Sustainability' is a useful tool for airports to assess the sustainability impact of a particular digital transformation technology on sustainability.

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