Airport 4.0:

Technology Adoption Framework for Airports (TAFA)

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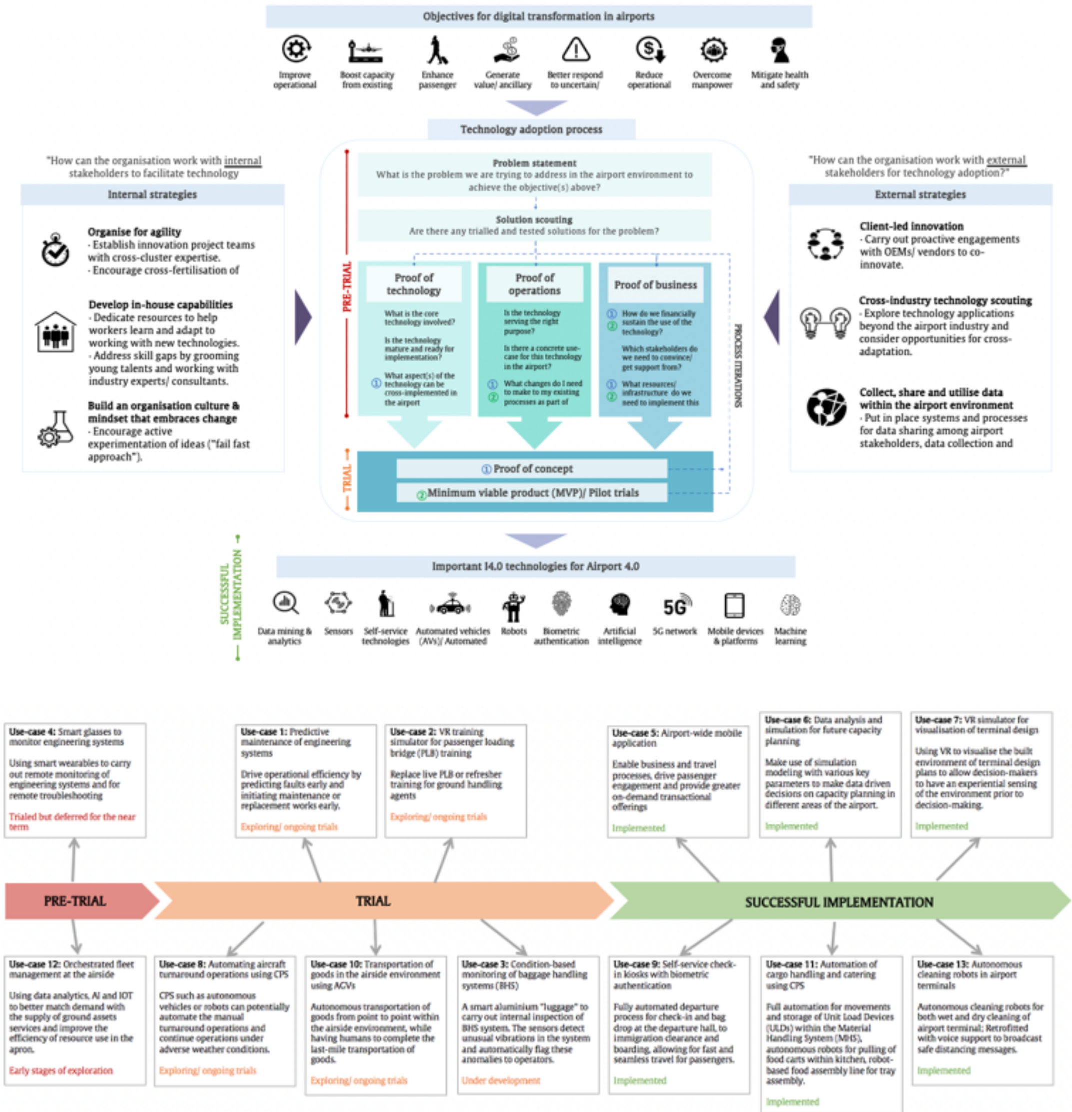

Highlights

- Adoption of emerging technologies (particularly Industry 4.0) has been instrumental in helping airport operators in mitigating operational and health concerns, including those related to the COVID-19 pandemic.
- The proposed TAFA framework is the first-of-its-kind to study Industry 4.0 technology adoption in airports.
- The framework for the adoption of Industry 4.0 technologies was developed based on the insights from an industry survey of 102 airport operators and managers around the world and 17 semi-structured interviews.
- The framework provides a 'three-proof' approach (proof of technology, proof of operations and proof of business) to guide airport operators in their decision-making process in adopting Industry 4.0 technologies in airports.
- This framework is verified through a technology implementation case study of a leading Asian airport.
- This article also extends the theoretical knowledge of Technology-Organisation-Environment (TOE) framework.

Title: Airport 4.0 – Technology Adoption Framework for Airports (TAFA)

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Abstract:

Airports have taken centre stage in the fight against the ongoing COVID-19 pandemic, and adoption of technologies has been instrumental in helping airport operators to mitigate operational and health concerns relating to the pandemic. A novel framework for the adoption of Industry 4.0 technologies was developed based on the insights gathered from an industry survey of 102 airport operators and managers around the world and 17 semi-structured interviews. The framework provides a 'three-proof' approach (proof of technology, proof of operations and proof of business) to guide airport operators in their decision-making process in adopting Industry 4.0 technologies in airports. This framework is further verified through a case study of the technology implementation efforts of a leading Asian airport.

One Sentence Summary: A novel framework and case study for the adoption of Industry 4.0 technologies in airports

Keywords: Airport 4.0; Airport; Industry 4.0; Technology; Technologies; Adoption; Digital Transformation; Digitalisation; Aviation 4.0; Aviation; Aerospace; Robotics; TAFA Framework; Framework; Case study; Interviews; Use cases.

1. Introduction

Traditionally, airports have served as gateways to the world to connect families, businesses, cultures and economies. In the ongoing COVID-19 pandemic, countries have taken unprecedented measures to close their international borders and to implement strict testing and quarantine regimes in airports to identify passengers who may have contracted the coronavirus. Airports have since evolved into crucial gateways for countries to stem the spread of COVID-19 and has thus presented a fresh set of challenges for airport operators.

Based on a recent industry survey (Tan & Masood, 2021b), airport operators faced increasing pressure to implement safe distancing measures and periodic sanitisation protocols to provide a safe travelling environment (ICAO, 2020). Despite a marked reduction in passenger volume compared to pre-COVID years, manpower shortage is a pertinent issue faced by airport operators to facilitate airport operations while mitigating health and safety concerns relating to the pandemic. These has culminated in a greater push to adopt Industry 4.0 (I4.0) technologies in airports to resolve these challenges.

Technology adoption is not a new phenomenon for airports. According to a recent structured literature review (SLR), airports have increasingly adopted I4.0 technologies as part of their digital transformation journeys with data mining and analytics being the most widely-adopted technology among other I4.0 technologies identified (Tan & Masood, 2021a). However, the adoption of I4.0 technologies is marred by several technological, organisational and environmental challenges, with organisational readiness being one of the most statistically significant factor in influencing the success of technology adoption in airports (Tan & Masood, 2021b).

The research presented in this article is aimed at investigating the following overarching research question: *"How can airport operators or managers develop airports of the future using I4.0 technologies?"*. While there are technology adoption frameworks such as the TOE framework and DOI theory that are most prevalently referenced in academic literature to study technology adoption in firms (Oliveira & Martins, 2011), there is a lack of generic criteria for airport operators to assess the feasibility of I4.0 technologies for adoption in airports. Sohn *et. al.* (2013) developed a preliminary smart airport framework to establish an integrated view of the use of smart technology to improve passenger service and airport resource management but has also highlighted the need to extend the strategic framework to include airport operations.

Due to the lack of a technology adoption framework to complement the digitalisation strategy of airports, a novel Technology Adoption Framework for Airports (TAFA framework) was developed. The TAFA framework serves to guide airport operators in their digital transformation process, particularly in the adoption of I4.0 technologies in the airport. Furthermore, a case study was developed to validate the use of the TAFA framework in the context of the technology implementation efforts of a leading Asian airport.

The rest of this article is structured as follows. Section 2 provides background and literature review on Airport 4.0. Section 3 presents research methodology. Section 4 presents the TAFA framework and its components. Section 5 presents a case study of a leading Asian airport using the TAFA framework. Section 6 discusses some of the key contributions of the TAFA framework and case study to industrial practice and academia as well as limitations and possible future work. Section 7 concludes the article.

2. Airport 4.0

2.1 Definition of Airport 4.0

Establishing clear definitions provide the fundamental starting ground for research. Based on the SLR, the terms "Aviation 4.0" and "Airport 4.0" were mentioned briefly in a handful of papers. The term Aviation 4.0 captures the paradigm shift in the aviation industry through the incorporation of I4.0 technologies (Valdés et al., 2018). However, as pointed out by Valdés et al. (2018), Aviation 4.0 is mainly related to aerospace manufacturing processes, with minimal or little reference to airline or airport operations. In this regard, the term Airport 4.0 is more appropriate to capture the new digital age of airports. Out of the papers reviewed, only 4 papers mentioned the term "Airport 4.0" in the title, abstract, list of keywords or the general content (**Table 1**) (Tan & Masood 2021a).

Both Felkel et al. (2017) and Koenig et al. (2019) discussed applications involving data analytics and sensor technologies. Zaharia & Pietreanu (2018) emphasised data analytics as a core capability of Airport 4.0 and illustrates a range of technologies that support the objectives of improving efficiency of airport operations, enhancing passenger journey and creating ancillary revenues. From these papers, it is evident that the term Airport 4.0 is used as a broad term to imply advancement and adoption of technologies in airports, with a weak reference to the associated term "Industry 4.0".

Furthermore, considering the lack of academic publications that mention Airport 4.0, it can be concluded that there is no general definition for the term "Airport 4.0" in academic literature, unlike the term "Industry 4.0" which has been widely defined and discussed (Fettermann et al., 2018). Consequently, the I4.0 technologies that are important for future airports are not explicitly captured in literature.

Table 1: Review of "Airport 4.0" literature (Tan & Masood 2021a).

Authors	Year	Title	Description	Research Methodology	Reference to Airport 4.0
Büyüközkan *et a*	*2020*	Analysis of success factors in aviation 4.0 using integrated intuitionistic fuzzy MCDM methods	Proposed methodology to prioritise success factors of aviation 4.0 among 3 airline companies using MCDM methods	Literature review	Moderate. Airport 4.0 and Aviation 4.0 used to describe the era of digital transformation in line with Industry 4.0
Koenig *et al.*	*2019*	Innovative airport 4.0 condition-based maintenance system for baggage handling DCV systems	Pilot trial in Heathrow airport to collect real-time high frequency vibration data for baggage carts to facilitate predictive/ condition-based maintenance of baggage handling system.	Case Study	Limited. Airport 4.0 is only mentioned in title.
Zaharia and Pie	*2018*	Challenges in airport digital transformation	Challenges in adopting digital solutions adopted across different areas in Henri Coanda International Airport	Case Study	Moderate. Airport 4.0 used as a section header with no clear defintion and as a diagram label with a suite of technologies to achieve operational efficiency, passenger journey and retail ancillary revenue.
Felkel *et al.*	*2017*	Hub airport 4.0 - How frankfurt airport uses predictive analytics to enhance customer experience and drive operational excellence	Overview of recent projects in Frankfurt airport that made use of predictive analytics to improve passenger flow management, optimising aircraft positioning and forecast retail revenue.	Case Study	Limited. Airport 4.0 is only mentioned in title.

2.2 Frequency and challenges of I4.0 technology adoption in airports

This section outlines the frequency of adoption of I4.0 technologies as well as the key challenges faced in their adoption.

Figure 1 illustrates the frequency of adoption across the different functional categories of I4.0 technologies in airports based on the papers reviewed. Some papers reviewed discussed more than one category of I4.0 technology and these are counted accordingly. From the figure, data analysis and processing is the most prevalent functional category of I4.0 technology that is adopted in airports. This is consistent with the observation from Mullan (2019) that the airport environment is rich with data that is generated across all stages of the passengers' journey. Also, since the SLR is focused on the airport which has no manufacturing operations, it is not surprising to find no reference to additive manufacturing in the literature reviewed. Even though cloud computing is rarely discussed in the papers reviewed, it is likely to be underrepresented in this frequency analysis. This is because the functional category of cloud computing consists mainly of backend services and infrastructure that enables the remote processing of data and facilitates data storage and applications (Fettermann et al., 2018). Thus, even though cloud computing is not explicitly discussed in the papers reviewed, it is likely to be a key technology that enables other I4.0 technology applications in the airport, such as data analytics and the implementation of SSTs (Yau & Tang, 2018).

Table 2 summarises the key challenges faced in adopting I4.0 technologies in airports from the papers reviewed in the SLR. The various challenges are grouped into three main categories (technology, organisational and environmental). From the table, it is evident that technological challenges were most frequently discussed in literature, with specific technology limitations relating to the I4.0 technologies being the most prevalent challenge faced.

The I4.0 technologies were adopted across various functions in the airport, namely: passenger handling services, commercial services, airside operations, air traffic control and management, airport planning, design and construction, airport logistics and airport security.

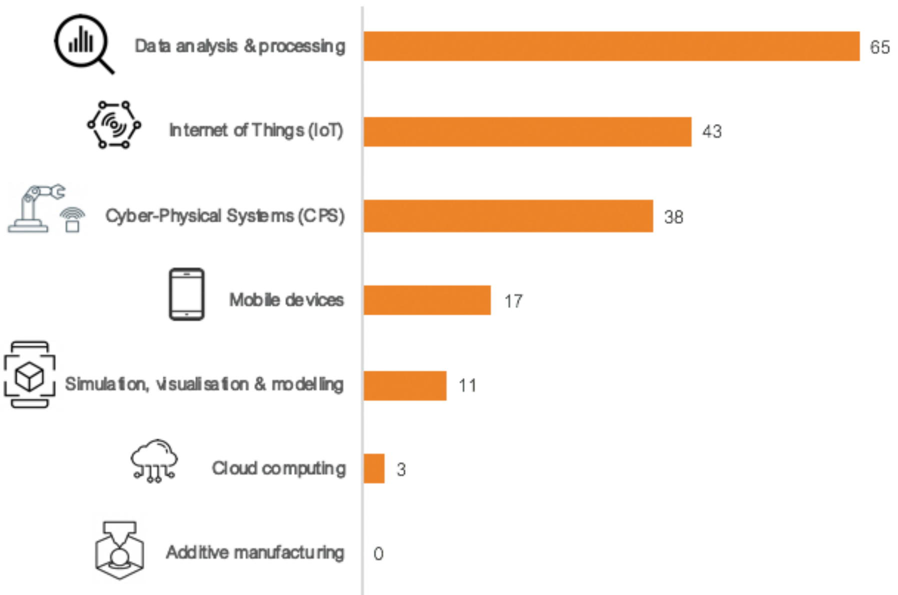

Figure 1: Frequency of I4.0 technologies appearing in literature

Table 2: Challenges in adopting I4.0 technologies in airports

Cluster	Challenge	Number of publications
Technology	Specific technology limitations	29
	Data limitations	15
	Need for accompanying infrastructure/ technology/ processes	13
	Cybersecurity and privacy concerns	12
	Heavy financial investment	12
	Need for customisation	8
	Need for usability tests/ trials	8
	Technology complexities/ infeasibilities/ disruptions	8
	Legacy systems and processes	3
	Hard to replace humans	2
	Health and safety concerns	2
Organisation	Need for specialised skills and training	9
	Need for organisational culture that promotes digitalisation	7
	Need for human resource redeployment to support digitalisation efforts	3
	Staff receptivity	3
Environment	Passenger receptivity	9
	Cooperation of multiple stakeholders across organisations	5

2.3 Results and analysis of a Recent Industrial Survey

The results and analysis of a recent industrial survey of airport operators and managers (Tan & Masood 2021b) provides current state of adoption of I4.0 technologies in airports.

2.3.1 Success factors for adopting I4.0 technologies in airports

In the survey questionnaire (Tan & Masood 2021b), airport operators were provided with a list of I4.0 technologies that were identified from the initial literature review (Tan & Masood 2021a). From this list, airport operators had to identify the technologies which they perceive to be important for future airports based on their airport management experience. Thereafter, they were tasked to indicate the technologies which are currently implemented within the airports that they operate based upon their selections. Two scores were computed based on how often the technology was selected in the survey in percentage terms. *Implementation score* reflects how often the particular I4.0 technology is implemented in current airports while *importance score* reflects the relative importance of the I4.0 technology for future airports.

The implementation scores were calculated based on how often survey participants have indicated that the I4.0 technology was implemented in airports currently. The importance score was calculated based on how often the survey participants have indicated that the technology was important for future airports. **Figure 2** provides a snapshot of the current state of adoption of I4.0 technologies in the airport based on their importance and implementation scores. The I4.0 technologies shown in the top-right quadrant (green) are considered to be both important and are widely implemented in airports currently.

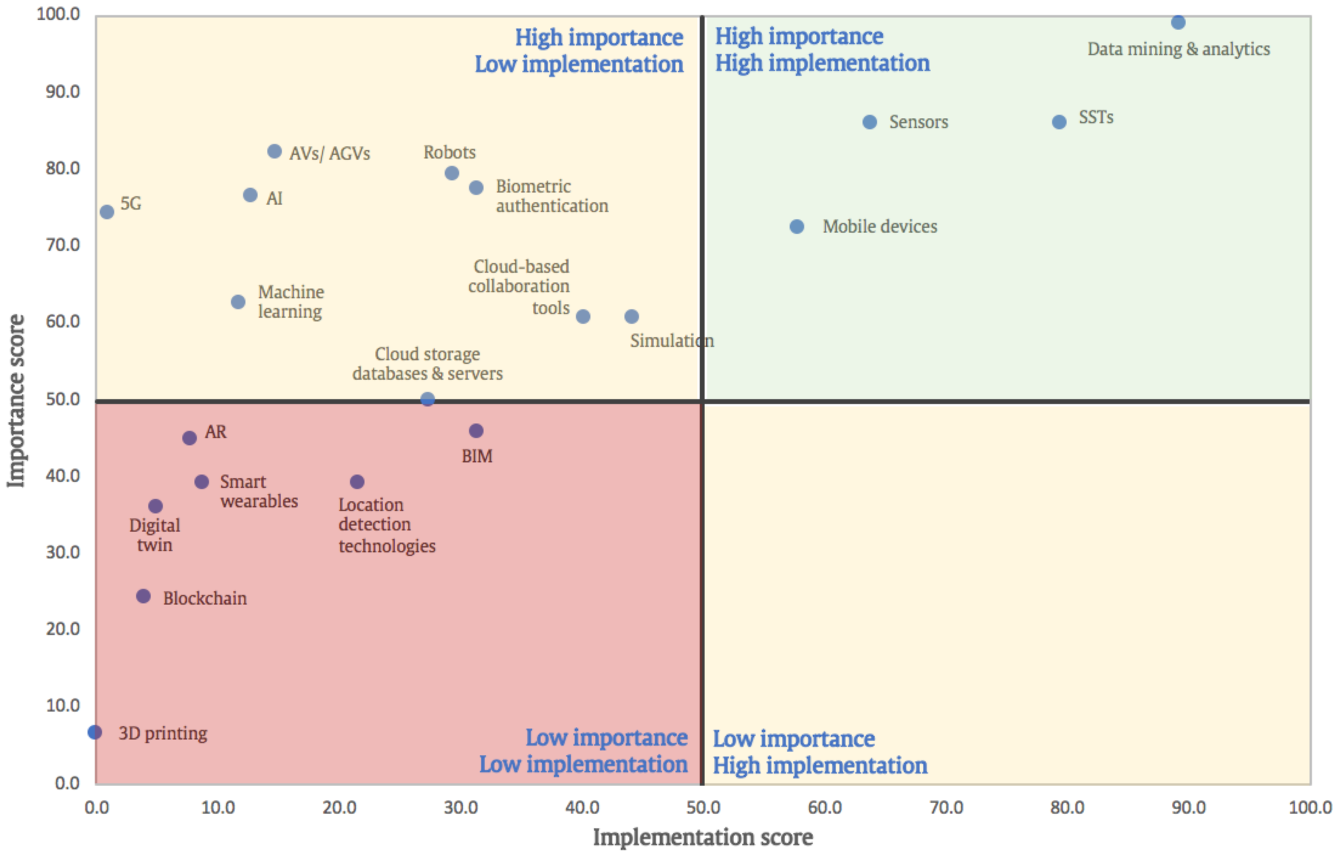

Figure 2: Implementation and importance scores of I4.0 technologies in airports (Tan & Masood 2021b)

2.3.2 Success factors for adopting I4.0 technologies in airports

In the survey questionnaire (Tan & Masood 2021b), airport operators were also tasked to identify key success factors for successful adoption of I4.0 technologies in the airport from a pre-defined list of success factors based on literature review (Tan & Masood 2021a) and interview inputs. For airport operators who have indicated that the airports they manage do not have any past successes in implementing I4.0 technologies, their responses in this category were excluded. Thereafter, they were tasked to rank the success factors based upon their selections. Two sets of data were generated from the data collected: (i) *Frequency*: Percentage of how often the factor was selected by survey respondents to be a success factor for I4.0 technology adoption; and (ii) *Average normalised rank*: Based on the ranking that survey respondents have indicated for their selection of success factors, normalisation was carried out to account for the different number of success factors that may have been selected by different respondents. Thereafter, the average of the normalised ranks for each success factor was computed. The normalised rank for each success factor can range from 1 to 10, with 1 being the most important success factor.

Figure 3 illustrates the various success factors mapped according to their frequencies and average normalised rank in the survey. The success factors in the top-right quadrant (green) were most frequently selected by survey respondents and also ranked highly in terms of their importance for I4.0 technology adoption in airports.

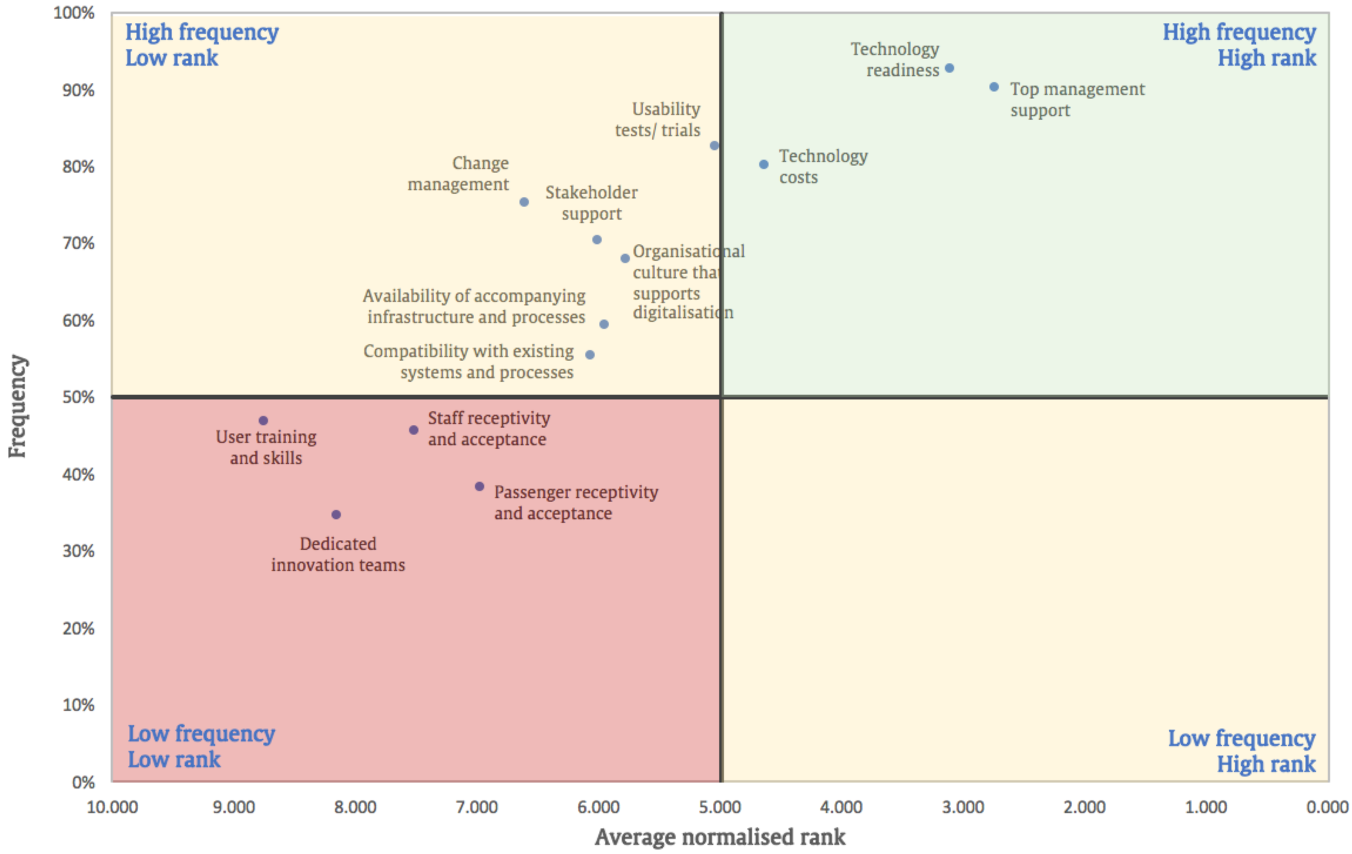

Figure 3: Frequencies and average normalised ranks of success factors (Tan & Masood 2021b)

2.4 Research gaps and objectives

This section outlines the research gaps that were identified from the literature. Research objectives (ROs) are then proposed based on the research gaps (RGs).

2.4.1 No clarity on I4.0 technologies that are important for future airports (RG1)

From the SLR (Tan & Masood 2021a), it is evident that the term "Airport 4.0" has been loosely adopted in literature to suggest an ongoing digitalisation trend in airports that is in line with I4.0. Furthermore, not all the functional categories of I4.0 technologies identified by Fettermann et al. (2018) are directly relevant to airports as the term I4.0 is mainly used in a manufacturing context. This observation is consistent with Jaffer & Timbrell (2014) who opined that academic researchers have yet to explore the strategic use of digital technologies in the context of an airport and analyse their impacts on customer experience.

Furthermore, the papers reviewed focused largely on the implementation of technologies for day-to-day operations to improve operational efficiency and enhance passenger experience (Kovynyov & Mikut, 2019) and have little references to uncertain and random events such as crises or disasters, some of which the airport has little control of. These events include but are not limited to flight delays, technical disruptions, cybersecurity, aviation accidents, pandemics and economic downturns. A handful of papers covered the use of data analytics to predict unexpected events such as flight delays and weather conditions, but have also highlighted challenges such as the lack of complete and quality datasets that can be used for prediction (Table 2) (Tan & Masood 2021a).

2.4.2 Lack of empirical research on challenges faced by airport operators in technology adoption (RG2)

The challenges in adopting I4.0 technologies in airports were sparsely discussed in recent literature. While the SLR has provided a summary of the key challenges faced from the papers reviewed (**Table 2**), majority of these challenges were identified by researchers in specific studies on a particular I4.0 technology use-case rather than by airport operators. Furthermore, most of the challenges identified had to be inferred from academic literature.

2.4.3 Lack of generic criteria to assess I4.0 technologies for adoption in airports (RG3)

The adoption and implementation of a technology or innovation is a strategic multi-stage process consisting of innovation awareness, attitude formation, evaluation, decision to adopt, trial implementation and sustained implementation (Damanpour & Gopalakrishnan, 1998). Considering the increasing trend of digital technology adoption in airports, the need for further research in digital or technology adoption strategy is necessary (Jaffer & Timbrell, 2014).

Based on the SLR (Tan & Masood 2021a), it is evident that the implementation of technologies in airports are mainly application-based and adopted in silos, instead of being part of an overall digital IT strategy. Furthermore, there is a lack of assessment methods to evaluate airport technologies and build reliable business cases relating to new technologies (Kovynyov & Mikut, 2019). Most of the future research directions identified by authors in the SLR (Table 2) (Tan & Masood 2021a) have highlighted the need for future technology tests or trials within the airport's operational environment which can potentially be incorporated into an airport's technology adoption strategy. Sohn et. al. (2013) developed a preliminary smart airport framework to establish an integrated view of the use of smart technology to improve passenger service and airport resource management but have also highlighted the need to extend the strategic framework to include airport operations.

2.5 Research question

The following research question (RQ) is thus proposed to address the RGs identified in the preceding section:

RQ: "How can airport operators or managers develop airports of the future using I4.0 technologies?"

Airport operators or managers refer to organisational or corporate entities that have management control of an airport in terms of developing and maintaining the airport's infrastructure and operating the airport on a daily basis. These airport operators can be government agencies or corporate entities depending on the ownership structure of the airport (Neufville & Odoni, 2013).

The main aim of the research is to answer the RQ using empirical data from airport operators. Thus, the following research objectives (ROs) were defined based upon the RQ:

- **RO1:** Understand the future-oriented objectives that airport operators have in adopting I4.0 technologies in the airport and the enabling I4.0 technologies to achieve the desired state of a smart, digital airport of the future (Airport 4.0).

- **RO2:** Obtain primary data from airport operators to verify the challenges they face in adopting industry 4.0 technologies as well as to understand any best practices or success factors that support technology adoption in airports.

- **RO3:** Develop a technology adoption framework for airports (operators) to assess their current status and take proactive action to mitigate any potential challenges in technology adoption.

- **RO4:** Develop a set of generic criteria for airport operators to assess the feasibility of I4.0 technologies and the economic case for implementation. These generic criteria can form part of an overall technology adoption strategy or framework to guide airport operators on the key infrastructural or process provisions that need to be in place in their digital transformation process.

The ROs address the respective RGs that were outlined in the preceding section as illustrated in **Figure 4**.

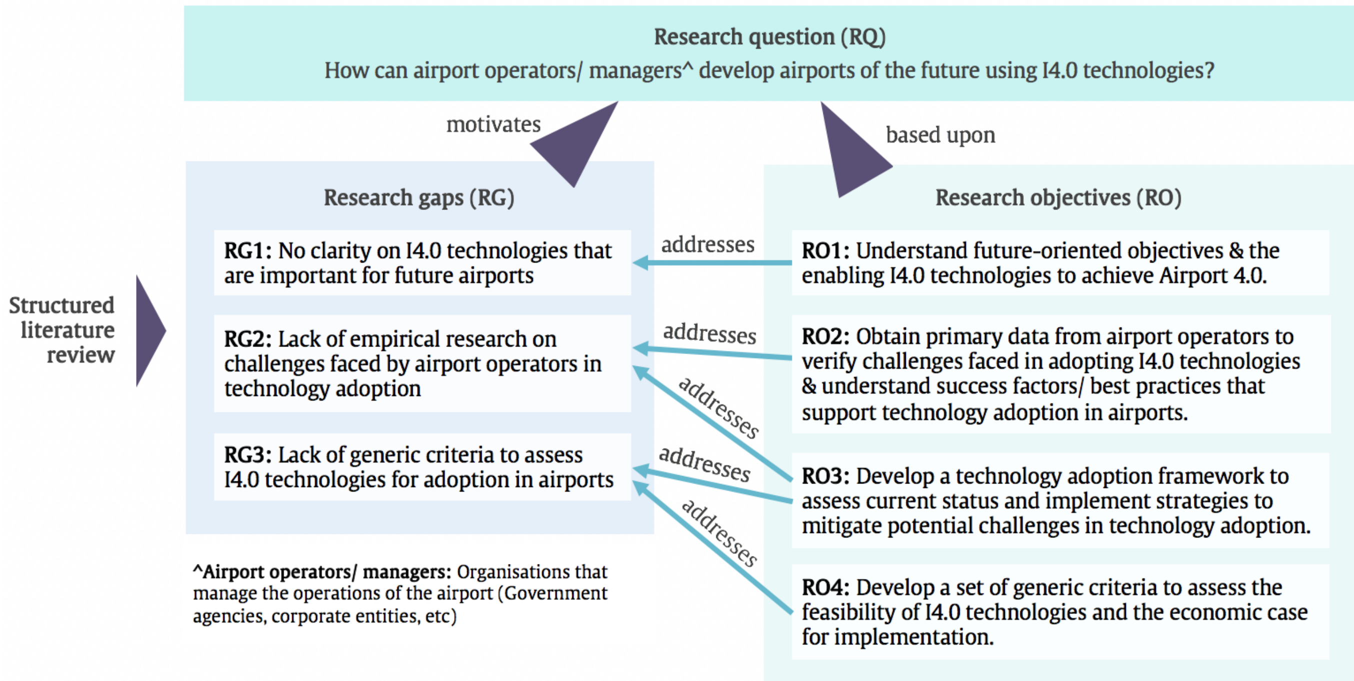

Figure 4: Research gaps, research question and research objectives

3. Methodology

This section presents the research methodology.

3.1 Established technology adoption models

A literature review was first conducted to understand established technology adoption models (**Table 3**) (Tan & Masood 2021b).

Table 3: Technology adoption models in literature (Tan & Masood 2021b)

Model/ theory	Source	Key aspects/ constructs
Technology-Organisation-Environment (TOE) framework	Tornatsky and Fleischer (1990)	Technological innovation decision-making based on technology, organisation and (external task) environment.
Diffusion of Innovation (DOI) theory	Rogers (1995)	Organisational innovativeness based on individual (leader) characteristics, internal and external characteristics of organisation (organisational structure, system openness).
Institutional theory	Scott and Christensen (1995), Scott (2001)	Institutional environment (including social and cultural factors, concerns for legitimacy) are crucial in shaping organisational structure and decisions.
Iacovou *et al.* model	Iacovou *et al. (1995)*	Adoption of innovation based on perceived benefits, organisational readiness and external pressure.
Technology acceptance model (TAM)	Davis (1989)	Adoption of technology by individuals are based on perceived usefulness and perceived ease of use.
Theory of planned behaviour (TPB)	Ajzen (1985), Ajzen (1991)	An individual's behavioural intentions are shaped by attitude, subjective norms and perceived behavioural control.
Unified Theory of Acceptance and Use of Technology (UTAUT)	Venkatesh *et al.* (2003)	User intentions are based on performance expectancy, effort expectancy, social influence and facilitating conditions.

As the RQ focuses on the adoption of I4.0 technologies by airport operators, technology adoption models that focus on technology adoption at the individual level such as the Technology Acceptance Model (TAM) (Davis et al., 1989), Theory of Planned Behaviour (TPB) (Ajzen, 1991) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003) models are not relevant.

The Technology-Organisation-Environment (TOE) framework (Tornatzky & Fleischer, 1990), Diffusion of Innovation (DOI) theory (Rogers, 1995), institutional theory and the Iacovou et al. model (Iacovou et al., 1995) which focus on technology adoption at the firm level are most relevant. Out of these models, the TOE framework and DOI theory are most prevalently referenced in academic literature that studies technology adoption in firms (Oliveira & Martins, 2011). The TOE framework is preferred for this study as it covers the external task environment of the firm which is absent in the DOI theory. The environmental aspect is important for the study of airports since the airport environment comprises multiple stakeholders such as passengers, airlines and ground handling agencies.

3.2 Research design

This section outlines the overall research design to answer the RQ using a four-phased approach as illustrated in **Figure 5**. The main focus of this article is on parts III and IV. Semi-structured interviews (parts I & II) are also presented in article in detail. See Tan & Masood (2021a) for detailed SLR. See Tan & Masood (2021b) for detailed industrial survey analysis, also using Qualtrics, PLS-SEM, Smart PLS3, NVIVO 12).

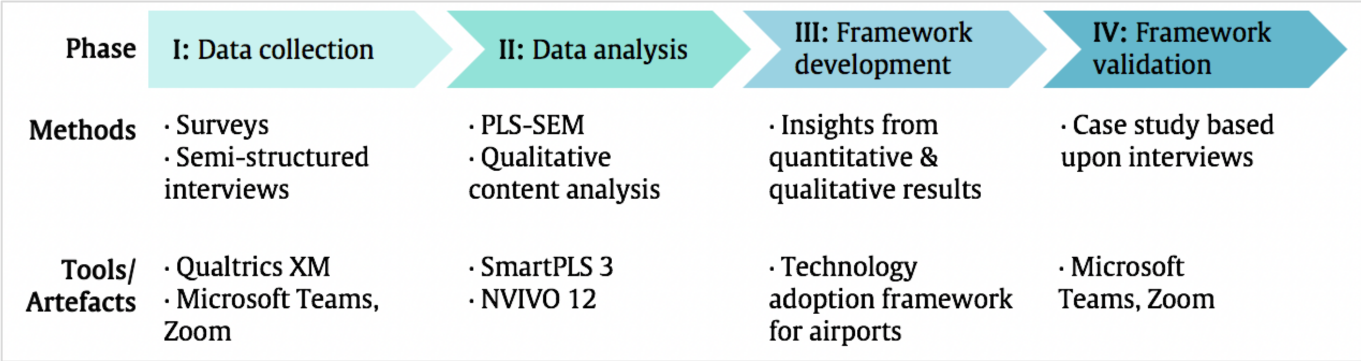

Figure 5: Overall research design (the main focus of this article is on parts III and IV; semi-structured interviews (parts I & II) are also presented in article in detail; see Tan & Masood (2021a) for detailed SLR, and Tan & Masood (2021b) for detailed industrial survey analysis, also using Qualtrics, PLS-SEM, Smart PLS3, NVIVO 12).

Given the lack of empirical research in the field of technology adoption in airports (RG2), a mixed method approach consisting of an industry survey and interviews was adopted for empirical data collection. The survey of airport operators and managers (Tan & Masood 2021b) serves as the primary source to collect both quantitative and qualitative inputs for the research study. As there is a lack of clarity on the important I4.0 technologies for future airports (RG1), the industrial survey identified I4.0 technologies that are important for future airports along with the key objectives for digital transformation in airports (RO1). Furthermore, the survey also collected empirical inputs from airport operators on the challenges and key success factors for adopting I4.0 technologies in airports (RO2). The data obtained was also used for testing of the hypotheses relating to their implementation challenges (Tan & Masood 2021b).

Surveys provide a cost-effective way for collecting empirical data which can be easily analysed using statistical methods (Queirós et al., 2017). However, as surveys rely greatly on the respondents to interpret the questions correctly and are highly rigid based on its structure, it constrains the researcher from obtaining deeper insights or elaborations relating to the research study (Premkumar & Roberts, 1999). To overcome this limitation, semi-structured interviews were also conducted with survey respondents who have indicated interest in the questionnaire using video conferencing platforms (Microsoft Teams, Zoom) to obtain more in-depth qualitative responses to supplement the survey responses (Creswell, 2009). The survey questionnaire (Tan & Masood 2021b) was used to guide the structure of the discussion, while questions were asked during the course of the interview to clarify and probe deeper into the responses of the participants.

Based upon the empirical data obtained from the survey (Tan & Masood 2021b) and interviews, results were analysed. Insights obtained from the results analysis were used to develop a preliminary technology adoption framework for airports (RO3). The framework encompasses key success factors identified after analysing the data collected in the form of strategies to facilitate technology adoption. The framework also provides a set of generic criteria to guide airport operators and managers to overcome common challenges in adopting I4.0 technologies in the airport (RO4), thereby addressing RG3.

The preliminary technology adoption framework was then validated through a case study with a leading award-winning airport that has a reasonable experience base with the trial or implementation of I4.0 technologies. The case study was developed through interviews with airport managers of the case airport to understand specific use-cases of I4.0 technologies in the airport and to assess the usefulness of the framework in guiding their decision-making processes in technology adoption.

3.3 Data collection

The industrial survey questionnaire design is discussed in detail in Tan & Masood (2021a). The participants were also asked to provide their email addresses at the end of the survey if they were interested in participating in the semi-structured interviews relating to the research topic.

A total of 13 participants were interviewed during the data collection period. These participants have indicated interest to participate in further discussions after providing their initial responses in the industry survey. They were subsequently contacted for an interview using video-conferencing tools. The sample profile of interview participants and their key inputs are summarised in **Table 4**.

Table 4: Profile of interview respondents

ID	Designation	Relevance to adoption of I4.0 technologies in airports
INT-1	General Manager, Engineering and Development	Use-cases relating to engineering systems
INT-2	Assistant Vice President, Innovation Lab	Technology adoption projects within dedicated innovation teams
INT-3	Assistant Manager, Engineering and Development	Use-cases relating to engineering systems
INT-4	Manager, Commercial	Cross-cluster innovation teams, use-cases in commercial area
INT-5	Director, Aviation Security	Use-cases relating to immigration and airport security
INT-6	Manager, Airport Planning	Use-cases relating to capacity planning and forecasts
INT-7	Manager, Airside Management	Use-cases relating to airside operations
INT-8	Manager, Airside Management	Use-cases relating to airside operations
INT-9	General Manager, Airport Planning	Use-cases relating to airside operations, multi-stakeholder collaboration
INT-10	Senior Manager, Airport Operations	Innovation process for airport operations team
INT-11	Manager, Airport Operations	Use-cases relating to facilities management in the airport terminals
INT-12	Vice President, PMO	Innovation projects undertaken by organisation relating to technology adoption
INT-13	Vice President, People Development	Organisational culture, change management, skills training for airport staff

3.4 Data analysis

Data was analysed and a new framework was developed, which is discussed in the following.

4. Technology Adoption Framework for Airports (TAFA framework)

The TAFA framework was first developed based upon the results and insights gathered from a recent industry survey of airport operators on their objectives for digital transformation and the associated challenges and success factors for adopting I4.0 technologies in airports (Tan & Masood, 2021b). The preliminary version of the TAFA framework was further refined based on semi-structured interviews with airport operators and the final version is shown in **Figure 6**.

The TAFA framework consists of 4 key parts: (1) Objectives for digital transformation in airports, (2) Important I4.0 technologies for Airport 4.0, (3) Technology adoption process and (4) Strategies to facilitate the technology adoption process. These parts will be elaborated in the sub-sections that follow.

4.1 Objectives for digital transformation

The framework begins with the eight objectives that were identified for digital transformation in airports based on the results from a recent industry survey of 348 airport professionals (Tan & Masood, 2021b). These objectives provide the key motivations for the technology adoption process to resolve problems within the airport environment.

4.2 Important I4.0 technologies for Airport 4.0

The bottom of the framework presents the top ten I4.0 technologies that were identified to be important for future airports (Airport 4.0) in a recent structured literature review (Tan & Masood, 2021a). These I4.0 technologies have the highest importance scores based on results from the industry survey (Tan & Masood, 2021b). The TAFA framework was developed with the aim of implementing these important I4.0 technologies in future airports.

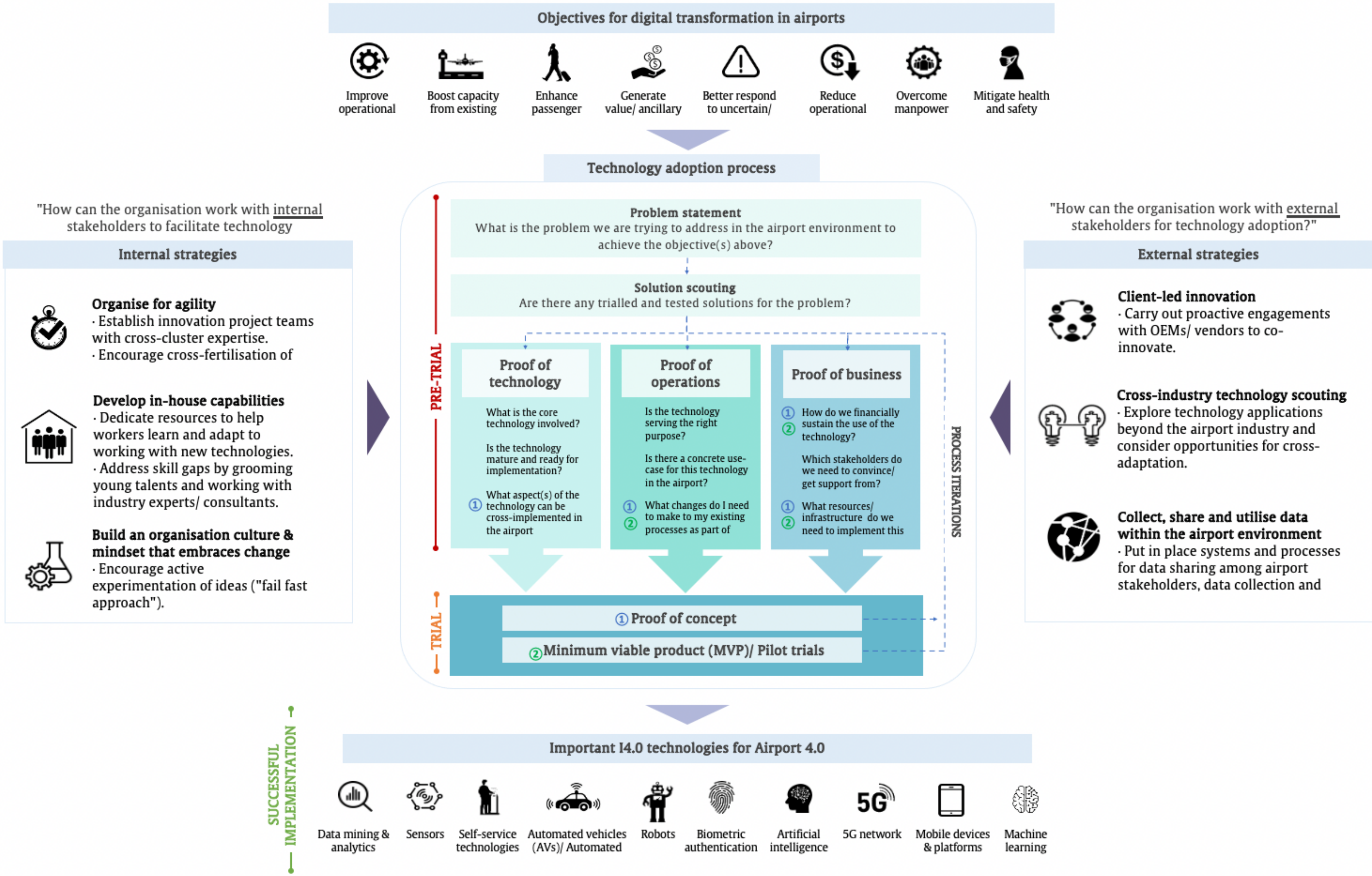

Figure 6: Technology adoption framework for airports (TAFA framework)

4.3 Technology adoption process

The technology adoption process forms the bulk of the framework and provides a guidance for airport operators in adopting technologies within the airport environment. It begins with the establishment of a clear problem statement for the issue that the airport operator is looking to address within the airport environment to achieve one or more of the digital transformation objectives. Taking a problem-based approach towards technology adoption ensures that the airport does not simply implement "fancy" technologies that do not present any tangible benefits for airport stakeholders (INT-9). Furthermore, understanding the primary objectives for digital transformation helps airport operators to understand business priorities and better establish a business case for technology adoption (INT-6).

Once the problem statement has been clearly defined, the next step involves sourcing for any trialled and tested solutions that exist for the problem. This is a fast and low-risk approach that allows airport operators to resolve problems quickly by "picking a solution off the shelf" and is especially suitable for solving problems that do not require extensive customization (INT-9). For example, autonomous cleaning robots that are used for cleaning large floor areas (e.g. in shopping malls, hotels, etc) can be easily adopted for cleaning of the airport terminals (INT-11). If a trialled and tested solution is absent for the problem, the solution scouting effort needs to be expanded to look into technological solutions across other industries or explore possible co-development efforts with solution providers to customise specific solutions for the airport (INT-9).

The third step in the technology adoption process is to assess potential solutions. This step involves a pre-trial phase to establish three "proofs" for the solution, namely the proof of technology, proof of operations and proof of business, while iterating with implementation trials. These three proofs cover various aspects that ensure the technological solution implemented is feasible for the airport environment while remaining sustainable for the business (INT-10).

4.3.1 Proof of technology

The proof of technology involves understanding the core technology involved in the particular technological solution, and assessing if the technology is mature and ready for implementation. For cross-industry solutions, airport operators should also seek to understand what aspect(s) of the technological solution can be cross-implemented to the airport environment (INT-10). Establishing the proof of technology allows airport operators to assess technology readiness and whether accompanying infrastructure and processes are necessary prior to the implementation of the technology solution. These are two important success factors for technology adoption based upon the industry survey results (Tan & Masood, 2021b).

4.3.2 Proof of operations

The proof of operations considers the relevance of the technology in solving the problem described in the problem statement. While the technology may be mature and ready for implementation, airport operators need to consider whether the technology serves the intended purpose and whether there are concrete use-cases for the technology in the airport (INT-7, INT-10). An important question in establishing the proof of operations is to understand whether any changes need to be made to existing work processes to accommodate the technology adoption (INT-9). Airport operators should not be discouraged to adopt the technological solution should changes need to be made to existing work processes. Instead, this pushes airport operators to take a holistic, outcome-based approach to address the problem statement by considering the technological solution along with associated work processes and the stakeholders involved.

4.3.3 Proof of business

The proof of business focuses on the financial and business implications for adopting the technological solution. While the technology may be ready to address the problem statement effectively, airport operators need to question the financial sustainability of the technology solution for the business. Airport operators will also need to garner support from relevant airport stakeholders when implementing the technology solution. This is because the end-users of these technological innovations tend to be airport stakeholders such as ground service agents and airline staff rather than the airport operators themselves (INT-7). Furthermore, depending on the ownership structure of the airport, stakeholder support is paramount in order to obtain financial approval for the investment in the technology solutions (INT-12). For trialled and tested airport solutions that are readily available in the market, the proof of business is often the main decision factor in the implementation of these solutions as the proof of technology and operations can be easily established from implementation case studies in other airports (INT-9).

4.3.4 Technology trials

After the airport operator has established initial proof of the technology, operations and business of the technology solution, they may carry out technology trials in the airport environment. Usability tests and trials have consistently been touted as a key success factor for technology adoption based upon the survey results (Tan & Masood, 2021b). Five of the 13 interviewees have emphasized the importance of usability tests to aid their decision-making on whether to ultimately adopt these technologies in the airport environment.

At this stage, the airport operators may yet to have full confidence of the feasibility of the technology within the airport environment. Thus, the purpose of these technology trials is to test the technological solutions within the operational environment of the airport, further strengthen the respective proofs that were previously highlighted and also contribute towards confidence building in end-users of the technologies (INT-7). The framework functions in an iterative manner where airport operators will constantly establish and strengthen the proofs of technology, operations and business even during the technology trials. In the framework, some questions were annotated to remind airport operators to revisit these specific questions during specific stages of the trials.

The first set of trials involves the development and testing of a proof-of-concept (POC), which aims to test and verify some key technical concepts and assumptions before developing the technical solution further (Skelia, 2018). The POC often involves only a fraction of the entire system. This is particularly important for cross-industry technology solutions as the POC will allow the airport operator to determine whether a particular technology concept can be cross-implemented in the airport environment. The POC can guide the airport operator in deciding how the technological solution should be developed further to suit the airport environment, and provide the operator with a better sense of any infrastructural or process changes that need to be made to accommodate the technological solution. Furthermore, it may also serve to gather stakeholder buy-in to obtain initial seed funding for further development of the product (INT-6).

The second set of trials involves the development and testing of a minimum viable product (MVP), which is a simpler version of the final product that only has sufficient features to be viable (Skelia, 2018). With the MVP, the airport operator can better engage the end-user of the technological solution with a better "look-and-feel" of how the final technological solution will operate. New work processes (if any) can be tested alongside the MVP in pilot trials within the operational environment. These trials may bring about further refinement to the MVP or work processes. Ultimately, the success of the pilot trials will provide greater confidence for further investment in the final stage of development of the MVP towards the eventual implementation of the technological solution.

Both the POC and MVP are reduced versions of the final product that help the airport operator to test and verify certain assumptions of the final technological solution while saving on time and financial investment (Skelia, 2018). For trialled and tested solutions, the POC and MVP will be less relevant since the final product has already been implemented in the airport industry. However, as the operational conditions vary among different airports, pilot trials should still be conducted with the final technological product to test its feasibility within the unique operational environment of the airport and assess the need for customisations to fit any specific operational requirements of the airport (INT-3).

4.4 Strategies to facilitate the technology adoption process

This sub-section describes a set of internal and external strategies that were developed based on the success factors identified in the industry survey (Tan & Masood, 2021b) and the interview inputs. Airport operators can consider these strategies to facilitate the technology adoption process described earlier. Organisational readiness has shown statistically significant influence on the successful adoption of I4.0 technologies in the airport (Tan & Masood, 2021b). Similarly, organisational factors such as top management support, establishing an organizational culture that supports digitalization and change management have been consistently ranked as important success factors for I4.0 technology adoption (Tan & Masood, 2021b). These further establishes the importance of the organisation in facilitating technology adoption.

4.4.1 Internal strategies

Internal strategies focus on a set of strategies that the airport operator can undertake to work with internal stakeholders in the firm to facilitate technology adoption. Three key internal strategies are discussed here.

First key internal strategy is to organize for agility by establishing innovation project teams with cross-cluster expertise. A phenomenon exists in an organisation where different divisions are innovating in silos and there is little effort to synchronise the innovations efforts and minimise potential overlaps (INT-9). The establishment of cross-cluster teams can potentially resolve this issue while encouraging the cross-fertilisation of ideas and expertise across divisions, thereby speeding up the technology adoption process (INT-4).

Second internal strategy is to develop in-house technological capabilities. This can be done by dedicating resources on an organisational level towards helping employees learn and adapt to new technologies. This helps to upskill workers and ensure they have the necessary skills to adopt new technologies once they have implemented in the airport. INT-09 highlighted that airport operators tend to lack sufficient technical expertise to establish the proof of technology, such as in determining the technology maturity and its suitability for implementation in the airport environment. Such skill gaps can be addressed by working with industry experts or consultants while grooming young talents within the organisation in the longer term (INT-13).

Building staff receptivity towards new technological solutions has been challenging in a particular airport (INT-1). For example, a VR simulator was developed to provide scenario training for ground handling agents in the operation of passenger loading bridges (PLB). These simulators reduced the need to book operational aircraft stands for training while providing training for situations which cannot be tested using the real PLB. However, the agents felt that the simulator training was useless and unrealistic, and were initially against the use of such simulators. To overcome such resistance to change, a third internal strategy is to build an organisational culture and mindset that embraces change. For example, the airport operator can actively encourage employees to experiment with ideas and not be afraid to "fail fast" (INT-4).

4.4.2 External strategies

External strategies focus on a set of strategies that the airport operator can undertake to work with external stakeholders of the firm to facilitate technology adoption. These external stakeholders include passengers, ground handling agents, airlines and even technological vendors or Original Equipment Manufacturers (OEMs). Three key external strategies are discussed here.

First key external strategy is to carry out client-led innovation by proactively engaging technological vendors to co-innovate. This strategy is particularly important if the industry is not incentivized to innovate (INT-1). For example, the maintenance of engineering systems in the airport involves maintenance contracts that provide a long-term stream of income to vendors. This may reduce the incentives for these system vendors to explore innovations such as predictive maintenance which may potentially cannibalise their own revenues (INT-1).

Second external strategy is to carry out cross-industry technology scouting. This involves exploring technology applications beyond the airport industry and considering opportunities for cross-adaptation. This strategy is particularly useful if trialled and tested airport solutions are absent (INT-9). From the recent structured literature review, it is evident that I4.0 technologies which are predominantly used in the manufacturing industry have potential applications within the airport environment (Tan & Masood, 2021a). However, the need for airport operators to consider the following unique characteristics of the airport environment when implementing cross-industry solutions was emphasised (INT-8):

- Sensitive interfaces (interactions with expensive aircrafts and ground equipment)
- Safety concerns involving the movement of large, heavy and dangerous equipment.
- Tightly regulated environment about how things operate, including safety parameters.
- Time-sensitive operations such as aircraft turnaround services.
- Multi-stakeholder environment, thus any automation or digitalisation efforts will need to consider the ripple effect on the entire operation.
- A network of critical operations where every step is critical for successful operations.
- End-users of technology solutions (e.g. baggage handlers, ground service agents) may belong to an older age group (above 40), thus they may be less receptive towards using new

technologies for their work. This phenomenon is more prevalent for countries with an ageing work force.

Third external strategy is to collect, share and utilise data within the airport environment. Several interviewees have highlighted the lack of quality data in the airport that are easily accessible (INT-6, INT-9). This impedes the development of data models to generate insights and facilitate decision-making processes. INT-9 cited an example where airport operators can potentially prioritise a lane for the transfer of 'hot bags' (baggage that needs to be transferred across aircrafts within an hour during transit) if airlines are willing to share information about these 'hot bags'. Thus, airport operators should work closely with other airport stakeholders to put in place systems and processes that encourage data sharing and data collection to benefit the entire airport ecosystem.

5. Case study: Technology adoption by leading Asian airport operator using TAFA framework

The framework was validated in interviews with personnel from a leading airport operator in Asia. The airport operator manages one of the most awarded airports in the world based on passenger votes and has also won several awards in digital transformation and innovation in recent years. These lend credence to their experience in successful technology implementation efforts. The profile of interview participants can be found in **Table 4**.

During the validation interviews, the participants were asked to share specific use-cases of I4.0 technology implementations in the airport. Specific examples relating to these projects form the basis for this case study in highlighting different aspects of the TAFA framework. A total of 13 use-cases were established for the case airport. The corresponding objectives for digital transformation and the I4.0 technologies involved were identified for the 13 use-cases based on the TAFA framework. These are illustrated in **Table 5** and **Table 6** respectively. **Figure 7** summarises the key I4.0 technology projects in the case airport that were shared during the validation interviews based on their stage in the technology adoption process within the TAFA framework.

Use-case 4 is an interesting case that demonstrates the iterative process of technology adoption and the importance of establishing the three "proofs" prior to successful technology adoption. The use-case involves the use of smart wearables to carry out remote monitoring and troubleshooting of engineering systems in the airport. While the wearables are generally affordable, the trials have revealed several ergonomic and infrastructural challenges. Thus, in the context of the TAFA framework, while the proof of technology and the proof of business were sufficiently established, the proof of operations was not established with confidence. Thus, the result of the trial was to defer the full implementation of the solution for the near term until the ergonomic and infrastructural challenges are resolved (INT-3).

Table 5: Objectives for digital transformation in airports for use-cases in a leading Asian airport

	I4.0 technologies that are important for future airports							
	Improve operational efficiency	Enhance passenger experience	Boost capacity from existing infrastructure	Better respond to uncertain/ random events	Generate value/ ancillary revenue	Reduce operational costs	Overcome manpower shortages	Mitigate health and safety concerns
Use-case 1: Predictive maintenance of engineering systems	X			X		X	X	
Use-case 2: VR training simulator for passenger loading bridge (PLB) training	X		X	X				
Use-case 3: Condition-based monitoring of baggage handling systems (BHS)	X					X	X	
Use-case 4: Smart glasses to monitor engineering systems	X					X	X	
Use-case 5: Airport-wide mobile application		X			X			
Use-case 6: Data analysis and simulation for future capacity planning	X		X					
Use-case 7: VR simulator for visualisation of terminal designs	X	X						
Use-case 8: Automating aircraft turnaround opertaions using CPS	X					X	X	
Use-case 9: Self-service check-in kiosks with biometric authentication	X	X				X	X	X
Use-case 10: Transportation of goods in the airside environment using AGVs	X					X	X	
Use-case 11: Automation of cargo handling and catering using CPS	X					X	X	
Use-case 12: Orchestrated fleet management at the airside	X			X		X	X	
Use-case 13: Autonomous cleaning robots in airport terminals	X					X	X	X

Table 6: Important I4.0 technologies for Airport 4.0 for use-cases in a leading Asian airport

	Important I4.0 technologies for Airport 4.0									
	Data mining & analytics	Self-service technologies (SSTs)	Sensors	Artificial intelligence (AI)	Biometric authentication	Robots	Automated vehicles (AVs)/ Automated guided vehicles (AGVs)	Mobile devices & platforms	Machine learning	5G
Use-case 1: Predictive maintenance of engineering systems	X		X						X	
Use-case 2: VR training simulator for passenger loading bridge (PLB) training	X									
Use-case 3: Condition-based monitoring of baggage handling systems (BHS)	X									
Use-case 4: Smart glasses to monitor engineering systems	X		X					X	X	X
Use-case 5: Airport-wide mobile application	X	X						X		
Use-case 6: Data analysis and simulation for future capacity planning	X									
Use-case 7: VR simulator for visualisation of terminal designs	X									
Use-case 8: Automating aircraft turnaround opertaions using CPS			X	X		X	X		X	
Use-case 9: Self-service check-in kiosks with biometric authentication	X	X			X					
Use-case 10: Transportation of goods in the airside environment using AGVs			X				X			
Use-case 11: Automation of cargo handling and catering using CPS				X		X	X			
Use-case 12: Orchestrated fleet management at the airside	X		X				X			X
Use-case 13: Autonomous cleaning robots in airport terminals			X	X		X	X		X	

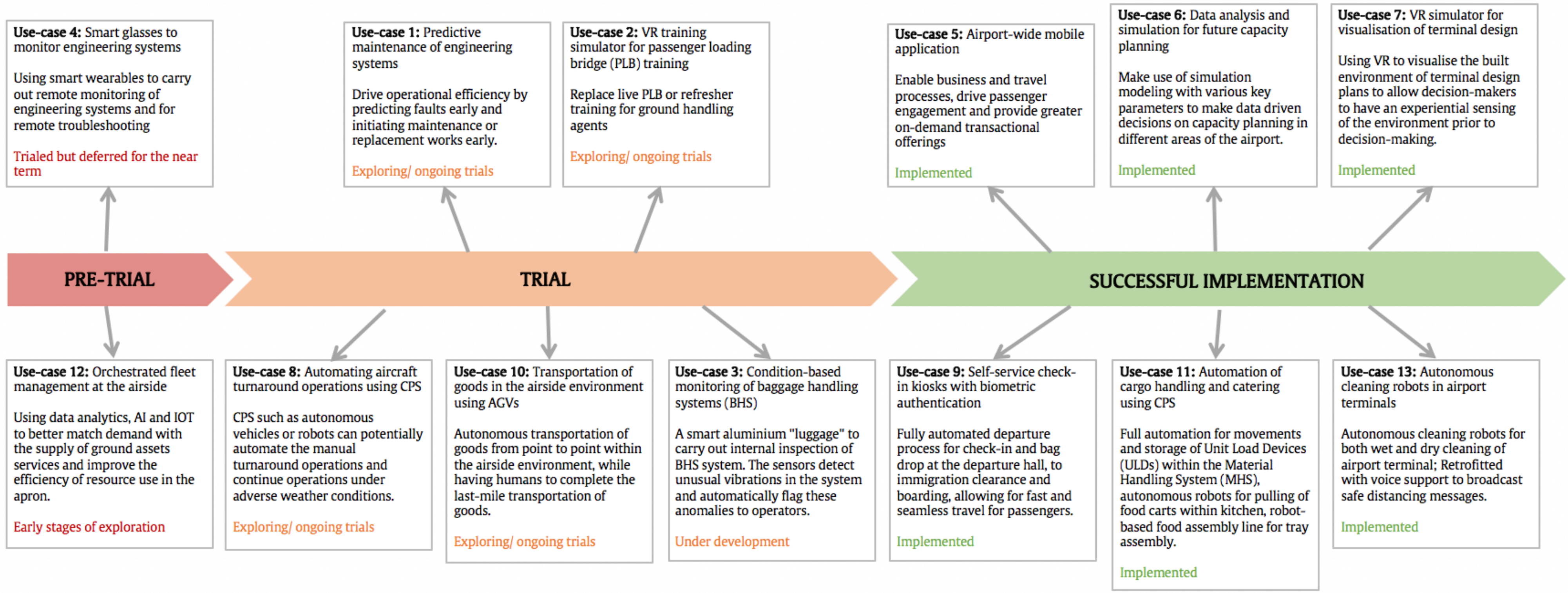

Figure 7: I4.0 use-cases and their stage of technology adoption in leading Asian airport

During the validation interviews, respondents were also asked to share examples of strategies that the airport operator has implemented to facilitate the technology adoption process. These correspond to the internal and external strategies in the TAFA framework to allow the organisation to work with both internal and external stakeholders to facilitate the technology adoption process.

For example, the case airport has set up an internal digital hub which consists of a multi-disciplinary team with niche digital skills to enable business users to develop and deliver digital products and services for passengers. The digital hub also provides a physical space for staff to co-create new digital products with eco-system partners where they are matched with experts with necessary skillsets as well as colleagues from other divisions to achieve a particular outcome (INT-4). The company has also set aside a training fund to support the upskilling of employees in competency areas such as data-driven thinking and agile way of working which they have identified to be important for the digital future of work (INT-13). These demonstrates how the company organises for agility and dedicates resources to develop in-house capabilities. Furthermore, an example of client-led innovation was shared for the case of implementing autonomous cleaning robots in the airport terminals. The airport operator worked closely with the technology vendor to customise the cleaning robots for the airport's needs, such as in retrofitting a voice support mechanism into the cleaning robot to broadcast safe distancing messages in the airport (INT-11).

Lastly, the interview participants were asked to provide feedback on the potential usefulness of the TAFA framework in aiding their technology adoption process. Overall, the feedback received about the framework was largely positive, and interview participants have shown keen interest in potentially adopting the framework to guide their technology adoption process. They have highlighted the importance of iterating between trials and keeping in mind business considerations for technology adoptions which were succinctly captured within the three 'proofs' in the framework (INT-7). To extend the usability of the framework, the interviewees have suggested the introduction of an assessment tool to aid them in transiting between the stages. However, as technology adoption may differ depending on a specific project, they recognised the potential difficulties in developing a tool that could be relevant for all the technology adoption projects within the airport (INT-6).

6. Discussion

6.1 Contributions to knowledge

This article contributes to knowledge in the following main ways:

1) The TAFA framework provides **a set of generic criteria for airport operators and managers to assess the feasibility of I4.0 technologies** and the economic case for implementation in airports, thereby guiding their decision-making processes in technology adoption. Based on the insights gathered from the case study, airport operators can proactively refine their internal and external strategies to better organize themselves and work with airport stakeholders to mitigate the challenges and capitalize on the success factors in their digital transformation journeys.

2) Furthermore, considering the unique and complex operating environment of the airport, practitioners will also be encouraged to **consider cross-industry technology solutions** such as I4.0 technologies in solving problems within the airport based upon **successful use-cases in other airports**, and to use the TAFA framework to complement any technology adoption or digital transformation strategy that may have.

3) The TAFA framework also contributes to existing streams of research involving the **TOE framework**. While earlier studies have implemented the TOE framework to examine the adoption of I4.0 technologies such as for AR (Masood & Egger, 2019), the TAFA framework is the first-of-its-kind to study I4.0 technology adoption in airports which extends the applicability of the TOE framework. The specific focus on airports provide academia with an understanding of context-specific challenges and success factors for I4.0 technology adoption.

6.2 Limitations and future work

As the process of technology adoption takes time, the technology adoption framework can be further validated through case studies of I4.0 technology adoption in airports that utilises the proposed framework. The challenges and success factors can also be superimposed onto the respective phases (pre-trial, POC, MVP) identified in the technology adoption framework for airport operators to better target and address the myriad of challenges involved. The current framework does not provide a quantitative assessment method for airport operators to decide when it is appropriate to move on to different phases of technology adoption, and the establishment of the respective proofs depends heavily on the experience of airport managers. While the iterative process of the framework provides a certain degree of flexibility (INT-07), a quantitative assessment method can be developed in future research to complement the technology adoption framework for airports to better assist the decision-making process of airport operators. Furthermore, the TAFA framework also has the potential to be refined and extended to suit different industrial contexts beyond airports, thus paving the way for future research relating to technology adoption strategies.

7. Conclusions

The TAFA framework and case study crystallize the insights gained from an empirical study consisting of an industry survey (Tan & Masood, 2021b) and semi-structured interviews of fellow airport practitioners based upon the current outlook of I4.0 technology adoption in the airport environment.

The COVID-19 pandemic is not the first nor the last health crisis that the world will face. With the emergence of new COVID-19 variants in this evolving pandemic, airport operators need to ramp up their digital transformation efforts and integrate I4.0 technologies into their processes in order to rejig their operations and usher in an era of pandemic-proof travel.

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Recommended reading list:

1) Tan & Masood (2021a) Adoption of Industry 4.0 technologies in airports - A systematic literature review, pre-print, *arXiv*. pp. 1-25, 28/12/2021. doi: https://arxiv.org/abs/2112.14333.

2) Tan & Masood (2021b) Industry 4.0: Challenges and success factors for adopting digital technologies in airports, pre-print, *arXiv*. pp. 1-25, 29/12/2021. doi: https://arxiv.org/abs/2112.14574.