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Architecture–Operational Efficiency Interactions in Smart Airport Transformation: Insights from Airport Practice

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Abstract

Smart-airport transformation depends on interactions between the built environment, airport operations and enabling digital systems rather than on the adoption of isolated technologies. This study examines how participants describe the interaction between architecture and operational efficiency during smart-airport transformation, with technology treated as an enabling layer and new and transitioning airports considered as different development contexts. A qualitative descriptive study was conducted using semi-structured interviews with 20 participants. The interview framework was developed from 267 architecture and operational efficiency sub-indicators identified through a preceding systematic literature review. Participant responses were coded, reviewed and scored using a five-point scoring system, followed by participant–sub-indicator, cross-participant and direct cross-domain analyses. Of the 267 literature-derived sub-indicators, 162 were identified in the interview dataset and grouped according to mean score and domain participant support. In total, 24 were classified as broadly supported, 17 as moderately supported and 111 as context-specific. A further 10 fell below the inclusion threshold and were excluded from the final analytical set, leaving 152 sub-indicators for interpretation. Direct cross-domain analysis identified 23 participant-level connection occurrences representing 19 unique architecture–operational efficiency connections, comprising 11 architecture-to-operational efficiency and eight operational efficiency-to-architecture connections. Technology enabled these interactions through sensing, data collection, real-time processing, analytics, AI-supported applications and digital infrastructure. The findings also showed that new airports provide greater opportunity to integrate spatial, infrastructural and digital requirements during initial planning, whereas transitioning airports must accommodate comparable capabilities within existing buildings, legacy systems and continuing operations. Sustainability emerged through the combined effects of architectural, operational, asset-management and technology-related conditions. For airport planners, architects, operators, asset and facilities managers and digital teams, the findings provide a structured basis for identifying supported conditions, recognising dependencies between physical and operational systems and anticipating the infrastructure and operational requirements associated with smart-airport transformation.

Keywords: smart airports; airport architecture; operational efficiency; airport buildings; built environment; digital transformation; airport technology; transitioning airports

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1. Introduction

Smart-airport transformation extends beyond the adoption of individual digital technologies. Airports are increasingly described as interconnected environments in which physical infrastructure, sensing, data systems, automated processes and organisational arrangements operate together [1–3]. Digital transformation therefore depends on coordination across technical and operational systems rather than the isolated use of individual technologies [1,2,4]. Cybersecurity research similarly shows that greater connectivity creates dependencies between sensing, control, information and governance systems [5–7]. These studies support examining smart-airport transformation through the relationships between infrastructure, information and operational processes.

This study focuses on architecture and operational efficiency as two related areas of smart-airport transformation. Digital technologies such as sensing, data collection, analytics and automation are treated as an enabling layer through which architectural and operational systems can interact [8,9]. Technology is therefore considered as an enabler rather than as a separate analytical domain. Sustainability is considered as an outcome influenced by coordinated architectural, operational and technology-related conditions.

The built environment plays an important role in these relationships because digital systems depend on physical infrastructure, spatial conditions and building services [8,10]. Airport environments must accommodate sensing, communications, passenger-processing systems and changing operational requirements, while airport operations increasingly depend on connected assets, real-time information and data-supported decision-making [11–13]. Research on Airport BIM and digital twins has further demonstrated how physical asset information can be combined with operational, planning and facilities-management data across the airport lifecycle [10,14,15]. These studies indicate that digital capability depends not only on technology, but also on system integration, organisational readiness and coordination between physical and operational systems [12,13].

Passenger experience represents a related but distinct dimension of smart-airport transformation. Passenger evaluations are influenced by processing efficiency and service delivery, as well as by spatial conditions, facility quality, perceived safety and service interactions [16–19]. Automated processing, information services and biometric systems can also influence how passengers experience airport services [20–22]. Passenger-centred studies have therefore examined issues including satisfaction, trust, perceived benefit, privacy and willingness to use or share data for digital services [22,23]. In the present study, passenger experience is not analysed as a primary domain, although passenger-facing consequences are retained where participants explicitly connect them with architecture or operational efficiency conditions.

Despite the growing smart-airport literature, research remains distributed across separate disciplinary areas. Built-environment studies commonly examine terminal performance, energy use, environmental modelling and asset integration, while operational studies place greater emphasis on optimisation, automation and artificial-intelligence applications [11,24–27]. Passenger-centred studies, in contrast, tend to focus on satisfaction, trust, perceived safety and behavioural responses [16,18,21,23,28]. Although earlier research has begun to describe airports as integrated socio-technical systems, there remains limited understanding of how people working across architecture, operations and technology describe the relationships between the built environment and operational performance in practice [1–3,13]. This is particularly relevant to airport planners, designers, operators, asset and facilities teams because spatial, building-system and operational decisions are often interdependent within the same airport environment.

Development context adds a further consideration. New airports can incorporate spatial flexibility, infrastructure capacity and digital systems during initial planning, whereas

transitioning airports must accommodate comparable capabilities within existing buildings, legacy systems and continuing operations [8,29,30]. In transitioning airports, existing layouts, information systems, cabling, power capacity and live operational requirements can constrain how new capabilities are accommodated [8,10,11,29]. These conditions may require retrofit, spatial adaptation, modification of existing systems and operational adjustment rather than direct integration within a purpose-built environment [8,29,31]. However, there remains limited research on how these differences are experienced across new and transitioning airport settings and how they influence the interaction between architectural and operational conditions.

Against this background, the aim of this study is to examine how architecture and operational efficiency interact during smart-airport transformation and how these interactions are shaped by enabling digital technologies across new and transitioning airport contexts. The study also examines how literature-derived sub-indicators are reflected in participant responses and where direct architecture–operational efficiency connections emerge. In doing so, it provides airport planners, designers, operators, asset and facilities managers and digital teams with a structured account of the physical, operational and digital dependencies that can influence smart-airport transformation.

The study is guided by the following research question:

How do participants describe the interaction between architecture and operational efficiency during smart-airport transformation?

2. Methods

2.1. Research Design

This study adopted a qualitative descriptive design to examine how participants describe the interaction between architecture and operational efficiency during smart-airport transformation [32]. Semi-structured interviews were conducted with participants from architecture, operations and airport technology backgrounds. The interview framework was developed from the architecture and operational efficiency indicators and sub-indicators identified through the preceding systematic literature review (SLR). The use of literature-derived factors as an initial analytical structure, followed by examination through expert interviews, is consistent with recent built-environment research integrating systematic review findings with practitioner perspectives [33].

The study followed a sequential analytical process. The SLR-derived indicators and sub-indicators were first used to structure the interview questions. Participant responses were then coded, reviewed and scored against the relevant sub-indicators. Participant–sub-indicator and cross-participant matrices were constructed to examine the distribution and recurrence of sub-indicators across participants.

Sub-indicator-level descriptive analysis was then undertaken using the participant scores and domain participant support. All Scores 1–5 were included when calculating the mean for each identified sub-indicator. The mean score and domain participant support were used to group the 162 identified sub-indicators into four categories: broadly supported, moderately supported, context-specific and below inclusion threshold. The first three categories formed the final analytical set, while sub-indicators falling below the inclusion threshold were retained in the classification table for transparency but were not carried forward into the final interpretation. Contributions from participants outside the relevant architecture or operational efficiency domain cohort were recorded separately as other-domain contributions and did not increase the domain denominators.

The coded statements were then re-examined to identify explicit directed connections between architecture and operational efficiency sub-indicators. Repeated occurrences of the same directed connection across participants were consolidated so that participant-

level occurrences could be distinguished from unique cross-domain connections. The analysis also examined contextual differences between new and transitioning airports and considered how technology, sustainability and passenger-facing consequences were described in relation to architecture and operational efficiency.

Figure 1 summarises the overall research process.

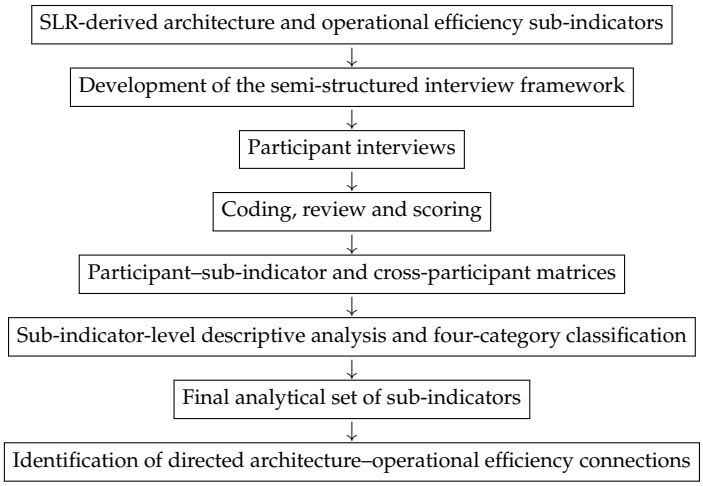


Figure 1. Overview of the research process used in this study. *Source: Authors' own work.*

2.2. Data Collection

2.2.1. Search Strategy and Data Sources

The interview framework used in this study was derived from a systematic literature review conducted in accordance with PRISMA 2020 principles [34]. The review is summarised here to explain the origin of the architecture and operational efficiency sub-indicators used to develop the interview framework. It covered smart-airport research relating to architecture, operational efficiency, passenger experience, technology and sustainability and included studies published from 2019 to 2024. Searches were conducted using Scopus, ScienceDirect and Google Scholar between 14 June and 10 July 2024.

The search strategy comprised 44 Scopus searches, 47 ScienceDirect searches and 27 Google Scholar searches, yielding 118 searches in total. Boolean combinations used the term "smart airport" with topic-specific terms relating to airport operations, infrastructure, digital systems, security, passenger processing and other smart-airport functions. The searches returned 16,056 records before screening. Table 1 summarises the search sources and representative Boolean structures.

Table 1. Search sources and representative Boolean structures used in the systematic literature review.

Source	Searches	Records	Representative Boolean Structure
Scopus	44	3760	"smart airport" AND (operations OR "air traffic" OR terminal OR "flight schedule" OR "real-time tracking" OR "collaborative decision making" OR "passenger flow management" OR "facility maintenance" OR "retail management")
ScienceDirect	47	4338	"smart airport" AND (operations OR security OR safety OR "biometric screening" OR "threat detection" OR "emergency response")
Google Scholar	27	7958	"smart airport" AND ("Smart Infrastructure" OR "Digital Transformation" OR "Smart Adaptability" OR "Technology Integration" OR "Intelligent Systems")
Total	**118**	**16,056**	The totals represent the complete search programme across the three sources.

Source: Authors' SLR search records.

2.2.2. Eligibility Criteria and Screening

Eligibility criteria were defined before screening and applied across the three search sources. Table 2 summarises the inclusion and exclusion criteria. The screening process followed the PRISMA sequence of identification, screening and eligibility assessment, reducing the initial 16,056 records to a final corpus of 511 studies.

Table 2. Systematic literature review inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Studies addressing smart airports in relation to infrastructure, architecture, operational efficiency, passenger experience, sustainability or smart-technology implementation.	Studies outside the review period or unrelated to airport environments.
Empirical studies, case studies and implementation-oriented peer-reviewed research relevant to smart-airport development or operation.	Editorials, opinion pieces and records without sufficient empirical or conceptual content for the review.
English-language material, or records containing sufficient English-language content for assessment.	Non-English records without sufficient English-language material for assessment.
Comparative or contextual studies of new, existing or transitioning airport environments where relevant to smart-airport transformation.	Records that remained outside the identified smart-airport areas after title, abstract or full-text review.

Source: Authors' SLR screening protocol.

Figure 2 presents the identification, screening and final inclusion process.

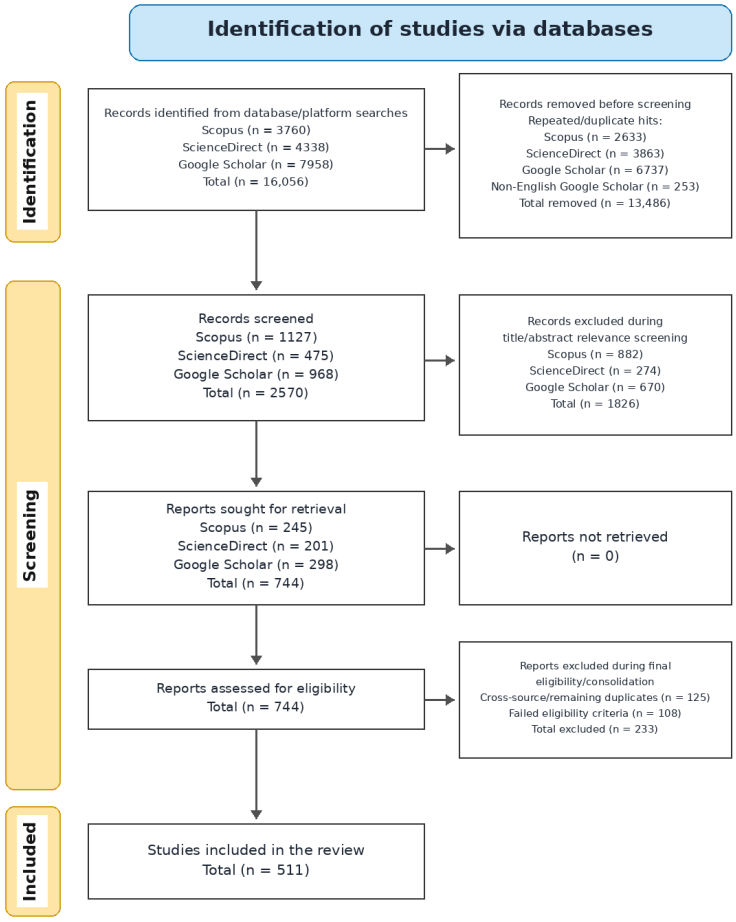


Figure 2. PRISMA flow diagram for the systematic literature review. *Source: Authors' own work, following PRISMA 2020 [34].*

2.2.3. Coding and Development of the Four-Level Literature-Derived Structure

Following screening, the 511 included studies were organised for coding and analysis. JabRef was used for reference management and duplicate checking, while Microsoft Excel was used to record screening decisions and organise the corpus. Full texts were imported into MAXQDA 24 for coding and to retain links between coded passages and their source documents.

Coding followed a hybrid inductive–deductive process using open, axial and selective coding. Open coding identified recurring concepts, technologies, spatial conditions, operational processes and passenger-related factors across the reviewed studies. Axial coding grouped related codes into broader categories, while selective coding refined these categories and organised them according to the study areas. The original text was retained alongside each code so that classifications could be checked against the source.

Semantic similarity was used to locate passages in which similar concepts were expressed using different terminology. The all-MiniLM-L6-v2 Sentence-Transformer model and cosine similarity were used to identify candidate passages, but the model did not assign codes. Each candidate passage was reviewed against its surrounding text before a code was retained. The primary researcher undertook the coding, while ambiguous or overlapping classifications were reviewed with the supervisory team and resolved through discussion.

For interview development, the literature-derived items were organised into a four-level structure comprising theme, sub-theme, regrouped indicator and SLR-derived sub-indicator. The theme represented the broad study domain. Sub-themes grouped related areas within each domain. Regrouped indicators provided functional groupings within each sub-theme, while SLR-derived sub-indicators represented the detailed items retained from the review. Their codes were retained throughout the interview and analysis stages.

The grouping was based on conceptual similarity and shared functional purpose. Related sub-indicators were grouped where they described parts of the same architectural, building-system or operational function. The sub-themes and regrouped indicators were researcher-developed groupings used to structure the interview questions. Original SLR indicator names were retained separately to trace each sub-indicator to the SLR coding structure. Participant responses were coded at the sub-indicator level. Original SLR indicators were retained for traceability rather than treated as an additional level in the interview structure.

Final consolidation produced 433 unique sub-indicators: 106 under architecture, 161 under operational efficiency and 166 under passenger experience. The present study used the 267 architecture and operational efficiency sub-indicators to develop the interview framework and subsequent analysis. Passenger experience was not included as a primary analytical domain in this study. Figure 3 summarises the coding, consolidation and four-level organisation leading to the structure used for interview development and analysis.

2.2.4. Interview Design and Mapping to the Literature-Derived Structure

The semi-structured interview guide was developed from the 267 architecture and operational efficiency sub-indicators identified through the SLR. The four-level structure was used to translate the detailed sub-indicators into practical interview questions. Sub-themes and regrouped indicators provided intermediate groupings between the broad domains and the detailed sub-indicators. This allowed related items to be addressed together rather than through separate questions for each sub-indicator.

The interview guide contained a common set of questions followed by specialist questions for architecture, operations and technology backgrounds. Participants first answered the common questions and were then asked specialist questions aligned with their areas of experience. Participants whose experience extended across more than one

area could receive questions from more than one specialist set. Individual participants were not asked about all 267 sub-indicators. Instead, the complete literature-derived structure informed the interview design, while question selection reflected participant background and experience. Follow-up questions were used where clarification or further explanation was required [35]. The common and cohort-specific interview questions are supplied in Supplementary File S1 to show how question allocation followed participant expertise.

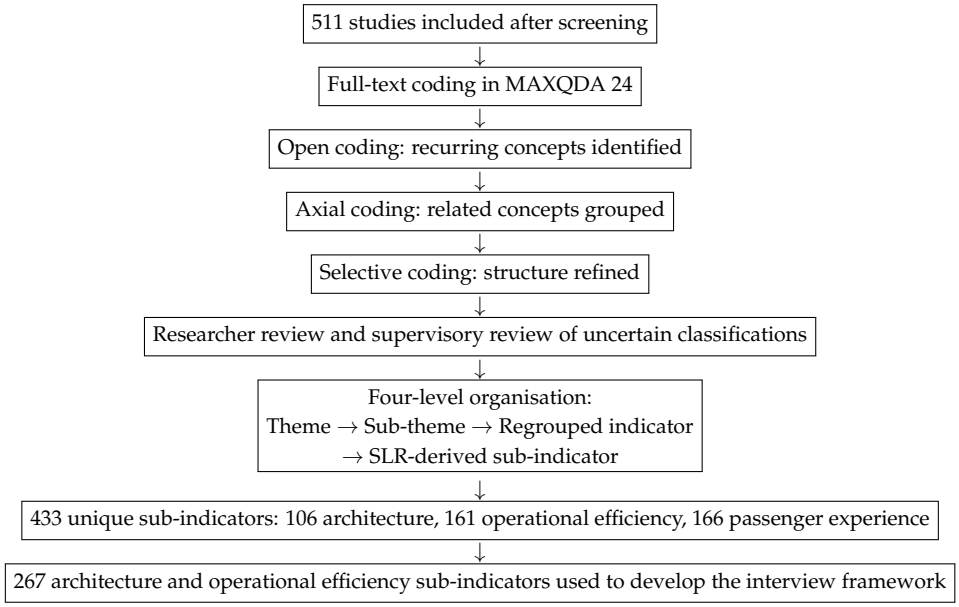


Figure 3. Coding, consolidation and four-level organisation used to develop the literature-derived structure for the interview study. *Source: Authors' own work.*

Table 3 presents the four-level structure used to organise the interview framework.

Table 3. Four-level literature-derived structure used to organise the interview framework.

Level	Element	Function in the Structure	Use in the Present Study
1	Theme	Broad study domain.	Architecture and operational efficiency formed the two analytical domains used in this study.
2	Sub-theme	Groups related areas within a theme.	Organised related architectural or operational areas for interview development.
3	Regrouped indicator	Researcher-developed functional grouping of related SLR-derived items within a sub-theme.	Linked groups of related sub-indicators to practical interview topics and questions.
4	SLR-derived sub-indicator	Most detailed literature-derived item retained in the structure.	Used to code participant responses and construct the participant–sub-indicator and cross-participant matrices.

Note: The four-level structure was used for interview development. Original SLR indicator names are retained separately in Table 4 for traceability. They do not form an additional level in this structure. Participant responses were coded at the sub-indicator level. *Source: Authors' own work.*

Participants were able to develop their responses according to their own experience rather than being restricted to a fixed list of sub-indicators. Relevant architecture and operational efficiency sub-indicators were identified from the content of those responses during coding. Table 4 maps the interview questions to the four-level structure and retains the original SLR indicator names alongside the regrouped indicators for traceability. Some questions appear more than once because they address more than one grouped area within or across the two domains. These rows represent multiple mappings rather than additional interview questions.

Table 4. Mapping of interview questions to the four-level architecture and operational efficiency literature-derived structure.

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
Common questions (CM)						
CM Q1	How do roles in the airport sector typically contribute to operational efficiency and passenger experience?	Architecture	Modular Design and Digital Connectivity	Adaptive Components and Connected Systems	Modular Design Element; Technology-Enabled Adaptability	Interchangeable components (AM 1); Scalable structure (AM 2); IoT device integration (ST 2); Real-time data processing (ST 3)
CM Q1	*as above*	Operational Efficiency	Operational Efficiency and Service Performance	Passenger Flow and Timeliness	Robotic Process Automation; Key Performance Indicator	Operational efficiency (ARP 1); Passenger wait times (OK 1); On-time performance (OK 3); Security screening effectiveness (OK 4); Baggage handling efficiency (OK 2)
CM Q2	What are the most significant day-to-day challenges airports face in managing operations, and what approaches have been used to address them?	Architecture	Disaster Resilience and Emergency Preparedness	Structural Safety and Crisis Continuity	Disaster Resilient Infrastructure; Resilient Communications Infrastructure; Emergency Power and Backup Systems	Earthquake-resistant structures (AD 1); Redundant communication channels (AR 1); Emergency alert systems (AR 2); On-site power generation (AEP 1)
CM Q2	*as above*	Operational Efficiency	Risk Management and Operational Resilience	Threat Monitoring and Adaptive Response	Risk Assessment; Compliance Monitoring; Incident Management; Dynamic Scheduling	Risk assessment—threat identification (ORA 1); Compliance monitoring (OC 1–4); Incident management (OIM 1–4); Dynamic scheduling (ED 1–4)
CM Q2	*as above*	Operational Efficiency	Airside Operations and Air Traffic Systems	Collaborative Decision Making	Collaborative Decision Making	Stakeholder communication platform (AC 1); Weather adaptation strategies (AC 2); Emergency response coordination (AC 3)
CM Q2	*as above*	Operational Efficiency	Security and Compliance Systems	Emergency Response	Emergency Response	Evacuation procedures (SER 1); Medical emergency protocols (SER 2); Fire suppression systems (SER 3); Crisis communication networks (SER 4)
CM Q4	What are the key drivers behind smart airport development initiatives, and what outcomes have been observed from integration of technologies such as IoT?	Architecture	Intelligent Sensing and Automation	Sensor Networks and AI-Driven Response	Technology-Enabled Adaptability; Environmental Monitoring Systems	IoT device integration (ST 2); AI and machine learning (ST 1); Real-time data processing (ST 3); Sensors and IoT devices (SEM 1); Energy management systems (SEM 2)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
CM Q4	*as above*	Operational Efficiency	Digital Infrastructure and Data Intelligence	Connected Devices and Cloud-Based Analytics	IoT Integration and Utility Management; Big Data Analysis; Machine Learning Applications; Cloud Computing	IoT integration and utility management (DII 1–3); Big data analysis (DB 1–5); Machine learning applications (DM 1–4); Cloud computing (DC 1–3)
CM Q4	*as above*	Operational Efficiency	Performance Management and Governance	Innovation Hubs	Innovation Hubs	Number of startups incubated (OI 1); Collaborative projects with universities (OI 2); Success rate of innovations implemented (OI 3)
CM Q4	*as above*	Operational Efficiency	Performance Management and Governance	R&D Investments	R and D Investments	New technology pilot and trial result matrix (OR 1); Patent filings related to airport operations (OR 2); Investment returns on R&D projects (OR 3)
CM Q6	What potential do big data analytics and machine learning have to optimise areas such as energy consumption and dynamic scheduling in airports?	Architecture	Intelligent Energy Performance	AI-Driven HVAC and Efficiency	Technology-Enabled Adaptability; Environmental Monitoring Systems; HVAC Innovations	AI and machine learning (ST 1); Data analytics (SEM 3); Energy management systems (SEM 2); Smart HVAC systems (EH 1); Energy efficiency (EH 2)
CM Q6	*as above*	Operational Efficiency	Predictive Analytics and Energy Optimization	Consumption Forecasting and Real-Time Scheduling	Big Data Analysis; Machine Learning Applications; Predictive Analytics; Energy Consumption Monitoring; Dynamic Scheduling	Big data analysis (DB 1–5); Machine learning applications (DM 1–4); Predictive analytics (DP 1–3); Energy consumption monitoring (EE 1–5); Dynamic scheduling (ED 1–4)
Operations specialist questions (C1)						
C1 Q1	What strategies have airports used to optimise gate allotment and aircraft sequencing to improve turnaround times?	Operational Efficiency	Aircraft Flow and Turnaround Efficiency	Gate Sequencing and Flexible Routing	Flight Schedule Optimisation; Smart Taxiway and Routing Systems; Advanced Air Traffic Control; Dynamic Scheduling	Gate assignment efficiency (AF 1); Aircraft sequencing (AF 2); Dynamic routing flexibility (EST 1); Arrival/departure efficiency (EAA 2); Turnaround time (ED 2); Crew scheduling (AF 3)
C1 Q2	What approaches have airports adopted to improve efficiency in cargo handling and integration with customs and security?	Operational Efficiency	Cargo Handling and Customs Integration	Freight Processing and Customs Clearance	Automated Cargo Handling Systems	Cargo processing speed (EAR 1); Real-time tracking—cargo (EAR 2); Cargo handling equipment (EAR 3); Cargo safety measures (EAR 4)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C1 Q2	*as above*	Architecture	Connectivity and Mobility Infrastructure	Cargo and Freight Solutions	Cargo and Freight Solutions	Efficiency of cargo handling operations (ECF 1); Integration with customs and security (ECF 2); Use of technology (ECF 3)
C1 Q3	What strategies have airports used to manage workforce needs, including how technology supports shift coverage and training?	Operational Efficiency	Workforce Management and Training Effectiveness	Staff Satisfaction and System Training	Workforce Management; Technology Adoption	Employee satisfaction rates (EWM 1); Shift coverage effectiveness (EWM 2); Training completion rates (EWM 3); Staff turnover rates (EWM 4); Employee training on new systems (OT 2); Rate of implementation of new technology (OT 1); User satisfaction with newly adopted technologies (OT 3)
C1 Q4	How have advanced air traffic control systems and smart taxiway/routing systems been used to enhance arrival/departure efficiency and reduce towing time?	Operational Efficiency	Air Traffic Coordination and Ground Automation	Conflict Detection and Autonomous Ground Support	Advanced Air Traffic Control; Smart Taxiway and Routing Systems; Automated Guided Vehicles for Aircraft Towing	Conflict detection algorithms (EAA 1); Arrival/departure efficiency (EAA 2); ATC communication systems (EAA 3); Dynamic routing flexibility (EST 1); Taxiway lighting systems (EST 2); Towing time reduction (EAG 1); AGV reliability (EAG 3); AGV navigation accuracy (EAG 4); ATC personnel (EAA 4); Taxiway surface condition (EST 3); Taxiway design (EST 4)
C1 Q4	*as above*	Operational Efficiency	Airside Operations and Air Traffic Systems	Runway Design and Management	Runway Design and Management	Runway capacity (ER 1); Pavement quality (ER 2); Lighting and markings (ER 3); Runway length and width (ER 4)
C1 Q4	*as above*	Operational Efficiency	Airside Operations and Air Traffic Systems	Taxiway Efficiency and Management	Taxiway Efficiency and Management	Taxiway throughput (ET 1); Surface detection equipment (ET 2); Taxiway design (ET 3); Taxiway surface condition (ET 4)
C1 Q5	What role do predictive maintenance tools and automated fault detection play in supporting smooth operations and facility longevity?	Operational Efficiency	Predictive Maintenance and Facility Energy Management	Fault Prediction and IoT-Based Energy Control	Facility Maintenance; IoT Integration and Utility Management	Predictive maintenance tool (AFM 1); Automated fault detection (AFM 2); Energy management solutions—facility (AFM 3); IoT-based energy management (DII 3)
C1 Q5	*as above*	Operational Efficiency	Workforce and Facility Management	Smart Hangar Design	Smart Hangar Design	Maintenance turnaround time (ES 1); Space utilisation efficiency (ES 2); Hangar safety measures (ES 3); Hangar environmental control (ES 4)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C1 Q6	What methods have airports used to ensure efficient ground traffic management and optimise vehicle flow?	Operational Efficiency	Ground Traffic Management and Safety	Traffic Flow and Personnel Coordination	Ground Traffic Management; Real-time Tracking	Vehicle flow optimisation (EGT 1); Ground traffic safety measures (EGT 2); Ground traffic communication systems (EGT 3); Ground traffic control personnel (EGT 4); Ground vehicle coordination (ATR 3)
C1 Q7	What methods have airports adopted to track assets and monitor their utilisation, including baggage tracking?	Operational Efficiency	Asset Tracking and Utilisation Monitoring	Location Accuracy and Maintenance Scheduling	Asset Tracking; Real-time Tracking	Tracking accuracy (EA 1); Maintenance schedule (EA 2); Utilisation monitoring (EA 3); Lost luggage tracking (EA 4); Baggage tracking system (ATR 2); Aircraft location monitoring (ATR 1)
C1 Q7	*as above*	Operational Efficiency	Automation and Process Efficiency	Automated Sorting	Automated Sorting	Baggage identification (AAS 1); Destination sorting (AAS 2); Priority handling (AAS 3)
C1 Q8	What measures have airports used to minimise passenger wait times at touchpoints such as check-in and security screening?	Operational Efficiency	Passenger Processing and Biometric Systems	Self-Service Verification and Wait Time Reduction	Passenger Flow Management; Smart Kiosks; Self-Service Kiosks; E-Gates; Key Performance Indicator	Queue management services (AP 1); Biometric identification process (AP 2); Dynamic signage and wayfinding (AP 3); Reduced wait times—kiosks (AS 2); Check-in services (ASS 1); E-gate biometric verification (AE 1); Security screening effectiveness (OK 4); Passenger wait times (OK 1)
C1 Q9	What initiatives have airports used to enhance customer experience in retail and concessions, including digital payment integration?	Operational Efficiency	Retail Analytics and Customer Experience	Data-Informed Service and Digital Payments	Retail and Concessions Management	Sales data analysis tool (ARC 1); Customer experience enhancement (ARC 2); Digital payment options integration (ARC 3)
C1 Q10	What approaches have airports used to integrate renewable energy sources and energy storage systems as part of sustainability efforts?	Architecture	Renewable Energy and Smart Distribution	Multi-Source Generation and Intelligent Storage	Renewable-Energy Integration; Emergency Power and Backup Systems; Automated Energy Management Systems	Solar panels on roofs (SR 1); Wind turbines (SR 2); Geothermal energy (SR 3); Energy storage (SR 4); Power-grid integration (SR 5); On-site power generation (AEP 1); Energy storage systems (AEP 2); IoT-based energy management (EAE 1); Energy harvesting (EAE 2)
C1 Q10	*as above*	Architecture	Connectivity and Mobility Infrastructure	Green Parking Solutions	Green Parking Solutions	Electric vehicle charging stations (EG 1); Carpooling incentives (EG 2); Use of permeable materials (EG 3); Shuttle services (EG 4)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C1 Q11	What water management strategies have airports adopted, including rainwater harvesting and recycling systems?	Architecture	Water Recycling and Drought-Resilient Design	Rainwater Capture and Drought-Adapted Landscaping	Climate Resilient Water Management; Green Roofs and Living Walls	Water recycling systems (EC 1); Rainwater harvesting (EC 2); Rainwater collection system (SG 2); Drought-resistant landscaping (EC 3)
C1 Q12	What approaches have you observed in the airport sector regarding carbon capture, storage, or offsetting to reduce environmental footprint?	Architecture	Carbon Capture and Offsetting	Direct Capture and Offset Programmes	Carbon Capture and Storage Initiatives	Carbon capture technologies (ECC 1); Carbon storage solutions (ECC 2); Carbon offsetting programmes (ECC 3)
C1 Q13	What challenges do airports face in integrating new technologies with existing infrastructure and systems?	Architecture	Modular Systems and Intelligent Connectivity	AI-Responsive Components and Prefabrication	Technology-Enabled Adaptability; Modular Design Element	AI and machine learning (ST 1); IoT device integration (ST 2); Real-time data processing (ST 3); Modular design element codes (AM 1, AM 2, AM 3)
C1 Q15	What long-term sustainability goals are airports pursuing, and how might continued innovation in renewable energy and carbon capture support these goals?	Architecture	Renewable Energy and Emissions Reduction	Clean Power Generation and Carbon Offsetting	Renewable-Energy Integration; Carbon Capture and Storage Initiatives; Waste Management and Reduction	Solar panels (SR 1); Wind turbines (SR 2); Energy storage (SR 4); Carbon capture technologies (ECC 1); Carbon offsetting programmes (ECC 3); Composting initiatives (EW 2); Waste reduction policies (EW 3)
Architecture specialist questions (C2)						
C2 Q1	How have airport terminal designs incorporated natural light and bioclimatic principles to improve comfort and energy efficiency?	Architecture	Environmental Comfort and Daylighting	Passive-Active Thermal and Light Balance	Energy-Efficient Building Design; Advanced Bioclimatic Architecture	Natural light (SE 1); Solar energy utilisation (EAB 1); Thermal comfort design (EAB 2); Natural lighting optimisation (EAB 3); HVAC systems (SE 3); Smart lighting (SE 4); Insulation (SE 2); Smart appliances (SE 5)
C2 Q2	What examples have you seen of airports using flexible layouts and multi-purpose spaces to adapt to changing operational needs or passenger volumes?	Architecture	Flexible Spaces and Modular Construction	Reconfigurable Layouts and Prefabricated Systems	Transformable Public Areas; Modular Design Element	Multi-purpose spaces (AT 1); Flexible layouts (AT 2); Retractable structures (AT 3); Convertible furniture (AT 4); Interchangeable components (AM 1); Scalable structure (AM 2); Prefabricated modules (AM 3)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C2 Q2	*as above*	Architecture	Adaptive and Resilient Infrastructure	Interactive and Dynamic Features	Interactive and Dynamic Features	User engagement elements (AI 1); Adaptability (AI 2)
C2 Q3	What role do intelligent façade systems and smart lighting play in improving energy efficiency and creating comfortable passenger environments?	Architecture	Smart Envelope and Energy Systems	Adaptive Façades and Responsive Lighting	Intelligent Façade Systems; Light Manipulation; HVAC Innovations	Energy-efficient design (SI 1); Smart materials (SI 2); IoT device integration—façade (SI 3); Smart lighting (EL 1); Biometric lighting (EL 2); Smart HVAC systems (EH 1); Energy efficiency (EH 2)
C2 Q4	What eco-friendly materials and waste management practices have airports adopted during renovation or new construction?	Architecture	Sustainable Materials and Waste Management	Responsible Sourcing and Circular Waste Practice	Eco-Friendly Material and Practices; Material Innovations; Waste Management and Reduction	Use of recycled or recyclable materials (SEF 1); Low-VOC paints and finishes (SEF 2); Locally sourced materials (SEF 3); Waste management during construction (SEF 4); Sustainable materials (EM 1); Recycling programmes (EW 1); Waste reduction policies (EW 3); Long-term replacement plans (SEF 5)
C2 Q5	How have airport terminal designs addressed disaster resilience and integrated robust evacuation and safety systems?	Architecture	Hazard-Resistant Design and Emergency Readiness	Multi-Hazard Structures and Evacuation Support	Disaster Resilient Infrastructure; Evacuation and Safety Systems; Resilient Communications Infrastructure; Emergency Power and Backup Systems	Earthquake-resistant structures (AD 1); Flood-resistant design (AD 2); Fire-resistant design (AD 3); Wind and storm resistant design (AD 4); Clear signage (AES 1); Accessible escape routes (AES 2); Emergency alert systems (AR 2); On-site power generation (AEP 1); Energy storage systems (AEP 2)
C2 Q6	What examples have you observed of airport terminal designs incorporating local culture and art into architectural identity?	Architecture	Cultural Identity and Design Character	Heritage Expression and Contextual Aesthetics	Local Culture and Art; Architectural Identity; Aesthetic Integration	Representation of local artists (CL 1); Cultural symbols (CL 2); Traditional motifs (CL 3); Unique design elements (AA 1); Historical references (AA 2); Signature style (AA 3); Harmony with environment (CA 1); Visual appeal (CA 2); Material selection (CA 3); Colour scheme (CA 4)
C2 Q7	How have airports used modular design elements and prefabricated modules to support scalable and adaptable infrastructure?	Architecture	Modular Construction and Spatial Flexibility	Component Scalability and Multi-Use Design	Modular Design Element; Transformable Public Areas	Interchangeable components (AM 1); Scalable structure (AM 2); Prefabricated modules (AM 3); Multi-purpose spaces (AT 1); Flexible layouts (AT 2)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C2 Q8	What role does digital signage and wayfinding play in improving navigation and accessibility across airport environments?	Architecture	Digital Wayfinding and Communication	Digital Signage and Pathway Navigation	Communications and Information Systems; AR and VR Integration; Infrastructure for Non-Motorised Transport	Digital signage and displays (SC 1); Real-time information systems (SC 2); Mobile and web-based communication (SC 3); AR for navigation (SA 1); Pedestrian pathways (EI 1); Signage (EI 3); Bicycle lanes (EI 2); Safety measures (EI 4); Storage facilities (EI 5)
C2 Q8	*as above*	Architecture	Connectivity and Mobility Infrastructure	Multimodal Transport Facilities	Multimodal Transport Facilities	Availability of different transport modes (EMT 1); Connectivity between modes (EMT 2); Frequency of service (EMT 3); Accessibility (EMT 4); Information system (EMT 5)
C2 Q9	What role have green roofs, living walls, and drought-resistant landscaping played in advancing sustainability within airport environments?	Architecture	Water Conservation and Native Landscaping	Native Planting and Water Recycling Systems	Green Roofs and Living Walls; Climate Resilient Water Management	Plant selection (SG 1); Rainwater collection system (SG 2); HVAC integration (SG 3); Native or adaptive species (SG 4); Drought-resistant landscaping (EC 3); Water recycling systems (EC 1); Rainwater harvesting (EC 2); Regular maintenance (SG 5)
C2 Q10	What emerging technologies or architectural trends do you believe will have the most significant impact on airport design over the next 5–10 years?	Architecture	Biomimetic Design and Smart Modularity	Nature-Inspired Structures and Immersive Tech	Technology-Enabled Adaptability; Modular Design Element; Biomimicry In Architecture; AR and VR Integration	AI and machine learning (ST 1); IoT device integration (ST 2); Modular design elements (AM 1–3); Biomimicry in architecture (AB 1–3); AR/VR integration (SA 1–2)
Technology specialist questions (C3)						
C3 Q1	How are airports adopting AI and machine learning to support operations, and what potential do you see for further integration?	Architecture	Smart Technology and Security Intelligence	AI-Powered Surveillance and Real-Time Monitoring	Technology-Enabled Adaptability; Security and Surveillance Innovations	AI and machine learning (ST 1); IoT device integration (ST 2); Real-time data processing (ST 3); AI in security processes (SS 1); Advanced surveillance technologies (SS 2); Biometric identification (SS 3)
C3 Q1	*as above*	Operational Efficiency	Predictive Analytics and AI Security	Machine Learning-Driven Threat Detection	Machine Learning Applications; Big Data Analysis; Predictive Analytics	Machine learning applications (DM 1–4); Big data analysis (DB 1–5); Predictive analytics (DP 1–3)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C3 Q2	How are real-time data processing and analytics being used to support decision-making, particularly in dynamic scheduling and resource allocation?	Operational Efficiency	Predictive Scheduling and Real-Time Dashboards	Resource Forecasting and Live Reporting	Predictive Analytics; Dynamic Scheduling; Real-time Tracking; Dashboard Reporting	Predictive analytics (DP 1–3); Dynamic scheduling (ED 1–4); Resource allocation (ED 3); Real-time tracking—aircraft and baggage (ATR 1–3); Dashboard reporting (OD 1–3)
C3 Q2	*as above*	Operational Efficiency	Performance Management and Governance	Performance Analysis	Performance Analysis	Trend analysis over time (OP 1); Comparative benchmarking (OP 2); Root cause analysis for delays or failures (OP 3)
C3 Q3	What role can IoT devices play in enhancing operational efficiency and environmental monitoring in airport environments?	Architecture	IoT-Enabled Energy Intelligence	Sensor Data and Automated Energy Response	Technology-Enabled Adaptability; Environmental Monitoring Systems; Automated Energy Management Systems; Material Innovations	IoT device integration (ST 2); Sensors and IoT devices (SEM 1); Energy management systems (SEM 2); Data analytics (SEM 3); IoT-based energy management (EAE 1); Sensor-based IoT devices (EM 2)
C3 Q3	*as above*	Operational Efficiency	Connected Utilities and Energy Monitoring	Device Connectivity and Consumption Tracking	IoT Integration and Utility Management; Energy Consumption Monitoring	IoT integration and utility management (DII 1–3); Device connectivity (DII 1); Utility optimisation (DII 3); Energy consumption monitoring (EE 1–5)
C3 Q4	How have smart kiosks and automated passenger processing systems influenced passenger experience and reduced wait times?	Operational Efficiency	Self-Service Check-In and Personalisation	Kiosk Automation and Digital Boarding	Smart Kiosks; Self-Service Kiosks; Mobile Check-in	Self-service smart kiosks (AS 1); Reduced wait times (AS 2); Personalised experience (AS 3); Check-in services (ASS 1); Seat selection (ASS 2); Bag tag printing (ASS 3); Digital boarding passes (AMC 2)
C3 Q5	How might autonomous vehicles and robotic process automation transform ground operations and cargo handling in the future?	Operational Efficiency	Autonomous Vehicle Operations and Automation	24/7 Automation and Cargo Handling	Autonomous Vehicles; Robotic Process Automation; Automated Cargo Handling Systems; Automated Guided Vehicles for Aircraft Towing	Extended operating efficiency (AAV 1); Safety—AV (AAV 2); Fuel efficiency (AAV 3); Passenger comfort—AV (AAV 4); Operational efficiency—RPA (ARP 1); Cost savings (ARP 2); 24/7 operation (ARP 3); Automated cargo handling (EAR 1–4); AGV for towing (EAG 1–4); Safety—RPA (ARP 4)

Table 4. *Cont.*

Q.No	Interview Question	Theme	Sub-Theme	Regrouped Indicator	Original SLR Indicator(s)	SLR-Derived Sub-Indicators
C3 Q6	What role do mobile applications and real-time information systems play in improving communication with passengers and staff?	Architecture	Digital Communication and Navigation Tech	Real-Time Displays and Augmented Guidance	Communications and Information Systems; AR and VR Integration	Real-time information systems (SC 2); Mobile and web-based communication (SC 3); Digital signage and displays (SC 1); AR for navigation (SA 1)
C3 Q6	*as above*	Operational Efficiency	Mobile App Engagement and Digital Services	Remote Check-In and Real-Time Updates	Mobile Applications; Mobile Check-in	User engagement (DMA 1); User retention (DMA 2); App performance (DMA 3); Remote check-in capability (AMC 1); Digital boarding passes (AMC 2); Real-time notifications (AMC 3)
C3 Q7	What key cybersecurity measures have been observed to protect sensitive data and digital identity systems?	Operational Efficiency	Cybersecurity and Digital Compliance	Identity Protection and Compliance Auditing	Threat Detection Systems; Digital Identity Management; Cloud Computing; Compliance Monitoring	Cybersecurity measures (STD 4); Digital identity management (DD 1–3); Audit and compliance (DD 3); Cloud computing data security (DC 3); Compliance monitoring (OC 1–4); Metal detectors (STD 1); Explosive trace detectors (STD 2); Advanced imaging technology (STD 3)
C3 Q8	How do biometric screening methods and e-gates contribute to enhancing the passenger journey while maintaining security?	Operational Efficiency	Biometric Verification and Identity Technology	Multi-Modal Biometrics and Checkpoint Integration	Biometric Screening; E-Gates; Passenger Flow Management	Facial recognition (SB 1); Fingerprint analysis (SB 2); Iris scanning (SB 3); Behavioural biometrics (SB 4); E-gate biometric verification (AE 1); Boarding pass scanning (AE 2); Security screening integration (AE 3); Biometric identification process (AP 2)
C3 Q9	What examples have you seen of airports using technology such as mobile check-in and real-time notifications for personalised passenger experiences?	Operational Efficiency	Personalised Digital Journey	Mobile Self-Service and Tailored Engagement	Mobile Check-in; Smart Kiosks; Mobile Applications	Remote check-in capability (AMC 1); Digital boarding passes (AMC 2); Real-time notifications (AMC 3); Personalised experience—kiosks (AS 3); User engagement (DMA 1)
C3 Q10	What risks do airports face when implementing advanced technologies, and how can these be managed effectively?	Operational Efficiency	Risk Governance and Process Improvement	Compliance Monitoring and Incident Learning	Risk Assessment; Compliance Monitoring; Incident Management; Process Improvement Tools	Risk assessment (ORA 1–5); Compliance monitoring (OC 1–4); Incident management (OIM 1–4); Process improvement tools (OPI 1–3)

Note: CM = common questions, C1 = operations, C2 = architecture and C3 = technology. Repeated question entries indicate mapping to more than one grouped area. Regrouped indicators are researcher-developed groupings. Original SLR indicator names are retained separately for traceability and do not form an additional level in the four-level interview structure. *Source: Authors' own work based on the architecture and operational efficiency literature-derived structure and interview guide.*

2.2.5. Ethical Considerations

Ethical approval was granted by the Auckland University of Technology Ethics Committee (AUTEC) under Ethics Application 25/251 on 30 September 2025, prior to participant recruitment and data collection. The study was conducted in accordance with the Auckland University of Technology Code of Conduct for Research and the conditions approved by AUTEC.

Participants received information about the purpose of the study, the voluntary nature of participation, confidentiality arrangements and their right to withdraw in accordance with the approved ethics protocol. Informed consent was obtained before participation, and participants contributed in their individual capacity rather than as representatives of their organisations.

Participant information was de-identified during analysis and reporting. Names, organisations and other identifying details were not included in the manuscript. Interview recordings and transcripts were stored securely in accordance with the approved research data-management arrangements.

2.2.6. Participant Recruitment

Participants were selected purposively because the study required knowledge of airport architecture, operations, planning, asset management, passenger processing, sustainability or digital systems [36]. Eligibility required at least three years of relevant experience. Semi-structured interviews were used because they allowed a common set of questions to be applied while permitting participants to elaborate on issues relevant to their experience. This approach is consistent with qualitative built-environment studies using expert interviews to identify and organise recurring themes, benefits, barriers and practice-based factors [37,38].

The recruitment plan, agreed through discussions between the researcher and supervisory team, sought five participants with architecture expertise, ten with operations expertise and five with technology expertise, within the ethics-approved maximum of 20 interviews. Greater representation was sought from operations because airport operations involve continuous, interdependent activities across multiple functions. Architecture and technology contribute to the planning, implementation and modification of airport systems, whereas operational decisions and processes continue throughout daily airport activity. The intended distribution therefore reflected the study's emphasis on the ongoing interaction between airport infrastructure and operations, rather than equal comparison groups. The final cohort comprised four architecture, nine operations, five technology and two cross-domain participants. The Cross-domain category describes overlapping expertise identified in the final cohort rather than a separate recruitment target. The intended distribution was a recruitment guide, not a documented quota. The interviews were not designed to estimate population-level differences between professional groups.

All participants first answered the common interview questions and then proceeded to specialist questions relevant to their experience in airport management and operations, architecture and planning, or technology and digital systems. Participants with overlapping experience could also discuss topics beyond their primary specialist question set. The primary cohort labels therefore described professional background rather than restricting which analytical themes a participant could inform.

The architecture and operations cohorts formed the domain cohorts used to calculate domain participant support for the sub-indicator classification. Contributions from participants outside the relevant domain cohort were recorded separately as other-domain contributions and did not increase the architecture or operational efficiency domain denominators.

Participants' roles and functions included airport design and planning, operational management, passenger processing, airfield systems, emergency response, asset management, sustainability and digital systems. Table 5 summarises the participant cohort, role and function and experience.

Table 5. Participant cohort, role and function and experience.

Participant	Participant Cohort	Role and Function	Experience (Years)
P01	Architecture	Smart Airport Design and Operations Expert	6
P02	Architecture	Operational Coordination, Passenger Processing, and Technology Adoption	11
P03	Technology	Spatial Data, Building-Information and Digital-Asset Management	5
P04	Technology	Digital Systems and Network Infrastructure	4
P05	Cross-domain	Airport Operations and Passenger Experience	5
P06	Operations	Airport Operations and Emergency Response	15
P07	Cross-domain	Operations and Technology Implementation	8
P08	Technology	Airfield Maintenance/Airside Standpoint	9
P09	Operations	Airport Architecture, Planning and Design/Sustainability Consultant	7
P10	Operations	Airfield Lighting and Maintenance	6
P11	Operations	Airport Operations and Operational Management	6
P12	Operations	Airport Operations Management	5
P13	Operations	Airport Operations	8
P14	Operations	Airport Operations and Management	8
P16	Architecture	Architecture, Planning and Design Professional	11
P17	Architecture	Architecture, Planning and Design Professional	8
P18	Operations	Airport Management, Operations and Sustainability Professional	10
P19	Operations	Operations Planning, Infrastructure Interfaces, Asset Performance and Sustainability Programmes	5
P20	Technology	Technology and Digital Systems Professional	7
P21	Technology	Technology and Digital Systems Professional	4

Note: Participant cohort represents the primary analytical grouping. Architecture and operations formed the domain cohorts used to calculate domain support. Contributions to a sub-indicator from participants outside its relevant domain cohort were recorded as other-domain contributions. *Source: Authors' own work.*

2.2.7. Interview Procedure

Interviews were conducted individually using the approved semi-structured interview guide. Each interview began with the common questions before moving to specialist questions selected according to the participant's background in architecture, operations or technology. Where a participant's experience extended across more than one area, questions from more than one specialist set were used where relevant.

The interview sequence remained flexible so that follow-up questions could be used where clarification or further explanation was required [35]. Participants were able to develop their responses according to their own experience rather than being restricted to a fixed response format. This allowed the discussion to follow relevant issues raised during the interview while maintaining the common and specialist question structure. Interviews were recorded and transcribed before analysis.

Participants contributed in their individual professional capacity, not as representatives of their employers. In accordance with the approved participant information, interviews sought general industry knowledge rather than organisation-specific procedures or confidential information. Participants reported relevant airport experience across 14 countries: New Zealand, the United Kingdom, Finland, India, the United Arab Emirates, Singapore, Malaysia, Myanmar, Saudi Arabia, the United States, Qatar, Jordan, Brunei and Kuwait. Sixteen participants reported experience in more than one country. These

figures describe reported professional experience, not nationality or the location of a current employer. Recruitment was not intended to achieve geographic representation.

2.3. Data Analysis

2.3.1. Coding and Scoring

The interview transcripts were analysed in three phases.

Participants were classified by primary professional background for descriptive reporting. Their statements were coded under architecture or operational efficiency according to content, regardless of their primary cohort. Other-domain contributions were retained in the participant–sub-indicator matrix but did not increase the denominators used for within-domain support categories. In the first phase, the primary researcher reviewed the transcripts question by question and coded participant statements against the relevant architecture and operational efficiency sub-indicators. Coding was based on meaning rather than exact keywords. Equivalent wording was coded to the relevant sub-indicator where the participant clearly referred to the same concept.

The coding and scoring approach was developed and refined through consultation with the primary supervisor. The primary researcher undertook the coding. The primary supervisor subsequently examined selected interview passages and their assigned codes to check the classification logic, and changes were made where necessary before proceeding to the next analytical stage. Statements that did not clearly match the literature-derived categories were recorded separately and considered for additional coding; statements conveying an existing concept in different words were assigned to the relevant code after examining their meaning. The review was not independent parallel coding; therefore, no formal intercoder-reliability statistic was calculated [39].

In the third phase, the coded statements were assigned scores using the five-point scoring system shown in Table 6. Scores 1–4 represented increasing levels of directness, explanation and practical detail within an individual coded statement. Score 5 required a statement that independently satisfied the Score 4 criteria and a second detailed reference by the same participant to the same exact sub-indicator elsewhere in the interview.

Table 6. Five-point scoring system applied to coded participant statements.

Score	Classification	Scoring Rule
1	Indirect reference	The participant referred indirectly to the relevant sub-indicator, but the statement did not clearly describe the sub-indicator itself.
2	Direct reference	The participant directly mentioned the sub-indicator or used an equivalent expression that clearly represented the same sub-indicator.
3	Direct reference with explanation	The participant described the sub-indicator and explained how it operated, why it mattered, or how it related to the airport system.
4	Explained reference with practical detail	The participant satisfied the Score 3 criteria and additionally provided a practical example, mechanism, consequence or operational constraint.
5	Repeated detailed reference	The coded statement independently satisfied the Score 4 criteria, and the same participant described the same exact sub-indicator at Score 4 level again elsewhere in the interview.

Source: Authors' own work.

To illustrate the application of the scoring system, a worked example from Participant P01 is presented below and summarised in Table 7. The example shows the participant's response used for coding and, for the sub-indicator receiving Score 5, the second reference to the same sub-indicator.

Worked scoring example: Participant P01, Question C2Q2

Question: In your experience, what examples have you seen of airports using flexible layouts and multi-purpose spaces to adapt to changing operational needs or passenger volumes?

Participant response (00:13:43–00:15:09):

uh yeah sure I have um um common use technology is a major enabler of spatial flexibility if counters you know gates kiosks the automatic bag drops can be reassigned across airlines the terminal can respond to changing demand but common use only works when the operational agreements staff training branding data interfaces and data information are aligned the system layer and the spatial layer have to be you know designed together they cant be in isolation to each other they are interdependent

and you know flexibility should extend beyond the terminal right its not just when we say the airport its not the terminal itself you know rail bus ride hailing parking and pedestrian connections a terminal that cannot absorb shifts in access mode will experience kerbside congestion or poor passenger arrival experience again I said I really believe smiles on the passengers are really important so strong airport planning treats the landside interface as an adaptable system not a fixed uh forecourt and yeah that's what I believe

Repeated reference for AT 2 (00:33:26–00:34:24):

you know forget about passengers everyone in this life in this world people they don't like hassles they don't like problems so my answer to your question would be a frictionless processing will change the sequence and footprint of check in security immigration and boarding but will but will not remove the need for space airports will need exception areas privacy sensitive enrolment fallback processes and clear transitions between automated and staffed service

Table 7. Worked example of participant coding and scoring.

Sub-Indicator	Code	Participant Extract	Score	Scoring Basis
Flexible layouts	AT 2	**00:13:43–00:15:09:** common use technology is a major enabler of spatial flexibility if counters you know gates kiosks the automatic bag drops can be reassigned across airlines the terminal can respond to changing demand *Second reference, 00:33:26–00:34:24:* a frictionless processing will change the sequence and footprint of check in security immigration and boarding but will but will not remove the need for space airports will need exception areas privacy sensitive enrolment fallback processes and clear transitions between automated and staffed service	**5**	The first statement explains a practical mechanism through which spatial flexibility is achieved and therefore satisfies Score 4. The later statement independently explains how changes in passenger processing alter spatial requirements and identifies practical conditions that must be accommodated. The same sub-indicator is therefore described twice at Score 4 level, satisfying the criterion for Score 5.
Adaptability	AI 2	strong airport planning treats the landside interface as an adaptable system not a fixed uh forecourt	**3**	Adaptability is directly identified and its relationship to airport planning is explained.

Table 7. *Cont.*

Sub-Indicator	Code	Participant Extract	Score	Scoring Basis
Connectivity between modes	EMT 2	a terminal that cannot absorb shifts in access mode will experience kerbside congestion or poor passenger arrival experience	**4**	The participant explains a practical consequence of inadequate transport-mode integration through its effect on kerbside conditions and passenger arrival.
Availability of different transport modes	EMT 1	rail bus ride hailing parking and pedestrian connections	**2**	Different transport modes are directly identified, but the statement does not independently explain how they operate or affect the airport system.
Self-service smart kiosks	AS 1	counters you know gates kiosks the automatic bag drops can be reassigned across airlines	**4**	The participant identifies self-service facilities and explains the practical mechanism through which reassignment supports changing operational demand.

Note: The principal example is drawn from Participant P01, Question C2Q2. The second extract shown for AT 2 is drawn from the same participant's response to C2Q11. *Source:* Authors' own work.

The scores represented increasing levels of directness, explanation and practical detail within participant responses and were not added together. Where the same participant referred to the same sub-indicator more than once, the highest score for that sub-indicator was used in the participant–sub-indicator matrix. Repeated references could therefore result in Score 5 but did not increase the participant count for that sub-indicator.

The analytical records included the participant identifier, question identifier, coded statement, sub-indicator code, assigned score and coding rationale. These records were used to construct the participant–sub-indicator and cross-participant matrices described in the following subsection.

2.3.2. Participant–Sub-Indicator and Cross-Participant Matrices

Following coding and scoring, two analytical matrices were constructed. The first was a participant–sub-indicator matrix in which participants formed the rows and the 267 architecture and operational efficiency sub-indicators formed the columns. Matrix-based approaches have similarly been used in built-environment research to retain traceability between source records and identified factors and to examine factor occurrence across the resulting structure [40,41]. Where a participant referred to the same sub-indicator more than once, the highest score assigned to that participant for the exact sub-indicator was retained. The complete participant–sub-indicator scoring matrices are provided in Appendix A.

The second matrix summarised recurrence across participants. For each sub-indicator, the number and identity of different participants referring to it were recorded. Repeated references by the same participant were counted once when determining participant recurrence. The matrices therefore distinguished the level of directness, explanation and practical detail in an individual participant's response from the breadth of recurrence across different participants.

The complete 267-sub-indicator structure was retained during coding so that literature-derived items could be traced through the interview analysis. Of these, 162 architecture and

operational efficiency sub-indicators were identified in at least one participant response. All Scores 1–5 remained represented in the analytical records. The populated participant–sub-indicator data were then used to calculate the mean score, domain participant support and other-domain contributions for each of the 162 identified sub-indicators.

The populated participant–sub-indicator data formed the basis for the sub-indicator-level descriptive analysis and classification described in Section 2.3.3. Sub-indicators not identified in the interview responses remained part of the literature-derived structure but were not included in the sub-indicator-level analysis and classification.

2.3.3. Sub-Indicator-Level Descriptive Analysis and Classification

Descriptive analysis was undertaken at the sub-indicator level. For each of the 162 architecture and operational efficiency sub-indicators identified in the interviews, the analysis recorded the contributing participant IDs, the participant scores, the mean score and participant support within the relevant domain cohort. Contributions from participants outside the relevant domain cohort were recorded separately as other-domain contributions. Where the same participant referred to the same exact sub-indicator more than once, the highest score was used so that repeated references did not increase the participant count.

All Scores 1–5 were included when calculating the mean for each sub-indicator. The mean was used to summarise the depth of the participant responses. The use of mean scores to summarise factor-level interview responses has also been applied in built-environment research to support comparison across identified factors [42]. Scores 1–2 represented indirect or direct reference, while Scores 3–5 represented responses containing explanation, practical detail or repeated detailed reference. A mean greater than 2.5 was therefore used to identify sub-indicators whose responses, on average, extended beyond direct reference alone. The scores describe how much detail participants provided, not the importance of a sub-indicator. The difference between consecutive scores was not assumed to be equal. The mean and the 2.5 cut-off were therefore used only to group responses for this study. We also checked the results using a median score of at least 3. This presented the same outcome: 152 sub-indicators were retained, and 10 were excluded. The check showed that using the median instead of the mean did not change which sub-indicators were retained. It did not establish that either cut-off was universally applicable.

Participant support was assessed separately within the relevant domain cohort. The architecture cohort comprised four participants and the operational efficiency cohort comprised nine participants. The proportion of participants within each domain cohort referring to a sub-indicator was used to distinguish broader and narrower recurrence. For architecture, 75% support corresponded to at least three participants and 50% support to at least two participants. For operational efficiency, the corresponding thresholds were seven and five participants.

The 162 identified sub-indicators were grouped into four categories using the mean score and domain participant support, as summarised in Table 8. Sub-indicators classified as broadly supported, moderately supported or context-specific were retained in the final analytical set. Sub-indicators with a mean score of 2.5 or lower were classified as below inclusion threshold. These items remained visible in the full classification table for transparency but were not carried forward into the subsequent interpretation of the findings.

Table 8. Sub-indicator classification rules.

Classification	Mean Score	Domain Support	Treatment
Broadly Supported	>2.5	≥75%	Retained
Moderately Supported	>2.5	50–<75%	Retained
Context-Specific	>2.5	<50%	Retained
Below Inclusion Threshold	≤2.5	Any	Reported for transparency but excluded from the final analytical set

Source: Authors' own work.

2.3.4. Architecture–Operational Efficiency Connection Analysis

Following the sub-indicator-level analysis, coded participant statements were examined for direct connections between architecture and operational efficiency. Examining identified factors together with their interrelationships has been used in built-environment research to move beyond isolated factor lists and examine how conditions interact within wider systems [43,44]. Two sub-indicators appearing within the same response were not treated as connected unless the participant explicitly or clearly described how one influenced, enabled, constrained or created a requirement for the other.

Direction was assigned from the participant's wording. Where an architectural or building-system condition was described as influencing an operational condition or outcome, the connection was represented as architecture → operational efficiency. Where an operational requirement was described as creating or modifying a requirement for the built environment, the connection was represented as operational efficiency → architecture.

Each connection was first recorded at participant level. Where the same directed connection appeared independently across more than one participant, the contributing participant IDs and participant count were recorded. Repeated instances of the same directed connection were therefore distinguishable from unique connections across the dataset.

Technology-related statements were retained where they explained or enabled the interaction between architectural and operational conditions. Technology was not treated as a separate analytical domain. Sustainability-related and passenger-facing consequences were retained only where participants directly linked them to architecture or operational efficiency conditions. Passenger experience was not analysed independently in this study.

3. Results

3.1. Sub-Indicator-Level Results

The architecture and operational efficiency dataset contained 789 coded statements from 20 participants. Of the 267 literature-derived architecture and operational efficiency sub-indicators available for coding, 162 were identified in at least one participant response. Architecture accounted for 279 coded statements across 69 sub-indicators, while operational efficiency accounted for 510 coded statements across 93 sub-indicators.

After repeated references to the same exact sub-indicator by the same participant were reduced to the highest score, the participant–sub-indicator matrix contained 613 populated combinations. Of these, 3 were classified as Score 1, 43 as Score 2, 73 as Score 3, 419 as Score 4 and 75 as Score 5. Across all 613 participant–sub-indicator combinations, the mean score was 3.85.

Participant recurrence varied across the 162 identified sub-indicators. Architecture sub-indicators were identified by an average of 3.22 participants, while operational efficiency sub-indicators were identified by an average of 4.20 participants. Seventy-three sub-indicators were identified by only one or two participants. The most widely recurring sub-indicators were resource allocation (ED 3), identified by 13 participants; predictive

maintenance tools (AFM 1), identified by 12 participants; sensors and IoT devices (SEM 1), identified by 11 participants.

For the sub-indicator classification, all Scores 1–5 were included when calculating the mean for each sub-indicator. Participant contributions were separated into support from the relevant architecture or operational efficiency domain cohort and contributions from participants outside that cohort. The mean score and domain participant support were then used to group the 162 identified sub-indicators into the four categories described in Section 2.3.3.

3.2. Classification of the Identified Sub-Indicators

The classification described in Section 2.3.3 was applied separately to the architecture and operational efficiency sub-indicators. Classification was based on the mean score and participant support within the relevant domain cohort. Contributions from participants outside the relevant domain cohort were recorded separately as other-domain contributions.

Of the 162 identified sub-indicators, 24 were classified as broadly supported, comprising 14 architecture and 10 operational Efficiency sub-indicators. A further 17 were classified as moderately supported, comprising 11 architecture and six operational efficiency sub-indicators. The largest group contained 111 context-specific sub-indicators, comprising 37 architecture and 74 operational efficiency sub-indicators.

The remaining 10 sub-indicators, comprising seven architecture and three operational efficiency sub-indicators, had mean scores of 2.5 or lower and were classified as below inclusion threshold. These items are retained in Table 9 for transparency but were not carried forward into the final analytical set. The final analytical set therefore comprised 152 sub-indicators.

Table 9 presents the complete classification of all 162 identified sub-indicators. The table reports the contributing participant IDs, domain participant support, other-domain contributions and mean score. A tick identifies the category assigned to each sub-indicator.

3.3. Architecture–Operational Efficiency Connections

The cross-domain analysis identified 23 participant-level connection occurrences between architecture and operational efficiency. After repeated instances of the same directed sub-indicator pair across participants were counted once, these represented 19 unique cross-domain connections. Eleven of the 20 participants contributed at least one cross-domain connection. The 23 occurrences came from two architecture participants (six occurrences), three operations participants (five), four technology participants (nine) and two cross-domain participants (three). These are counts of recorded directed connections, not measures of their operational effect. Sixteen of the 19 unique directed pairs were reported by one participant, two by two participants and one by three participants. Accordingly, the network depicts reported dependencies and should not be interpreted as a causal model or as a ranking of relationship strength.

Connections occurred in both directions. Thirteen participant-level occurrences represented architecture → operational efficiency connections and reduced to 11 unique directed connections. Ten participant-level occurrences represented operational efficiency → architecture connections and reduced to eight unique directed connections. Table 10 summarises these results.

Table 11 presents the 19 unique cross-domain connections individually. Each row represents one directed connection between an architecture and operational efficiency sub-indicator. The participant count indicates how many participants independently identified the same directed connection.

Table 9. Classification of the 162 identified architecture and operational efficiency sub-indicators.

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Architecture	SE 1	Natural light	P01, P02, P10	2/4	1	4.00		✓		
Architecture	SE 3	HVAC systems	P01, P02, P13, P14	2/4	2	3.50		✓		
Architecture	SE 4	Smart lighting	P16, P17	2/4	0	4.00		✓		
Architecture	SR 1	Solar panels on roofs	P06, P09, P11, P12, P18, P19	0/4	6	3.67			✓	
Architecture	SR 2	Wind turbines	P06, P11	0/4	2	3.00			✓	
Architecture	SR 3	Geothermal energy	P11, P13	0/4	2	3.00			✓	
Architecture	SR 4	Energy storage	P06, P12, P13, P14, P18, P19	0/4	6	3.33			✓	
Architecture	SR 5	Power-grid integration	P13, P14	0/4	2	3.00			✓	
Architecture	SG 1	Plant selection	P01, P13	1/4	1	4.00			✓	
Architecture	SG 4	Native or adaptive species	P01	1/4	0	2.00				✓
Architecture	SG 5	Regular maintenance	P16, P17	2/4	0	4.00		✓		
Architecture	SEF 1	Use of recycled or recyclable materials	P16, P17	2/4	0	2.50				✓
Architecture	SEF 3	Locally sourced materials	P02	1/4	0	2.00				✓
Architecture	SEF 4	Waste management during construction	P02, P16, P17	3/4	0	4.00	✓			
Architecture	SEF 5	Long-term maintenance and replacement plans	P01, P16, P17	3/4	0	4.00	✓			
Architecture	EAB 2	Thermal comfort design	P01, P02, P16, P17	4/4	0	4.25	✓			
Architecture	EAB 3	Natural lighting optimisation	P01, P02, P16, P17	4/4	0	4.00	✓			
Architecture	EC 1	Water recycling systems	P09, P11, P12, P13, P14, P18, P19	0/4	7	3.43			✓	
Architecture	EC 2	Rainwater harvesting	P11, P12, P18, P19	0/4	4	4.00			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Architecture	EC 3	Drought-resistant landscaping	P01, P02, P13, P16, P17	4/4	1	3.80	✓			
Architecture	ECC 1	Carbon capture technologies	P06, P11, P18, P19	0/4	4	3.00			✓	
Architecture	ECC 2	Carbon storage solutions	P13, P14	0/4	2	3.50			✓	
Architecture	ECC 3	Carbon offsetting programmes	P06, P09, P12, P13, P18, P19	0/4	6	4.67			✓	
Architecture	EW 1	Recycling programmes	P09	0/4	1	3.00			✓	
Architecture	EW 3	Waste reduction policies	P14	0/4	1	2.00				✓
Architecture	EH 1	Smart HVAC systems	P01, P09, P13	1/4	2	3.00			✓	
Architecture	EH 2	Energy efficiency	P09	0/4	1	4.00			✓	
Architecture	EAE 1	IoT-based energy management	P01, P07	1/4	1	4.00			✓	
Architecture	AM 1	Interchangeable components	P01, P02, P03	2/4	1	3.33		✓		
Architecture	AM 2	Scalable structure	P01, P02, P16, P17	4/4	0	4.25	✓			
Architecture	AM 3	Prefabricated modules	P01, P02, P03, P16, P17	4/4	1	4.00	✓			
Architecture	AT 1	Multi-purpose spaces	P02, P03, P16, P17	3/4	1	4.00	✓			
Architecture	AT 2	Flexible layouts	P01, P02, P03, P09, P12, P13, P16, P17	4/4	4	4.12	✓			
Architecture	AD 2	Flood-resistant design	P02, P03, P14	1/4	2	4.00			✓	
Architecture	AES 1	Clear signage	P01, P02, P03	2/4	1	3.00		✓		
Architecture	AES 2	Accessible escape routes	P16, P17	2/4	0	4.00		✓		
Architecture	AR 1	Redundant communication channels	P01	1/4	0	4.00			✓	
Architecture	AR 2	Emergency alert systems	P03	0/4	1	4.00			✓	
Architecture	AEP 1	On-site power generation	P05	0/4	1	4.00			✓	
Architecture	ST 1	AI and machine learning	P03, P07, P08, P09, P16, P18, P19, P20, P21	1/4	8	4.44			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Architecture	ST 2	Integration of IoT devices	P01, P02, P03, P09, P10, P12	2/4	4	4.17		✓		
Architecture	ST 3	Real-time data processing and analytics	P03, P04, P06, P07, P17, P20, P21	1/4	6	4.29			✓	
Architecture	SI 1	Energy-efficient design	P01, P02, P16, P17	4/4	0	4.00	✓			
Architecture	SI 3	Integration of IoT devices - facade	P01	1/4	0	4.00			✓	
Architecture	SS 2	Integration of advanced surveillance technologies	P04	0/4	1	4.00			✓	
Architecture	SS 3	Use of biometric identification	P01, P07, P16	2/4	1	3.67		✓		
Architecture	SC 1	Digital signage and displays	P01, P02, P03, P11, P16, P17	4/4	2	4.00	✓			
Architecture	SC 2	Real-time information systems	P01, P02, P03, P07, P09, P16, P17, P21	4/4	4	3.88	✓			
Architecture	SC 3	Mobile and web-based communication	P04, P05	0/4	2	4.50			✓	
Architecture	SEM 1	Sensors and IoT devices	P01, P03, P06, P07, P08, P09, P10, P14, P16, P17, P21	3/4	8	4.27	✓			
Architecture	SEM 2	Energy management systems	P01, P09, P13	1/4	2	3.67			✓	
Architecture	SEM 3	Data analytics	P09, P16	1/4	1	4.00			✓	
Architecture	SA 2	Use of VR for immersive entertainment or training	P09, P13	0/4	2	4.00			✓	
Architecture	EL 1	Smart lighting	P01, P02	2/4	0	4.00		✓		
Architecture	EM 1	Sustainable materials	P01, P02, P09	2/4	1	4.00		✓		
Architecture	CA 1	Harmony with environment	P02	1/4	0	4.00			✓	
Architecture	CL 2	Cultural symbols	P02	1/4	0	4.00			✓	
Architecture	CL 3	Traditional motifs	P02, P16, P17	3/4	0	3.00	✓			
Architecture	AA 1	Unique design elements	P02	1/4	0	3.00			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Architecture	AA 2	Historical references	P02	1/4	0	4.00			✓	
Architecture	AI 2	Adaptability	P01, P12, P13	1/4	2	3.67			✓	
Architecture	EMT 1	Availability of different transport modes	P01	1/4	0	2.00				✓
Architecture	EMT 2	Connectivity between modes	P01, P13	1/4	1	4.00			✓	
Architecture	EMT 3	Frequency of service	P13	0/4	1	2.00				✓
Architecture	EG 1	Electric vehicle charging stations	P09, P14	0/4	2	4.00			✓	
Architecture	EG 4	Shuttle services	P14	0/4	1	2.00				✓
Architecture	ECF 1	Efficiency of cargo handling operations	P05, P09, P12, P13, P14, P18, P19	0/4	7	4.00			✓	
Architecture	ECF 2	Integration with customs and security processes	P06, P09, P12, P14, P18, P19	0/4	6	4.00			✓	
Architecture	ECF 3	Use of technology in cargo handling	P09, P12	0/4	2	4.00			✓	
Operational Efficiency	AAV 1	Extended operating efficiency	P07, P20	0/9	2	3.00			✓	
Operational Efficiency	AAV 2	Safety	P07, P21	0/9	2	4.00			✓	
Operational Efficiency	ARP 1	Operational efficiency	P04, P07, P20, P21	0/9	4	3.75			✓	
Operational Efficiency	AS 1	Self-service smart kiosks	P01, P02, P06, P07, P09, P12, P16, P17, P20, P21	3/9	7	4.00			✓	
Operational Efficiency	AS 2	Reduced wait times	P04, P06, P07, P11, P20, P21	2/9	4	3.50			✓	
Operational Efficiency	AAS 1	Baggage identification	P10	1/9	0	4.00			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	AAS 2	Destination sorting	P09	1/9	0	2.00				✓
Operational Efficiency	AAS 3	Priority handling	P14	1/9	0	4.00			✓	
Operational Efficiency	AE 1	Biometric verification	P01, P07, P08, P09, P13, P14, P20, P21	3/9	5	3.75			✓	
Operational Efficiency	AMC 1	Remote check-in capability	P05, P07, P14, P18, P21	2/9	3	3.80			✓	
Operational Efficiency	AMC 3	Real-time notifications	P05, P07	0/9	2	4.00			✓	
Operational Efficiency	DB 3	Variety	P03	0/9	1	5.00			✓	
Operational Efficiency	DB 4	Veracity	P03, P07, P13, P14, P18	3/9	2	4.40			✓	
Operational Efficiency	DB 5	Value	P01, P07	0/9	2	3.50			✓	
Operational Efficiency	DP 3	Time series analysis	P07	0/9	1	4.00			✓	
Operational Efficiency	DMA 1	User engagement	P07	0/9	1	4.00			✓	
Operational Efficiency	DD 1	User authentication	P07, P14, P17, P20, P21	1/9	4	3.80			✓	
Operational Efficiency	DD 2	Access control	P02, P08	0/9	2	3.50			✓	
Operational Efficiency	DC 2	Service availability	P13, P21	1/9	1	4.00			✓	
Operational Efficiency	DC 3	Data security	P09, P10	2/9	0	3.00			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	DII 1	Device connectivity	P01, P02, P04, P06, P09, P18, P20	3/9	4	3.86			✓	
Operational Efficiency	DII 2	Data collection	P04, P07, P08, P09, P11, P14, P18, P20	4/9	4	4.12			✓	
Operational Efficiency	DII 3	Utility optimisation	P01, P08, P09	1/9	2	4.00			✓	
Operational Efficiency	EE 1	Energy consumption	P01, P07, P09, P10, P12, P13	4/9	2	4.17			✓	
Operational Efficiency	EE 2	Fuel consumption	P11	1/9	0	4.00			✓	
Operational Efficiency	EE 4	HVAC efficiency	P01, P09, P13, P19	3/9	1	3.00			✓	
Operational Efficiency	EE 5	Renewable energy share	P01, P09, P13	2/9	1	4.00			✓	
Operational Efficiency	ED 1	Gate allotment	P06, P09, P11, P12, P13, P14, P19	7/9	0	4.00	✓			
Operational Efficiency	ED 2	Turnaround time	P03, P06, P09, P11, P12, P13, P14, P18	7/9	1	3.62	✓			
Operational Efficiency	ED 3	Resource allocation	P02, P03, P06, P07, P09, P11, P12, P14, P16, P18, P19, P20, P21	7/9	6	4.00	✓			
Operational Efficiency	SB 1	Facial recognition	P03, P07, P08	0/9	3	4.00			✓	
Operational Efficiency	SB 2	Fingerprint analysis	P07	0/9	1	3.00			✓	
Operational Efficiency	STD 3	Advanced imaging technology	P12	1/9	0	4.00			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	STD 4	Cybersecurity measures	P01, P07, P08, P09, P13, P14, P19, P20, P21	4/9	5	3.56			✓	
Operational Efficiency	SER 1	Evacuation procedures	P05	0/9	1	4.00			✓	
Operational Efficiency	SER 3	Fire suppression systems	P05, P14	1/9	1	4.00			✓	
Operational Efficiency	AP 1	Queue management services	P07, P09, P11, P12, P13, P18, P19, P20	6/9	2	4.38		✓		
Operational Efficiency	AP 2	Biometric identification process	P07, P14	1/9	1	3.50			✓	
Operational Efficiency	AP 3	Dynamic signage and way-finding	P01, P02, P03, P06, P11, P13, P14	4/9	3	3.14			✓	
Operational Efficiency	AF 1	Gate assignment efficiency	P07, P09, P14, P18, P19	4/9	1	3.60			✓	
Operational Efficiency	AF 2	Aircraft sequencing	P06, P09, P11, P18, P19	5/9	0	4.00		✓		
Operational Efficiency	ATR 2	Baggage tracking system	P06, P07, P09, P10, P11, P12, P13, P14, P18, P19	9/9	1	4.00	✓			
Operational Efficiency	AC 1	Stakeholder communication platform	P03, P06, P09, P12, P14, P18, P19, P20	6/9	2	4.00		✓		
Operational Efficiency	AC 2	Weather adaptation strategies	P13	1/9	0	4.00			✓	
Operational Efficiency	AC 3	Emergency response coordination	P05	0/9	1	5.00			✓	
Operational Efficiency	ER 1	Runway capacity	P14	1/9	0	4.00			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	ER 2	Pavement quality	P14	1/9	0	4.00			✓	
Operational Efficiency	ER 3	Lighting and markings	P08, P10	1/9	1	5.00			✓	
Operational Efficiency	ET 1	Taxiway throughput	P13, P14	2/9	0	4.00			✓	
Operational Efficiency	ET 2	Surface detection equipment	P09, P12	2/9	0	4.00			✓	
Operational Efficiency	EAR 1	Cargo processing speed	P09, P13, P14	3/9	0	3.33			✓	
Operational Efficiency	EAR 3	Cargo handling equipment	P13, P19	2/9	0	4.00			✓	
Operational Efficiency	EAG 1	Towing time reduction	P13, P18, P19	3/9	0	4.00			✓	
Operational Efficiency	EGT 1	Vehicle flow optimisation	P09, P11, P12, P13, P14, P18, P19	7/9	0	4.00	✓			
Operational Efficiency	EGT 2	Ground traffic safety measures	P05, P08, P09, P11, P12, P13, P14, P18, P19	7/9	2	4.11	✓			
Operational Efficiency	EGT 3	Ground traffic communication systems	P11	1/9	0	4.00			✓	
Operational Efficiency	EGT 4	Ground traffic control personnel	P11	1/9	0	4.00			✓	
Operational Efficiency	EAA 1	Conflict detection algorithms	P09	1/9	0	4.00			✓	
Operational Efficiency	EAA 2	Arrival/departure efficiency	P06, P09, P13, P14, P18, P19	6/9	0	4.00		✓		

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	EST 1	Dynamic routing flexibility	P06, P09, P12, P19	4/9	0	3.75			✓	
Operational Efficiency	EST 2	Taxiway lighting systems	P09	1/9	0	2.00				✓
Operational Efficiency	EWM 2	Shift coverage effectiveness	P06, P07, P09, P11, P12, P13, P14, P18, P19	8/9	1	3.89	✓			
Operational Efficiency	EWM 4	Staff turnover rates	P11, P18, P19	3/9	0	3.33			✓	
Operational Efficiency	AFM 1	Predictive maintenance tools	P03, P06, P07, P08, P09, P10, P11, P12, P13, P14, P18, P19	9/9	3	4.58	✓			
Operational Efficiency	AFM 2	Automated fault detection	P03, P04, P07, P08, P09, P10, P17, P18, P19	4/9	5	4.22			✓	
Operational Efficiency	EA 1	Tracking accuracy	P11	1/9	0	3.00			✓	
Operational Efficiency	EA 2	Maintenance schedule	P06, P07, P08, P11	2/9	2	3.75			✓	
Operational Efficiency	EA 3	Utilisation monitoring	P06, P07, P09, P11, P12, P13, P18, P19	7/9	1	4.00	✓			
Operational Efficiency	ARC 1	Sales data analysis tools	P06, P13	2/9	0	4.00			✓	
Operational Efficiency	ARC 2	Customer experience enhancement	P01, P09, P11, P12, P13, P14, P18, P19	7/9	1	4.00	✓			
Operational Efficiency	ARC 3	Digital payment options integration	P06, P11, P18, P19	4/9	0	3.75			✓	
Operational Efficiency	OK 1	Passenger wait times	P03, P11, P12, P13, P14, P18, P19	6/9	1	4.43		✓		

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	OK 2	Baggage handling efficiency	P12, P13, P14	3/9	0	3.00			✓	
Operational Efficiency	OK 3	Flight on-time performance	P03, P05, P11, P13	2/9	2	2.50				✓
Operational Efficiency	OK 4	Security screening effectiveness	P07, P09, P11, P13, P14	4/9	1	3.60			✓	
Operational Efficiency	OD 1	Real-time passenger flow	P03, P09	1/9	1	3.50			✓	
Operational Efficiency	OP 1	Trend analysis over time	P07, P11, P14	2/9	1	3.33			✓	
Operational Efficiency	OP 2	Comparative benchmarking	P01, P02, P03, P04, P06, P07, P12, P14, P19	4/9	5	3.89			✓	
Operational Efficiency	OP 3	Root cause analysis for delays or failures	P07, P08	0/9	2	3.50			✓	
Operational Efficiency	OR 1	New technology pilot and trial result matrix	P07, P13, P14, P16, P17, P18, P19, P21	4/9	4	4.25			✓	
Operational Efficiency	OR 3	Investment returns on R&D projects	P03	0/9	1	4.00			✓	
Operational Efficiency	OI 3	Success rate of innovations implemented in airport operations	P04, P08, P14	1/9	2	4.33			✓	
Operational Efficiency	OT 1	Rate of implementation of new technology	P02, P03, P04, P05, P08, P19	1/9	5	4.17			✓	
Operational Efficiency	OT 3	User satisfaction rating with newly adopted technologies	P13, P18, P19, P20, P21	3/9	2	3.60			✓	
Operational Efficiency	ORA 1	Threat identification	P01, P02, P04, P09, P20, P21	1/9	5	3.50			✓	

Table 9. *Cont.*

Domain	Code	Sub-Indicator	Participant IDs	Domain Support	Other-Domain *n*	Mean	Broadly Supported	Moderately Supported	Context-Specific	Below Inclusion Threshold
Operational Efficiency	ORA 5	Control effectiveness	P01, P21	0/9	2	3.50			✓	
Operational Efficiency	OC 1	Regulatory adherence tracking	P01, P02, P04, P09, P11	2/9	3	3.80			✓	
Operational Efficiency	OC 3	Audit trail maintenance	P08, P14	1/9	1	3.00			✓	
Operational Efficiency	OC 4	Change management oversight	P03, P08, P11, P13, P14, P18, P19	5/9	2	4.00		✓		
Operational Efficiency	OIM 1	Incident detection	P01, P05, P07, P09, P11, P13	3/9	3	3.50			✓	
Operational Efficiency	OIM 2	Response coordination	P01, P05, P09, P12, P13	3/9	2	2.80			✓	
Operational Efficiency	OIM 3	Recovery planning	P01, P08, P11, P18, P19	3/9	2	4.00			✓	
Operational Efficiency	OIM 4	Lessons learned analysis	P01, P11	1/9	1	4.00			✓	
					Total sub-indicators		**24**	**17**	**111**	**10**
					Total identified			**162**		

Note: Domain support is based on the relevant architecture or operational efficiency cohort. Other-domain *n* records participants outside the relevant domain cohort. A tick identifies the category assigned to each sub-indicator. *Source:* Authors' own work.

Table 10. Summary of cross-domain architecture–operational efficiency connections.

Direction	Participant-Level Occurrences	Unique Connections
Architecture → Operational Efficiency	13	11
Operational Efficiency → Architecture	10	8
Total	**23**	**19**

Note: Repeated instances of the same directed sub-indicator pair across participants were counted once in the unique-connection total. *Source: Authors' own work.*

Table 11. Unique cross-domain architecture–operational efficiency connections.

Source Domain	Source Sub-Indicator	Direction	Destination Sub-Indicator	Destination Domain	Participants (n)
Architecture	Real-time data processing and analytics (ST 3)	→	Resource allocation (ED 3)	Operational Efficiency	3
Architecture	Real-time data processing and analytics (ST 3)	→	Turnaround time (ED 2)	Operational Efficiency	1
Architecture	Real-time data processing and analytics (ST 3)	→	Trend analysis over time (OP 1)	Operational Efficiency	1
Architecture	AI and machine learning (ST 1)	→	Resource allocation (ED 3)	Operational Efficiency	1
Architecture	AI and machine learning (ST 1)	→	Queue management services (AP 1)	Operational Efficiency	1
Architecture	IoT-based energy management (EAE 1)	→	Energy consumption (EE 1)	Operational Efficiency	1
Architecture	Energy management systems (SEM 2)	→	Energy consumption (EE 1)	Operational Efficiency	1
Architecture	Sensors and IoT devices (SEM 1)	→	Utility optimisation (DII 3)	Operational Efficiency	1
Architecture	Sensors and IoT devices (SEM 1)	→	Passenger wait times (OK 1)	Operational Efficiency	1
Architecture	Sensors and IoT devices (SEM 1)	→	Facial recognition (SB 1)	Operational Efficiency	1
Architecture	Multi-purpose spaces (AT 1)	→	Passenger wait times (OK 1)	Operational Efficiency	1
Operational Efficiency	Data collection (DII 2)	→	Real-time data processing and analytics (ST 3)	Architecture	1
Operational Efficiency	Veracity (DB 4)	→	AI and machine learning (ST 1)	Architecture	1
Operational Efficiency	Resource allocation (ED 3)	→	AI and machine learning (ST 1)	Architecture	1
Operational Efficiency	Device connectivity (DII 1)	→	Energy management systems (SEM 2)	Architecture	1
Operational Efficiency	Renewable energy (EE 5)	→	Energy management systems (SEM 2)	Architecture	2
Operational Efficiency	Renewable energy (EE 5)	→	Smart HVAC systems (EH 1)	Architecture	2
Operational Efficiency	Self-service smart kiosks (AS 1)	→	Flexible layouts (AT 2)	Architecture	1
Operational Efficiency	Threat identification (ORA 1)	→	Plant selection (SG 1)	Architecture	1

Note: Participant count indicates recurrence of the same directed connection across participants. *Source: Authors' own work.*

Three of the nineteen unique connections were identified independently by more than one participant. Real-time data processing and analytics (ST 3) → resource allocation (ED 3) was identified in three participant records (P07, P20 and P21). Renewable energy (EE 5) → energy management systems (SEM 2) and renewable energy (EE 5) → smart HVAC systems (EH 1) were each identified in two participant records (P09 and P13). The remaining 16 unique connections were identified in one participant record each. These recurrence counts describe how the connections were distributed within the interview dataset and are not interpreted as measures of relative importance or causal magnitude.

3.4. Airport Development Contexts

A contextual distinction emerged between new and transitioning airports. Six participants (P01, P03, P04, P09, P12 and P14) described differences in the conditions surrounding smart-airport development in these two settings.

In new-airport contexts, participants described greater opportunity to incorporate spatial flexibility, infrastructure capacity, digital integration and future expansion into the initial design. Spatial layouts, service routes, structural systems and technology infrastructure could therefore be planned around anticipated operational and digital requirements from the outset. In transitioning airports, participants described the need to work within fixed spatial conditions, existing building systems, legacy technologies and the requirement to maintain live airport operations during change.

Participants emphasised different aspects of this distinction according to their areas of experience. Architecture-focused responses referred to adaptable spatial arrangements and building infrastructure capable of accommodating future change. Operations-focused responses referred to the effects of existing geometry and capacity, including remote stands, towing, buffer time and altered operating procedures. Technology-focused responses referred to the difficulties of introducing new digital systems into existing environments, including cabling, power, interfaces, communications infrastructure and legacy-system compatibility.

These findings indicate different development and adaptation conditions rather than a hierarchy between new and transitioning airports. New airports allow physical and digital requirements to be incorporated during initial planning, whereas transitioning airports must accommodate smart-airport requirements within existing spatial, technical and operational constraints.

3.5. Technology, Sustainability and Passenger-Facing Consequences

The architecture–operational efficiency connections also showed how technology, sustainability and passenger-facing consequences were positioned within smart-airport development. Technology appeared as an enabling layer linking architectural conditions with operational activities. Sensors, IoT devices, data collection, real-time analytics and AI-supported applications were identified in several of the direct cross-domain connections reported in Section 3.3. Their role was most apparent where information generated through the physical airport environment supported maintenance, resource allocation and other operational activities.

Participants distinguished the presence of technology from its operational use. Data were described as useful where they supported a defined operational purpose, while consistency, veracity and system integration affected whether information could be applied effectively. Technology was therefore described through the collection, processing and use of information rather than through the presence of individual technologies alone.

Technology also created requirements for the physical airport environment. Two participants described IoT integration as requiring provision for sensors, cabling, power, communications infrastructure and maintenance access. These requirements were particularly relevant in transitioning airports, where existing spatial and infrastructure conditions could constrain the introduction of new digital systems. Digital systems therefore depended on suitable physical infrastructure, while new digital requirements could also create a need for changes to existing airport infrastructure.

Sustainability-related outcomes were described through the combined effects of building design, operational management and technology-enabled control. Participant statements connected these outcomes with energy efficiency, renewable-energy integration, energy-management systems, water management, asset replacement, operational resilience

and emissions reduction. Direct cross-domain connections included renewable energy (EE 5), energy management systems (SEM 2) and energy consumption (EE 1), while architecture sub-indicators also included IoT-based energy management (EAE 1) and other building-related environmental measures.

Participants also described sustainability outcomes as dependent on continued operation and maintenance rather than on the presence of individual systems alone. Renewable-energy and water-management systems were discussed in relation to maintainability, routine operational use and integration with wider airport systems. The interview findings therefore positioned sustainability as an outcome arising from combined architectural, operational and technology-related conditions rather than as a separate analytical domain.

Passenger-facing consequences were reported only where participants explicitly connected architecture or operational efficiency conditions with passenger outcomes. These included reduced uncertainty through reliable information, improved navigation through adaptive signage, reduced waiting through more effective processing and spatial arrangements, and greater confidence where operational information remained consistent across channels. These findings are reported as consequences of the architecture–operational efficiency conditions identified in the interviews and do not constitute an independent analysis of passenger experience.

4. Discussion

4.1. Architecture and Operational Efficiency as Interdependent Conditions

The findings show that architecture and operational efficiency should not be considered as separate sets of airport conditions. The systematic literature review established the wider range of architecture and operational efficiency sub-indicators, while the interviews showed where participants directly connected architectural, building-system and operational conditions. The interviews were not intended to reproduce all 267 literature-derived sub-indicators, but to examine how these conditions were described in practice and how they interacted.

The sub-indicator-level analysis showed that response depth and participant recurrence were not the same measure. Some sub-indicators were identified across a relatively broad section of the relevant domain cohort, while others were identified by fewer participants but received more detailed responses. The classification therefore combined mean score and domain participant support. Of the 162 identified sub-indicators, 24 were classified as broadly supported, 17 as moderately supported and 111 as context-specific. These 152 sub-indicators formed the final analytical set. The remaining 10 sub-indicators fell below the inclusion threshold and were reported in Table 9 for transparency but were not carried forward into the final interpretation. The classification was used to distinguish patterns within the interview dataset rather than to rank sub-indicator importance.

The direct connection analysis further showed that architecture and operational efficiency operated in both directions. Eleven unique connections ran from architecture to operational efficiency, while eight ran from operational efficiency to architecture. Architectural conditions such as spatial flexibility, sensing infrastructure, building services and energy-management capability were described as influencing operational activities. Operational requirements relating to resource allocation, safety, technology integration and service needs were also described as creating or modifying requirements for the built environment. This two-way relationship is consistent with airport digital-integration research that treats physical assets, information systems and facilities-management processes as interconnected [8,10,15].

The direction of a connection should not be interpreted as evidence of causal magnitude or as a complete reciprocal relationship. The connections were based on participant

descriptions of how one condition influenced, enabled, constrained or created a requirement for another. In several cases, the same sub-indicator appeared in more than one connection. Real-time data processing and analytics (ST 3), AI and machine learning (ST 1), sensors and IoT devices (SEM 1), energy-management systems (SEM 2) and resource allocation (ED 3) illustrate how individual conditions could participate in several different architecture–operational efficiency interactions.

The most recurrent exact connection was real-time data processing and analytics (ST 3) → resource allocation (ED 3), which was identified independently by three participants. Renewable energy (EE 5) → energy-management systems (SEM 2) and renewable energy (EE 5) → smart HVAC systems (EH 1) were each identified by two participants. The remaining direct connections appeared in single participant records. These findings indicate that some connections recurred across participants, while others reflected more specialised experience. They should therefore be interpreted as direct connections identified within the interview dataset rather than as rankings of relative importance.

4.2. Technology as an Enabling Layer

Technology remained central to the architecture–operational efficiency connections but was most consistently positioned as an enabling layer rather than as a separate analytical domain. Sensors and IoT devices supported information capture, while data collection, real-time processing, analytics and AI-supported applications were connected with operational activities such as resource allocation, maintenance and decision support. This interpretation is consistent with smart-airport research in which IoT, integrated information systems and analytics support airport processes and decision-making [4,9,45].

The findings also indicate that the presence of technology alone does not produce an operational outcome. Participants distinguished between collecting information and using that information for a defined purpose. Data consistency, veracity, integration and accessibility affected whether information could be applied effectively across physical assets, digital systems and airport operations. Technology therefore operated through its interaction with architectural and operational conditions rather than independently of them.

Technology also created requirements for the physical airport environment. Sensors, communications systems and automated processes depended on power, cabling, equipment locations, network infrastructure, maintenance access and interfaces with existing building systems. These requirements were particularly relevant in transitioning airports, where existing spatial and infrastructure conditions could constrain the introduction of new digital systems. The built environment therefore supported digital capability, while digital requirements could also create a need for physical or infrastructure change.

This positioning has implications for how smart-airport capability is interpreted. Individual technologies should not be treated as complete indicators of capability where the supporting spatial, infrastructure or operational conditions are absent. A digitally advanced system may provide limited operational benefit if information is unreliable, systems remain disconnected, infrastructure is unsuitable or airport processes are unable to use the resulting information. Technology is therefore better understood through the architectural and operational functions that it enables.

4.3. New and Transitioning Airport Contexts

The distinction between new and transitioning airports represented an important contextual finding. Participants described new airports as providing greater opportunity to incorporate spatial flexibility, infrastructure capacity, service routes and digital systems during initial planning. Transitioning airports, by contrast, were described as having

to accommodate comparable capabilities within existing buildings, legacy systems and continuing airport operations.

These settings represent different development and adaptation conditions rather than different levels of smart-airport capability. A capability incorporated during the original design of a new airport may require retrofit, spatial adjustment, changes to existing building systems or operational workarounds in a transitioning airport. This interpretation is consistent with airport BIM and infrastructure research showing that existing physical conditions and operating environments influence how digital and built-environment capabilities are accommodated [8,10,29,46].

The participant responses also showed that these constraints operated across different areas of airport activity. Architecture-focused responses referred to adaptable spatial arrangements, service distribution and infrastructure capacity. Operations-focused responses described the effects of existing geometry, capacity and live-airport constraints. Technology-focused responses described compatibility with legacy systems and the physical requirements associated with cabling, power, communications and system interfaces. These perspectives describe different aspects of the same development context rather than separate analytical domains.

Participants described phased system migration, interface testing, parallel operation and rollback arrangements as ways of managing legacy-system dependencies while maintaining live airport operations. Table 12 provides selected statements from the interview records. Other considerations included data quality, power and communications capacity, maintenance access and cybersecurity. These statements describe implementation conditions and proposed approaches rather than independently measured outcomes.

Table 12. Selected participant statements on technology integration in transitioning airports.

Participant	Implementation Aspect	Participant Statement
P04	Staged rollout	"There's a lot of stage work that happens. There's a lot of planning and it takes a lot of time to do a staged rollout"
P18	Infrastructure constraints	"A new sensor network needs power communications mounting locations and maintenance access"
P18	Interface testing and changeover	"Prove the data exchange run old and new systems in parallel where necessary and have a rollback plan"
P19	Phased migration	"Migration has to be phased tested and reversible with staff trained on both old and new arrangements during the crossover"
P19	Legacy-system integration	"Sometimes an interface gateway or data layer is safer than modifying the core system"

Note: P04: C1Q13; P18 and P19: Operations Q13. Extracts retain the wording recorded in the source files, including transcription punctuation conventions. These statements are participant-reported constraints and approaches, not independently assessed outcomes.

The findings therefore support treating development context as a condition influencing how smart-airport capability is implemented. The same functional requirement may be achieved through different combinations of spatial design, technology and operating procedures. New airports may incorporate those requirements during initial planning, whereas transitioning airports may achieve them through adaptation, retrofit or revised operating arrangements.

The findings also reinforce the importance of long-term adaptability. Airport infrastructure must accommodate technological and operational change over time. Spatial arrangements, service capacity, accessible infrastructure and maintainable building systems can therefore affect the ability of an airport to respond to later requirements. Smart-airport

architecture should consequently provide capacity for future technological and operational change rather than being designed only around current systems.

4.4. Implications for Smart Airport Transformation

The findings suggest that smart-airport assessment should consider both the characteristics of individual sub-indicators and the direct connections between them. The literature-derived sub-indicators identify relevant architectural and operational conditions, while the interviews show how these conditions vary in response depth, domain participant support and cross-domain interaction. An assessment approach based only on isolated indicators may therefore overlook dependencies between built-environment, digital and operational systems.

For airport owners and operators, smart-airport capability should be considered in relation to the systems required to support it. Sensors and analytics, for example, depend on appropriate infrastructure, reliable information, system integration and the ability of operational teams to use the resulting outputs. Architectural decisions can also affect passenger flow, maintenance access, equipment provision, adaptability and building-system performance. Considering these connections may reveal constraints that are less visible when building, operational and digital systems are assessed separately.

For architects, planners, asset managers and facilities-management teams, the findings highlight the operational consequences of spatial and building-system decisions. Adaptable layouts, accessible services and sufficient infrastructure capacity can affect the ability of airport environments to accommodate future technologies and changing operational requirements. Operational requirements relating to maintenance, resource allocation, safety and live-airport change can, in turn, influence how architectural solutions are designed or modified.

Sustainability also emerged through this integrated structure. Participant statements connected energy management, renewable-energy integration, water management, asset management, resilience and operational efficiency with both architectural and operational conditions. This is consistent with airport sustainability research linking energy efficiency, infrastructure resilience and resource management [47–49]. Sustainability is therefore better understood as an outcome influenced by decisions across building, asset, digital and operational systems rather than as an isolated smart-airport domain.

Passenger-facing consequences require a narrower interpretation because passenger experience was not independently evaluated within the present analysis. Participants nevertheless described outcomes associated with information reliability, navigation, waiting and operational consistency. These observations are consistent with research connecting passenger satisfaction with facilities, service processes, information quality and digitally enabled services [21,22,50,51]. They should therefore be interpreted as consequences of the architecture–operational efficiency conditions identified in the interviews rather than as an independent assessment of passenger experience.

The connection from threat identification (ORA 1) to plant selection (SG 1) concerns the aviation-safety risk of landscaping that attracts birds or insects. Participant P01 described the need to coordinate plant selection with aviation safety specialists. This is an operational constraint on a design choice, not a general relationship between security threats and landscaping.

The study therefore contributes a structured account of how architecture and operational efficiency interact within smart-airport transformation. It classifies the 162 identified sub-indicators according to mean score and domain participant support, retains 152 for final interpretation, identifies direct cross-domain connections and shows how these connections are shaped by technology and development context. Together, these findings provide a

clearer basis for understanding smart-airport transformation as an interaction between physical, digital and operational conditions rather than as a set of isolated capabilities.

4.5. Limitations and Future Research

Several limitations should be considered when interpreting the findings. The ethics approval permitted a maximum of 20 interviews. The study involved 20 participants with different areas of airport experience. The participant sample was purposively selected to obtain knowledge of architecture, operational efficiency and technology-enabled airport systems rather than to achieve statistical representation of a wider population. The findings should therefore be interpreted within the context of this qualitative sample.

The semi-structured interview design also meant that participants did not receive identical specialist question sets. Questions were selected according to the participant's area of experience, and responses developed according to individual knowledge and practice. The absence of a sub-indicator from one participant's response should therefore not be interpreted as indicating that the participant considered it unimportant or disagreed with it. Similarly, a connection identified in only one participant record may reflect specialist experience or differences in question exposure.

The five-point scoring system described increasing levels of directness, explanation and practical detail within participant responses. These scores should not be interpreted as measures of sub-indicator importance, agreement or causal magnitude. All Scores 1–5 were included when calculating the mean for each sub-indicator, while domain participant support described how widely each sub-indicator occurred within the relevant architecture or operational efficiency cohort.

The classification combined mean score and domain participant support to distinguish broadly supported, moderately supported and context-specific sub-indicators. Sub-indicators with mean scores of 2.5 or lower were classified as below inclusion threshold and were reported for transparency but were not carried forward into the final analytical set. The classification should therefore be interpreted as a descriptive grouping within this interview dataset rather than as formal consensus, a population-level estimate or a universal measure of smart-airport performance.

The mean was used as a simple summary of the participant scores for each sub-indicator. The threshold of 2.5 was used to distinguish sub-indicators whose responses, on average, extended beyond direct reference alone. The 75% and 50% domain-support thresholds were used to distinguish broader and narrower recurrence within the relevant domain cohort. These thresholds were defined for the present analysis and should not be interpreted as universal standards.

The interviews covered only part of the literature-derived architecture and operational efficiency structure. Of the 267 available sub-indicators, 162 were identified in at least one participant response, of which 152 were retained in the final analytical set. The absence of the remaining literature-derived sub-indicators should not be interpreted as evidence that they are invalid or unimportant because coverage depended on participant background, question allocation and the direction of individual responses. Passenger experience was also outside the primary architecture–operational efficiency analysis, so the passenger-facing consequences reported here remain contextual observations rather than an independent assessment of that domain.

The analysis involved researcher coding, supervisory review of uncertain classifications, participant-level scoring and separate examination of direct cross-domain connections. Where the same participant referred to the same sub-indicator more than once, the highest score was used. Repeated instances of the same directed connection across participants were consolidated when identifying unique connections. These procedures

provided a consistent basis for analysis but do not remove the interpretive limitations associated with qualitative interview research.

Future research could examine the retained sub-indicators and architecture–operational efficiency connections using larger and differently composed participant samples across other geographic regions, airport sizes and organisational settings. Comparative studies could examine whether similar patterns of participant support and cross-domain connection occur in other airport contexts. Longitudinal and case-based research may also examine how architecture–operational efficiency connections change as airports introduce new technologies, modify existing infrastructure or transition between operational states.

5. Conclusions

This study examined how architecture and operational efficiency interact during smart-airport transformation, with technology treated as an enabling layer and new and transitioning airports considered as different development contexts. Drawing on semi-structured interviews with 20 participants, the analysis identified 162 architecture and operational efficiency sub-indicators within the interview dataset and examined their mean scores, domain participant support, other-domain contributions and direct architecture–operational efficiency connections.

The sub-indicator-level analysis grouped the 162 identified sub-indicators according to mean score and domain participant support. In total, 24 were classified as broadly supported, 17 as moderately supported and 111 as context-specific. These 152 sub-indicators formed the final analytical set. A further 10 sub-indicators fell below the inclusion threshold and were retained in the classification table for transparency but were not carried forward into the final interpretation. The categories describe patterns within the interview dataset and should not be interpreted as universal rankings of importance or formal expert consensus.

The direct connection analysis identified 23 participant-level architecture–operational efficiency connection occurrences, representing 19 unique cross-domain connections after repeated instances of the same directed pair were counted once. Eleven unique connections ran from Architecture to operational efficiency, while eight ran from operational efficiency to architecture. These findings describe participant-reported dependencies in both directions: operational requirements can create demands for the built environment, while architectural and building-system conditions can affect how operations are organised.

Technology was consistently positioned within these connections as an enabling layer rather than as a separate analytical domain. Sensors, IoT devices, data collection, real-time analytics and AI-supported applications were linked with activities such as resource allocation, maintenance and operational decision support. At the same time, digital systems depended on appropriate physical infrastructure, system integration and operational use. Technology therefore operated through its interaction with architectural and operational conditions rather than independently of them.

Development context also influenced how smart-airport capability was described. New airports were associated with greater opportunity to incorporate spatial flexibility, infrastructure capacity and digital systems during initial planning. Transitioning airports were associated with existing spatial conditions, legacy systems, infrastructure constraints and the need to maintain live airport operations during change. These settings therefore represent different implementation and adaptation conditions rather than different levels of smart-airport capability.

Sustainability emerged through the combined effects of architectural, operational, asset-management and technology-related conditions. Energy management, renewable-energy integration, water management, infrastructure resilience and operational efficiency

were described across participant responses. Passenger-facing consequences were also identified where architecture or operational efficiency conditions affected navigation, waiting, information reliability or passenger confidence. These observations remain contextual because passenger experience was not independently evaluated within the present analysis.

The study contributes a structured account of how architecture and operational efficiency sub-indicators are supported and connected within smart-airport transformation. For airport planners, designers, operators, asset and facilities teams and digital teams, the findings highlight the value of considering spatial, building-system, digital and operational dependencies together rather than as isolated conditions.

The findings should be interpreted within the boundaries of a qualitative interview study involving 20 participants with different areas of experience and non-identical specialist question sets. The scoring system and analytical thresholds were applied to support systematic comparison within this dataset and should not be interpreted as population-level measures or causal effects. Further research should examine whether similar sub-indicator patterns and architecture–operational efficiency connections occur across different airport sizes, geographic settings and stages of technological and infrastructure transition.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/buildings16214405/s1.

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Institutional Review Board Statement: The study was conducted in accordance with the Auckland University of Technology Code of Conduct for Research and was approved by the Auckland University of Technology Ethics Committee (AUTEC; Ethics Application 25/251, approved 30 September 2025).

Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The participant–sub-indicator scoring matrices are provided in Appendix A. Interview recordings and transcripts are not publicly available because they contain potentially identifiable qualitative information. These materials are stored securely, with access restricted in accordance with the conditions of the institutional ethics approval.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Participant–Sub-Indicator Scoring Matrices

The participant–sub-indicator matrices provide the detailed scoring records underlying the sub-indicator-level analysis reported in the main text. Each populated cell reports the highest score assigned to a participant for the exact sub-indicator. Blank cells indicate that the sub-indicator was not identified in that participant's response. The matrices are presented separately for architecture and operational efficiency to preserve readability.

Table A1 presents the architecture matrix, and Table A2 presents the operational efficiency matrix.

Table A1. Participant–sub-indicator scores for architecture sub-indicators.

Participant	SE 1	SE 3	SE 4	SR 1	SR 2	SR 3	SR 4	SR 5	SG 1	SG 4	SG 5	SEF 1	SEF 3	SEF 4	SEF 5	EAB 2	EAB 3	EC 1	EC 2	EC 3	ECC 1	ECC 2	ECC 3	EW 1	EW 3	EH 1	EH 2	EAE 1	AM 1	AM 2	AM 3	AT 1	AT 2	AD 2	AES 1	AES 2	AR 1	AR 2	AEP 1	ST 1	ST 2	ST 3	SI 1	SI 3	SS 2	SS 3	SC 1	SC 2	SC 3	SEM 1	SEM 2	SEM 3	SA 2	EL 1	EM 1	CA 1	CL 2	CL 3	AA 1	AA 2	AI 2	EMT 1	EMT 2	EMT 3	EG 1	EG 4	ECF 1	ECF 2	ECF 3
P01	4	4							4	2					5	4	4			4						2		4	3	4	4		5		3		4				4		4	4		4	4	4		4	5			4	4						5	2	4						
P02	4	4											2	4		5	4			4									4	4	4	4	4	4	2						5		4				4	4						4	4	4	4	2	3	4									
P03																													3		4	4	2	4	4			4		5	3	4					4	4		5																			
P04																																									4			4				5																					
P05																																						4											4																					4		
P06				4	4		4													3		4																					4								5																				4	
P07																											4													5		4				3		4		5																				
P08																																							5											5																				
P09				4														3						4	3		3	4						4						4	4								2		4	3	3	4		4													4		4	4	4
P10	4																																									4								2																				
P11				2	2	2											3	4		2																														3																									
P12				4			4											4	4				5										5								5																								3						4	4	4
P13		2				4	2	2	4								3		3		3	5			4							4																				3		4								3		4	2			4		
P14		4					2	4									3					4			2										4																	4															4	2	4	4	
P16			4								4	2		4	3	4	4			4										5	4	4	5			4				4			4			4	4	4		4		5						3											
P17			4								4	3		4	4	4	4			4										4	4	4	4			4						5	4				5	4		4								4											
P18				4			4											4	4		4		5																		4																																4	4	
P19				4			4											4	4		3		5																		4																																4	4	
P20																																							5		4																													
P21																																							4		5						5		5																				
n	**3**	**4**	**2**	**6**	**2**	**2**	**6**	**2**	**2**	**1**	**2**	**2**	**1**	**3**	**3**	**4**	**4**	**7**	**4**	**5**	**4**	**2**	**6**	**1**	**1**	**3**	**1**	**2**	**3**	**4**	**5**	**4**	**8**	**3**	**3**	**2**	**1**	**1**	**1**	**9**	**6**	**7**	**4**	**1**	**1**	**3**	**6**	**8**	**2**	**11**	**3**	**2**	**2**	**2**	**3**	**1**	**1**	**3**	**1**	**1**	**3**	**1**	**2**	**1**	**2**	**1**	**7**	**6**	**2**

Note: Each populated cell shows the highest score (1–5) assigned to that participant for the exact sub-indicator. Blank cells indicate that the sub-indicator was not identified in that participant response. The final row (*n*) reports the number of participants with a populated score for each sub-indicator. Sub-indicator codes correspond to the full names reported in Table 9 of the main text.

Table A2. Participant–sub-indicator scores for operational efficiency sub-indicators.

Participant	AAV 1	AAV 2	ARP 1	AS 1	AS 2	AAS 1	AAS 2	AAS 3	AE 1	AMC 1	AMC 3	DB 3	DB 4	DB 5	DP 3	DMA 1	DD 1	DD 2	DC 2	DC 3	DII 1	DII 2	DII 3	EE 1	EE 2	EE 4	EE 5	ED 1
P01				4					4					4							4		4	5		3	3	
P02				4														3			3							
P03												5	5															
P04			4		2																4	4						
P05										3	4																	
P06				4	4																4							4
P07	2	4	3	4	4				3	4	4		3	3	4	4	2					4		4				
P08									4									4				5	5					
P09				4			2		3											2	4	5	3	5		3	4	4
P10						4														4				4				
P11					3																	4			4			4
P12				4																				5				4
P13									4				5						4					2		2	5	4
P14								4	4	4			5				4					3						4
P16				4																								
P17				4													4											
P18										4			4								4	4						
P19																										4		4
P20	4		4	4	4				4								5				4	4						
P21		4	4	4	4				4	4							4		4									
n	**2**	**2**	**4**	**10**	**6**	**1**	**1**	**1**	**8**	**5**	**2**	**1**	**5**	**2**	**1**	**1**	**5**	**2**	**2**	**2**	**7**	**8**	**3**	**6**	**1**	**4**	**3**	**7**

Participant	ED 2	ED 3	SB 1	SB 2	STD 3	STD 4	SER 1	SER 3	AP 1	AP 2	AP 3	AF 1	AF 2	ATR 2	AC 1	AC 2	AC 3	ER 1	ER 2	ER 3	ET 1	ET 2	EAR 1	EAR 3	EAG 1	EGT 1	EGT 2	EGT 3	EGT 4	EAA 1	EAA 2	EST 1	EST 2
P01						2					4																						
P02		4									4																						
P03	4	4	4								4				4																		
P04																																	
P05							4	4									5										4						
P06	2	3									3		4	4	4																4	4	
P07		5	4	3		4			4	4		2		4																			
P08			4			4														5							5						
P09	3	3				4			4			4	4	4	5							4	3			4	4			4	4	3	2
P10														4						5													
P11	4	5							4		3		4	4												4	4	4	4				
P12	4	4			4				4					4	4							4				4	4					4	
P13	4					3			5		3			4		4					4		3	4	4	4	4				4		
P14	4	4				4		4		3	1	4		4	4			4	4		4		4			4	4				4		
P16		4																															
P17																																	
P18	4	4							5			4	4	4	5										4	4	4				4		
P19		4				4			4			4	4	4	2									4	4	4	4				4	4	
P20		4				3			5						4																		
P21		4				4																											
n	**8**	**13**	**3**	**1**	**1**	**9**	**1**	**2**	**8**	**2**	**7**	**5**	**5**	**10**	**8**	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**2**	**3**	**7**	**9**	**1**	**1**	**1**	**6**	**4**	**1**

Participant	EWM 2	EWM 4	AFM 1	AFM 2	EA 1	EA 2	EA 3	ARC 1	ARC 2	ARC 3	OK 1	OK 2	OK 3	OK 4	OD 1	OP 1	OP 2	OP 3	OR 1	OR 3	OI 3	OT 1	OT 3	ORA 1	ORA 5	OC 1	OC 3	OC 4	OIM 1	OIM 2	OIM 3	OIM 4
P01									4								4							4	3	5			3	2	2	4
P02																	4					4		5		3						
P03			5	4							5		3		4		4			4		5						4				
P04				4													4				4	5		1		4						
P05													2									4							4	4		
P06	4		5			4	4	4		3							4															
P07	4		4	5		4	4							2		4	4	3	5										3			
P08			5	5		5												4			4	3					4	3			5	
P09	4		4	4			4		4					4	3									3		4			4	3		
P10			5	4																												
P11	4	2	4		3	2	4		4	4	4		2	4		4										3		5	3		4	4
P12	4		5				4		4		4	4					3													2		
P13	4		4				4	4	4		5	1	3	4					4				4					4	4	3		
P14	3		5						4		5	4		4		2	4		5		5						2	4				
P16																			4													
P17				4															4													
P18	4	4	5	4			4		4	4	4								4				3					4			4	
P19	4	4	4	4			4		4	4	4						4		4			4	3					4			5	
P20																							4	4								
P21																			4				4	4	4							
n	**9**	**3**	**12**	**9**	**1**	**4**	**8**	**2**	**8**	**4**	**7**	**3**	**4**	**5**	**2**	**3**	**9**	**2**	**8**	**1**	**3**	**6**	**5**	**6**	**2**	**5**	**2**	**7**	**6**	**5**	**5**	**2**

Note: Each populated cell shows the highest score (1–5) assigned to that participant for the exact sub-indicator. Blank cells indicate that the sub-indicator was not identified in that participant response. The final row (*n*) reports the number of participants with a populated score for each sub-indicator. Sub-indicator codes correspond to the full names reported in Table 9 of the main text.

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