Organization of Passenger and Baggage Transportation by Air

monograph

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The monograph summarizes the theoretical foundations, regulatory requirements, and applied approaches to organizing the transportation of passengers and their baggage by air. Air transportation is considered as an integrated service process that combines booking and ticketing, passenger and baggage check-in, aviation security, ground handling, boarding, baggage loading and delivery, service for passengers with special needs, and action during flight disruptions. Particular attention is paid to passenger rights, baggage acceptance and tracing, interaction between airlines and airports, service quality, safety, digital technologies, and operational decision-making.

The publication is recommended as an educational and scientific source for students of specialty J6 "Aviation Transport", postgraduate students, academic staff, and specialists in passenger service, baggage handling, airport operations, airline management, aviation logistics, and ground handling. The materials may be used for coursework, qualification and master's theses, educational course development, applied calculations, and justification of managerial decisions in the organization of passenger and baggage transportation by air.

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ANNOTATION

The monograph presents a comprehensive study of the organization of passenger and baggage transportation by air. Air transportation is considered as an integrated system in which commercial planning, passenger service, baggage handling, aircraft operation, airport infrastructure, ground resources, public regulation and digital information exchange must function coherently. The work emphasizes that passengers experience these activities as one continuous journey even though separate organizations perform individual operations.

The purpose of the publication is to combine theoretical principles with methods that can support practical aviation decisions. The material explains how demand, capacity, time, cost, quality, safety, environmental impact and risk can be represented through measurable indicators. Formulas, graphs, schemes and tables are used to demonstrate relationships between operational variables and to show how alternative solutions may be compared.

Particular attention is given to the relationship between local and system-wide performance. Increasing productivity at one checkpoint, baggage position or aircraft-service task does not necessarily improve the complete process. A local action may transfer a queue, workload or delay to another participant. The monograph therefore evaluates passenger and baggage operations across the entire journey and aircraft turnaround.

The study is intended for students of aviation transport, postgraduate researchers, academic staff and specialists employed by airlines, airports and ground handling organizations. It can be used when preparing educational materials, coursework, qualification studies, operational analyses and managerial justifications. The models are designed for adaptation to local data and operating conditions.

The work contains seven chapters covering regulation, participants, infrastructure, passenger flows, transportation processes, vehicles, digitalization and cybersecurity. Together they form a structured description of the resources, decisions and controls required to provide safe, reliable and passenger-oriented air transportation.

The first chapter establishes the theoretical and normative foundations of passenger air transportation. Aviation is examined as a component of the wider transport system and as an industry with strong international coordination requirements. Its advantages in speed and geographic reach are considered together with high capital intensity, infrastructure dependence, environmental effects and sensitivity to disruption.

International conventions, standards, recommended practices and national rules create a multi-level regulatory environment. The monograph explains why commercial agreements and internal procedures cannot replace mandatory safety, security, airworthiness, border and passenger-protection requirements. Regulation is presented as an operational input that determines responsibilities, documentation, permitted actions and control procedures.

Passenger air services are classified according to regularity, network role, market, operating model, distance and service concept. Scheduled, charter, regional, low-cost, full-service, direct and connecting operations create different requirements for aircraft, terminals, schedules and passenger information. Classification is used as a decision tool rather than as a purely descriptive exercise.

The second chapter examines the organizations and infrastructure that produce the service. Airlines, airports, ground handlers, air navigation providers, authorities and contractors have different objectives but share one operational process. Their interaction is analysed through milestones, information latency, responsibility allocation and coordinated decision-making.

Airport infrastructure is divided into airside, landside and terminal-interface elements. Functional zoning must separate passenger categories and security states while preserving accessible and comprehensible routes. Runways, taxiways, stands, check-in areas, control points, gates, baggage systems and ground roads are treated as interdependent capacity resources. The chapter relates infrastructure loading to service quality and demonstrates why sustainable capacity must include an operational reserve.

Aircraft ground handling is presented as a coordinated sequence of arrival, passenger, baggage, servicing, loading and departure tasks. Parallel execution shortens turnaround time, but safety restrictions and task dependencies limit concurrency. Effective control requires planned, predicted and actual milestone times, early identification of deviation and authority to reallocate resources.

The third chapter studies the formation of passenger flows between cities, countries and continents. Demand is described as a response to population, income, economic relations, journey purpose, fares, travel time, frequency, reliability, destination attractiveness and competing modes. Passenger volume is therefore treated as a variable outcome rather than a fixed characteristic of a route.

Origin–destination models, gravity relations, choice models and network assignment are used to represent spatial movement. The distinction between passenger journeys and individual flight segments is emphasized because connecting passengers and multi-airport regions can produce several feasible paths for one city pair. Hub-and-spoke networks create connectivity and density benefits but also concentrate transfer demand and disruption risk.

Seasonality and within-day concentration influence fleet use, terminal capacity, staff schedules and baggage resources. Forecasting methods should preserve both total passenger volume and its distribution among airports, routes and time periods. Forecast uncertainty is represented through scenarios, prediction errors and sensitivity analysis. Data from reservations, departure control, airport systems, surveys and observations require common definitions and quality documentation.

The fourth chapter follows the organization of passenger and baggage carriage from reservation to completion of the journey. Reservation and ticketing establish the commercial and information basis of transportation. Check-in, document verification, security procedures and boarding transform a booked passenger into an accepted and boarded passenger. Each channel requires consistent information, accessible exception handling and controlled transfer of status between systems.

Baggage handling is analysed as a chain of acceptance, identification, screening, sorting, reconciliation, loading, transfer, unloading and delivery. Tracking points improve traceability only when identifiers and event records remain reliable. The chapter also considers cabin service, passenger information, arrival procedures, irregular baggage and service recovery. Quality is evaluated across the full journey rather than through one isolated contact point.

Quantitative indicators describe booking development, channel completion, waiting, boarding progress, baggage traceability and delivery. Their purpose is to connect observed performance with specific operational action and responsible personnel.

The fifth chapter examines vehicles used in passenger air transportation. Passenger aircraft are classified by propulsion, capacity, range and operational role. Aircraft selection is linked to forecast demand, route distance, frequency, airport limitations, payload, baggage requirements and economic performance. A type that minimizes cost on one flight may be unsuitable for a network that requires schedule frequency or operational flexibility.

Cabin configuration affects seating capacity, comfort, boarding, carry-on baggage, accessibility and evacuation requirements. Hold volume and payload determine the ability to carry checked baggage and commercial cargo. The monograph shows why fleet and configuration decisions must be coordinated with terminal, stand and baggage processes.

Ground vehicles and servicing equipment include passenger buses, stairs, loaders, tractors, power units, service vehicles and specialized handling systems. Their quantity, travel time, compatibility, energy state and technical availability influence turnaround reliability. Maximum equipment utilization is not always desirable because a reserve is required for travel, charging, maintenance and disruption recovery.

Operational, economic and environmental indicators are used to compare vehicles. Unit cost depends on distance, load factor, productive time and fixed and variable expenditure. Environmental evaluation includes energy and emission intensity rather than technology labels alone. Maintenance and airworthiness support are examined through condition indicators, reliability, inspection intervals and the balance between preventive cost and failure risk.

The sixth chapter considers digitalization as an organizational transformation rather than the installation of isolated applications. Mobile check-in, kiosks, automated bag drop, biometric processing and digital wayfinding can reduce routine workload, but staffed exception channels and accessible fallback remain necessary. Performance optimization requires indicators connected to decisions, thresholds and accountable roles.

Integration of airline, airport and ground-handler systems depends on common identifiers, event definitions and authoritative sources. Artificial intelligence and digital twins can support forecasting, anomaly detection and comparison of alternatives when their uncertainty and assumptions are controlled. Digital investment is evaluated through life-cycle cost, measurable benefits, implementation readiness and cybersecurity requirements.

The seventh chapter addresses contemporary cyber threats in the aviation sector. Connected passenger systems, operational databases, communication links, surveillance services, industrial controllers and supplier platforms create a complex digital infrastructure. The chapter evaluates vulnerabilities through asset exposure, dependency concentration, interfaces and trusted recovery baselines.

Threats include credential compromise, malware, denial of service, data manipulation, spoofing, jamming and unauthorized unmanned aircraft. Their significance is determined by operational consequences and propagation between connected processes. Preventive controls are combined with anomaly detection, independent physical verification, segmentation and controlled fallback procedures.

Passenger information receives special attention because identity, itinerary, payment, baggage and assistance data are exchanged among several organizations. Data minimization, role-based access, traceability, protected exchange, retention limits and incident procedures are presented as elements of one information life cycle. Privacy protection must coexist with the availability and accuracy required for safe transportation.

Cyber resilience is defined through preparation, detection, containment, continuity, trusted restoration and learning. Incident response must connect technical teams with operational authorities capable of deciding which system may be isolated and which minimum service must continue. Exercises, role-based training and evidence-based risk acceptance strengthen organizational readiness.

The monograph concludes that effective passenger and baggage transportation depends on integration. Regulation establishes mandatory boundaries; infrastructure and vehicles provide physical capacity; personnel execute and supervise processes; digital systems create shared awareness; and management coordinates decisions under uncertainty. Improvement requires balanced attention to safety, security, service quality, cost, environmental performance and resilience.

The publication offers a unified analytical basis for education and applied research. Its models and indicators can support evaluation of existing operations, comparison of development alternatives and preparation of justified managerial decisions. The principal outcome is a system-oriented framework for organizing air transportation in which passenger needs and baggage reliability are coordinated with aircraft, airport and information processes.

Keywords: passenger air transportation; baggage transportation; airport operations; ground handling; service quality; digitalization; cybersecurity.

CONTENTS

INTRODUCTION

Passenger air transportation is an essential component of national and international mobility. It connects cities, countries and continents within time intervals that cannot be achieved by most alternative modes. Every journey depends on coordinated work by airlines, airports, ground handlers, air navigation organizations, security services and public authorities.

Passenger transportation is not limited to aircraft movement between airports. It includes itinerary selection, reservation, payment, check-in, baggage acceptance, controls, boarding, cabin service, arrival and baggage delivery. The passenger evaluates these operations as one service even though different organizations perform them. Airport service quality is consequently formed by several interrelated dimensions [1].

Baggage transportation constitutes a parallel material and information flow. Each item must be identified, screened, sorted, reconciled, loaded and delivered correctly. A discrepancy between physical location and recorded status causes delay, additional cost and loss of passenger confidence. Reliable organization therefore requires technological discipline and timely data exchange.

The relevance of the research is strengthened by changes in passenger expectations and aviation business models. Travellers increasingly expect continuous information, mobile services, predictable processing time and rapid assistance during disruption. Airlines simultaneously seek higher aircraft utilization and lower unit costs, while airports must process concentrated flows within limited terminal, stand and runway capacity. Network research demonstrates that local changes can influence connectivity and performance far beyond one airport or route [8].

Safety and security remain the binding conditions for every improvement. Productivity cannot be increased by omitting mandatory controls or reducing the time required for safe operations. New digital interfaces, biometric services, connected equipment and remotely operated systems also expand the cyber threat surface. Cybersecurity must therefore be incorporated into operational design and continuity planning rather than treated only as a separate technical activity [9].

Sustainable development adds another dimension to the organization of air transportation. Aircraft technology, fuel, load factor, network design, terminal energy use and ground operations jointly influence environmental performance. Technological improvement is important, but it must be evaluated together with operational, economic and policy measures [2, 7].

The purpose of this monograph is to systematize theoretical principles, regulatory requirements and applied methods for organizing passenger and baggage transportation by air. The study treats air transportation as an integrated service and production process. Its effectiveness is determined by the coordinated use of vehicles, infrastructure, personnel, information and time under safety, security, capacity, quality and economic constraints.

The object of the study is the process of passenger and baggage transportation within airline and airport networks. The subject of the study comprises organizational relationships, technological procedures, passenger and baggage flows, resource-allocation decisions, performance indicators and digital tools used during preparation and operation of air services.

The research tasks include analysis of aviation's transport role and regulation; classification of services; examination of participants and infrastructure; modelling of passenger flows; description of passenger and baggage procedures; assessment of vehicles; and evaluation of digitalization, sustainability and cybersecurity.

The methodology combines systems analysis, process representation, demand modelling, operations research and statistical evaluation. Quantitative relationships describe capacity, utilization, waiting, reliability, cost and risk. Graphs illustrate dependencies, while tables connect indicators with decisions. The formulas support transparent calculations using airline, airport or route data.

The work follows a passenger-centred but system-wide perspective. Satisfaction cannot be separated from punctuality, baggage reliability, infrastructure loading and aircraft readiness. An improvement at one point may transfer a queue or delay downstream. Decisions must therefore be assessed across the complete journey and aircraft turnaround.

Particular attention is paid to uncertainty in arrivals, service duration, weather, technical condition and punctuality. Average values are insufficient for peak planning. Scenarios, reserves and sensitivity testing show whether a solution remains feasible outside the central forecast.

The monograph also considers lessons from major disruptions. The pandemic demonstrated that aviation networks can experience simultaneous demand, operational and regulatory shocks, requiring airlines and airports to revise schedules, capacity and service procedures rapidly [11, 12]. Resilience consequently includes the ability to preserve essential functions, adapt resources and restore coordinated operation after an interruption.

The practical value of the presented material lies in its connection between concepts and measurable decisions. The proposed indicators can be used to evaluate passenger-processing channels, terminal zones, baggage operations, aircraft selection, ground equipment, digital projects and cyber controls. Their application requires local calibration because traffic composition, infrastructure, operating rules and service standards differ among airports and airlines.

The book is organized into seven chapters. The first chapter presents the theoretical and normative foundations of passenger air transportation. It explains the role of aviation in the transport system, the levels of regulation, classifications of air services and current development trends. These foundations establish the constraints within which later organizational and technological decisions are made.

The second chapter examines participants, terminal zoning, flight preparation, ground handling and infrastructure throughput. The third focuses on demand factors, passenger-flow models, hub connections, seasonality, data and route-network scenarios.

The fourth chapter follows the passenger and baggage journey from reservation to arrival. The fifth considers aircraft, cabin and baggage configurations, aircraft selection, ground equipment, environmental characteristics and maintenance.

The sixth chapter analyses self-service, biometric identification, optimization, sustainability, system integration, artificial intelligence and economic evaluation. Digital models provide value only when data quality, responsibility and operational action are clear.

The seventh chapter examines infrastructure vulnerabilities, threats to aviation systems, passenger-data protection, incident response, regulation, risk management and personnel competence. Its objective is trusted information exchange and controlled recovery.

The material is intended for students, researchers, teaching staff and aviation specialists. It may support academic papers, operational studies, training and managerial decisions. The models do not replace certified data, mandatory procedures or professional safety assessment.

Taken together, the chapters present passenger and baggage transportation as a single coordinated system. Its performance depends on the consistency of regulation, infrastructure, vehicles, technology and human decisions. This integrated perspective provides the basis for improving accessibility, safety, service quality, resilience and resource efficiency in passenger air transport.

CHAPTER 1

THEORETICAL AND NORMATIVE-LEGAL FOUNDATIONS OF AIR PASSENGER TRANSPORTATION

Passenger air transportation is a complex socio-technical system whose functioning depends on the coordinated interaction of legal institutions, transport operators, infrastructure facilities, technologies and passengers. Unlike an isolated production process, air carriage crosses organizational and territorial boundaries. A single journey may involve an airline, several airports, ground handling companies, air navigation service providers, border and customs authorities, security organizations, travel intermediaries and surface transport operators. The effectiveness of the system is therefore determined not only by the technical performance of an aircraft but also by the coherence of all processes that precede and follow the flight [27].

The theoretical foundations of passenger air transport explain its place in the general transport system, its economic and social functions, and the specific characteristics of the air transport service. These characteristics include the impossibility of storing unused seat capacity, the dependence of operations on schedules and airport slots, the concentration of high fixed costs, strict safety requirements and considerable sensitivity to external disturbances. Demand varies by route, season, day and passenger category, while capacity must be planned before the final number of passengers is known. Consequently, the organization of air carriage requires forecasting, network planning, resource coordination and continuous operational control [27].

The normative-legal foundation is equally important because international aviation cannot function through the rules of one operator or one state alone. Common principles regulate the use of airspace, admission of carriers to international markets, certification of aircraft and organizations, personnel licensing, aviation security, facilitation, environmental protection and carrier liability. International conventions and ICAO Standards are implemented through regional and national legislation, aviation regulations and oversight procedures. Contractual instruments, including tickets, conditions of carriage and handling agreements, specify the relationships between individual participants but remain subordinate to mandatory legal requirements [27].

Regulation performs several interconnected functions. It establishes a uniform minimum level of safety and security, distributes responsibility among participants, protects passenger rights and supports predictable international operations. At the same time, it creates the conditions for competition and commercial development. An effec-

tive regulatory system must maintain a balance: requirements should be sufficiently clear and enforceable to protect the public interest, yet sufficiently adaptable to accommodate new technologies, business models and methods of service delivery [27].

Contemporary passenger aviation is developing under the influence of digitalization, environmental constraints, changing consumer expectations and the need for greater resilience. Mobile services, biometric identification, automated baggage processing and data-driven decision support are altering the passenger journey. Fleet renewal, sustainable aviation fuels and more efficient operational procedures are becoming central to environmental policy. Recent large-scale disruptions have also demonstrated that efficiency cannot be evaluated without considering reserve capacity, business continuity, reliable communication and the ability to recover passengers and baggage when the original plan cannot be performed [26].

This chapter develops a unified conceptual basis for the subsequent analysis of passenger and baggage transportation. First, it defines the role of aviation within an integrated mobility system and examines its economic, territorial and social significance. Second, it presents the hierarchy of international, regional and national regulation and explains how legal requirements are transformed into operational procedures. Third, it classifies passenger services according to geography, schedule, network form, business model and production arrangement. Finally, it identifies the principal directions in which passenger aviation is currently developing. Together, these issues provide the theoretical and regulatory framework needed to examine infrastructure, passenger flows, service technologies, vehicles, digitalization and cybersecurity in the following chapters [26].

The mathematical expressions presented below are authorial formalizations and adaptations of the indicators, relationships and analytical approaches discussed in the cited literature. A source placed immediately before an expression identifies its conceptual or methodological basis and does not imply verbatim reproduction of the original publication [26].

1.1. The role of passenger air transport in the modern transport system

Passenger air transport is a component of the transport system that provides rapid spatial movement of people between settlements, regions and countries. Its principal techno-

logical advantage is speed over long distances. This advantage is not limited to the time spent in flight. It also includes the possibility of crossing seas, mountains, deserts and sparsely populated territories without constructing a continuous surface route. For this reason, aviation is especially important for island states, remote regions and large countries in which travel by road or rail requires considerable time [16].

The result produced by passenger aviation is a transport service rather than a material product. The service is created and consumed simultaneously: an unused seat on a departed flight cannot be stored and sold later. This characteristic has fundamental consequences for airline planning. Capacity must be formed before the exact level of demand is known, while revenue depends on the number and composition of passengers actually carried. Airlines therefore combine schedule planning, fleet assignment, revenue management, reservation control and operational dispatch in a single decision-making system [20].

Passenger transportation by air should be viewed as a chain of interdependent processes. It begins before the passenger arrives at the airport and normally includes searching for a suitable itinerary, reservation, payment, ticket issuance, notification of the conditions of carriage, check-in and acceptance of baggage. At the airport it continues through security and, where applicable, border, customs and health controls, followed by boarding and flight. After landing, the process includes disembarkation, transfer or arrival formalities, baggage delivery and the settlement of possible claims. The quality of the complete service is determined by the weakest element of this chain rather than by flight performance alone [23].

The total duration of the passenger's door-to-door journey can be represented as formula (1) [19]:

$$T_{\mathtt{d2d}} = T_a + T_p + T_w + T_f + T_{tr} + T_e, \tag{1}$$

where T_a is airport access time, T_p is the duration of terminal and control procedures, T_w is waiting time, T_f is flight time, T_{tr} is transfer time, and T_e is travel time from the arrival airport to the final destination. This expression demonstrates why comparison of transport modes based only on vehicle movement time is incomplete.

This relationship evaluates the complete passenger journey rather than the airborne segment alone. To calculate it, every consecutive stage must be measured in the same time unit and then added. The result makes it possible to compare air travel fairly with rail, road, or multimodal alternatives. The largest component identifies the stage

where operational improvement can produce the greatest reduction in total journey time. The indicator is therefore useful for timetable design, airport access planning, transfer coordination, and passenger information [14].

Modern passenger mobility is multimodal. A traveller rarely begins and ends a journey at an airport. Access may involve walking, a private car, taxi, bus, metro or railway, while the destination segment requires another surface mode. The real passenger itinerary is therefore a door-to-door movement. From this perspective, the airport is an interchange node connecting air transport with urban, regional and international networks [23].

The competitiveness of a flight depends partly on the quality of these connections. A fast flight can lose its advantage if the airport is difficult to reach, transfer intervals are unreliable, or information is fragmented between operators. Conversely, direct rail service to a terminal, coordinated timetables, through ticketing and predictable baggage procedures enlarge an airport's catchment area. They also make air services accessible to residents of cities that do not have their own airport [16].

Air and high-speed rail may function as competitors on routes where total travel times are comparable. They may also complement one another. Rail can replace short feeder flights at congested hubs, while the airline supplies long-distance connectivity. The appropriate relationship depends on geography, demand density, infrastructure, environmental policy and the organization of schedules. The central planning criterion is not protection of a particular mode but the reliability and resource efficiency of the whole passenger journey [20].

For multimodal comparison, the generalized cost of alternative m may be calculated as formula (2) [15]:

$$G_m = C_m + vT_m + C_m^d + C_m^{tr}, \tag{2}$$

where C_m is the direct monetary cost, v is the passenger's value of time, T_m is total travel time, C_m^d is the expected cost of delay, and C_m^{tr} represents the inconvenience and risk associated with transfers. The preferred alternative is not necessarily the one with the lowest fare; it is the alternative with the lowest generalized cost for the relevant passenger segment.

This indicator converts money, time, delay risk, and transfer inconvenience into one comparable measure. The calculation begins with the fare and other direct expenses, after which time-related and reliability-related costs are added. A lower value

indicates a more attractive alternative for the passenger segment whose value of time is used. Different values of v should be applied to business, leisure, and other passenger groups because their sensitivity to time differs. The result supports modal comparison, itinerary ranking, pricing analysis, and evaluation of airport accessibility [16]. The corresponding comparison is presented in Figure 1.

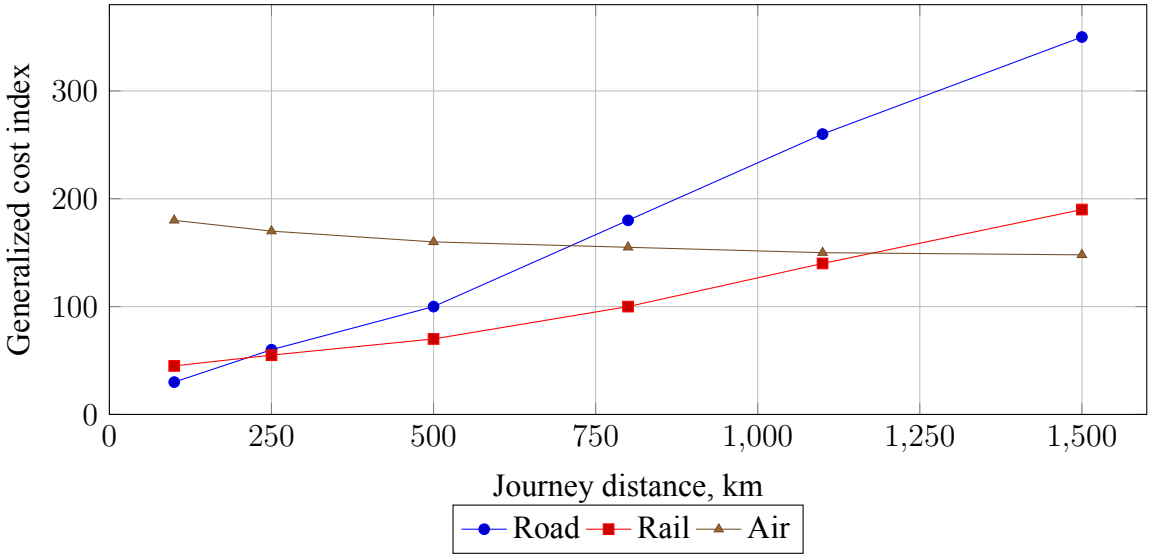

Figure 1: Illustrative relationship between journey distance and generalized transport cost. Author's calculation based on [3]

An integrated system requires common information. Passengers need consistent data concerning departure time, terminal, check-in deadline, platform or gate, baggage rules and disruption alternatives. Operators need timely data on connecting passengers, expected arrival times and capacity. Digital exchange reduces uncertainty, but it also creates requirements for data quality, cybersecurity, personal-data protection and clear allocation of responsibility [16].

Air connectivity supports economic activity by reducing the generalized cost of distance. It makes business meetings, tourism, education, labour mobility and visits to relatives possible within time limits that surface transport cannot always meet. The benefit is particularly significant for activities in which time has a high value or personal presence is required. Aviation also accompanies trade in high-value and time-sensitive goods, although freight transportation is outside the principal subject of this monograph [16].

The economic effect of an airport extends beyond the jobs of airlines and airport operators. Ground handling, maintenance, catering, security, retail, hotels and surface transport form a local service ecosystem. Indirect effects arise through purchases from suppliers, while induced effects arise when employees spend their income. Wider cat-

alytic effects may include tourism development, access to investment and participation in international production and knowledge networks. These effects must be assessed carefully: they vary by region and should not be equated automatically with gross passenger numbers [23].

The total regional economic effect may be expressed as formula (3) [22]:

$$E_{tot} = E_{dir} + E_{ind} + E_{induced} + E_{cat}, \tag{3}$$

Here, E_{tot} is the total regional economic effect; subscripts dir, ind, $induced$, and cat identify its direct, indirect, induced, and catalytic components, respectively.

This decomposition estimates how aviation activity affects the economy of a region. The calculation requires separate estimates of employment, income, expenditure, supplier activity, household spending, and wider connectivity effects. Adding the components produces a total effect, but care must be taken to avoid counting the same benefit more than once. The result can be compared across airports only when the same territorial boundary and methodology are used. It is applied in airport-development studies, public-investment appraisal, and assessment of regional transport policy. In this expression, the terms denote direct, indirect, induced and catalytic effects. If an empirically justified regional multiplier μ is available, the first three components may be approximated by formula (4) [22]:

$$E_{dir} + E_{ind} + E_{induced} = \mu E_{dir}. \tag{4}$$

Here, μ is the empirically estimated regional multiplier and E_{dir} is the direct economic effect; the left-hand side is the combined direct, indirect, and induced effect.

This simplified expression estimates the combined direct, indirect, and induced effect from a known direct effect. The direct value is multiplied by a regional coefficient obtained from input–output tables or an empirical economic study. A larger multiplier means that aviation expenditure circulates more intensively through local suppliers and household consumption. The coefficient must not be transferred mechanically between regions because their economic structures and import shares differ. The estimate is useful at an early planning stage when detailed sector-by-sector data are unavailable [17].

Connectivity is a more informative characteristic than the number of flights alone. A route has greater system value when its timetable permits useful trips and reliable onward connections. The connectivity of a city depends on the number of destinations, frequency, travel time, transfer quality, seat capacity and affordability. A

daily service may be more useful for business mobility than several weekly flights, whereas seasonal services can be appropriate for leisure demand [20].

A weighted connectivity index for airport i can be written as formula (5) [15]:

$$CI_i = \sum_{j=1}^{n} \frac{f_{ij} s_{ij} q_{ij}}{t_{ij}^{\alpha} c_{ij}^{\beta}}, \tag{5}$$

Here, CI_i is the connectivity index of airport i; i identifies the origin airport, j identifies a destination, n is the number of destinations, and $\sum$ denotes summation over all destinations.

This index measures the practical connectivity supplied by an airport rather than merely counting destinations. Each destination contribution is calculated from frequency, seats, service quality, travel time, and price, after which all contributions are summed. Higher frequency, capacity, and quality increase the result, whereas longer travel time and higher generalized fare reduce it. The parameters α and β can be calibrated to represent the observed sensitivity of passengers to time and cost. The index supports comparison of airports, route-development priorities, and evaluation of network changes. In this expression, f_{ij} is service frequency, s_{ij} is the number of seats offered, q_{ij} is a quality coefficient reflecting schedule and transfer convenience, t_{ij} is travel time, c_{ij} is the generalized fare, and α and β describe sensitivity to time and price. The index increases when a city receives more frequent, larger, faster and more affordable connections [23].

Air transport also influences the spatial organization of a country. Major hubs concentrate flows and provide economies of density. Regional airports support territorial accessibility and may perform social or strategic functions even when commercial demand is insufficient for fully profitable operation. Public service obligation schemes and other support mechanisms can preserve essential connections, but they require transparent selection, proportional financing and periodic review. Otherwise, support may maintain inefficient capacity or distort competition without delivering a commensurate public benefit [20].

Table 1: Principal functions of passenger air transport in the transport system

Function	Transport result	System-level implication
Spatial	Rapid connection over long distances and physical barriers	Expansion of accessible labour, education and service markets
Economic	Reduction of time costs for business and tourism	Support for investment, trade and regional service activity
Social	Personal, family, educational and humanitarian mobility	Inclusion of remote and island communities
Network	Concentration and redistribution of flows through hubs	Economies of density together with dependence on transfer reliability
Strategic	Emergency, evacuation and continuity capability	Need for resilient airports, fleets, personnel and communication systems
Integrative	Connection with road, rail and urban transport	Requirement for coordinated timetables, information and passenger rights

The passenger is not merely a unit of traffic. Air travel enables family relationships, cultural exchange, study, medical travel and participation in public life. These purposes explain why accessibility, dignity and non-discrimination are integral to transport organization. A service is not genuinely available if a passenger cannot obtain understandable information, reach the terminal, use the required processes or receive reasonable assistance [20].

Passengers are heterogeneous. Their needs vary according to age, health, mobility, language, travel experience, group size and the purpose of travel. Persons with disabilities and persons with reduced mobility may require assistance from the terminal entrance to the aircraft seat and during transfer. Families may need coordinated seating and carriage of child equipment. Unaccompanied minors require documented handover procedures. Elderly passengers and first-time travellers benefit from clear wayfinding and human support even where self-service technology is widespread [14].

Accessibility should be incorporated at the design stage. Retrofitting isolated solutions after a terminal, website or procedure has been designed is usually less effective and more expensive. Universal design includes step-free routes, readable signs, audible and visual information, accessible digital interfaces, suitable service counters and training for personnel. Operational plans must also protect passengers requiring assistance during irregular operations, when gates change, queues grow and normal processes are disrupted [19].

The gravity-type indicator of the spatial accessibility of airport i is given by

formula (6) [1]:

$$A_i = \sum_{j=1}^{n} \frac{Pop_j}{G_{ij}^{\theta}}, \tag{6}$$

Here, A_i is the spatial accessibility indicator of airport i; j is a population zone, n is the number of zones, and $\sum$ aggregates their accessibility contributions.

This indicator estimates how easily the population surrounding an airport can reach it. For every population zone, the number of residents is divided by the access impedance raised to the selected sensitivity power, and the zone values are added. Nearby populous zones contribute more than small or distant zones. Increasing θ makes the measure more sensitive to access cost and therefore reduces the contribution of remote areas. The result is used to compare airport catchment areas and to justify road, rail, or public-transport improvements. In this expression, Pop_j is the population of zone j, G_{ij} is the generalized cost of reaching airport i from that zone, and θ is the impedance parameter. A service-accessibility score can additionally be defined as formula (7) [19]:

$$A_s = \frac{\sum_{k=1}^{m} w_k a_k}{\sum_{k=1}^{m} w_k}, \tag{7}$$

Here, A_s is the service-accessibility score, w_k is the importance weight of criterion k, m is the number of criteria, and the denominator normalizes the weighted sum.

This score evaluates whether passenger services satisfy a set of accessibility requirements. Each criterion is assigned a performance value and an importance weight, after which the weighted values are summed and normalized. A value close to one indicates broad compliance, while a low result identifies significant barriers for passengers. The individual criterion values should also be reviewed because a strong aggregate result can conceal failure of a critical requirement. The score supports accessibility audits, terminal redesign, staff training, and monitoring of corrective actions. In this expression, a_k represents compliance with accessibility criterion k [14].

Affordability affects social accessibility as much as physical access. Liberalization and low-cost business models have expanded opportunities for travel, but a low advertised fare does not necessarily represent the total cost of the journey. Optional services, baggage, airport access and change restrictions can materially alter the final price. Transparent presentation allows passengers to compare alternatives and reduces disputes at later stages [19].

Passenger air transport operates under strict safety constraints and high fixed costs. Aircraft, airport infrastructure, air navigation services and qualified personnel

must be available before a flight can be performed. The system is also sensitive to weather, airspace restrictions, technical failures, security events and congestion. A disturbance at one hub can propagate through aircraft rotations and passenger connections across an entire network [14].

Capacity has several dimensions. Runway capacity determines the possible number of movements under specified operating conditions. Terminal capacity concerns processing at check-in, security, border control, gates and baggage reclaim. Airspace capacity depends on routes, separation standards, controller workload and traffic management. Airline capacity is expressed through seats and available seat-kilometres, but actual service depends on aircraft availability and crew legality. Increasing only one component may move a queue to another component rather than improve the system [23].

For a sequence of dependent processing stages, the effective system capacity limited by the bottleneck is given by formula (8) [15]:

$$Q_{\text{sys}} = \min\{Q_1, Q_2, \ldots, Q_k\}, \tag{8}$$

Here, Q_{sys} is total system capacity, $Q_1, \ldots, Q_k$ are the capacities of individual stages, k is the number of stages, and $\min$ selects the bottleneck capacity.

This relationship identifies the stage that limits the throughput of the complete passenger-processing chain. The sustainable capacity of every stage is measured under comparable operating conditions, and the smallest value is selected. Increasing the capacity of a stage that is not the minimum will not raise total system throughput until the actual bottleneck is improved. The calculation should be repeated for different traffic peaks, staffing plans, and equipment states. It is used in terminal planning, resource allocation, and evaluation of security, border-control, gate, and baggage processes. In this expression, Q_k is the sustainable throughput of stage k expressed, for example, in passengers per hour. The utilization of a stage is given by formula (9) [19]:

$$\rho_k = \frac{\lambda_k}{Q_k}, \tag{9}$$

Here, ρ_k is the utilization ratio of stage k, λ_k is its passenger-arrival rate, and Q_k is its sustainable service capacity; numerator and denominator must use the same time unit.

This ratio shows how intensively a processing stage is being used. The observed or forecast arrival rate is divided by the sustainable processing capacity for the same period. Values well below one indicate available reserve, whereas values close to or

above one signal growing queues and unstable operation. The indicator should be calculated separately for peak and off-peak periods because daily averages can conceal short-term congestion. It supports staffing decisions, queue management, and assessment of whether additional equipment or channels are required. The nonlinear increase in waiting time is illustrated in Figure 2.

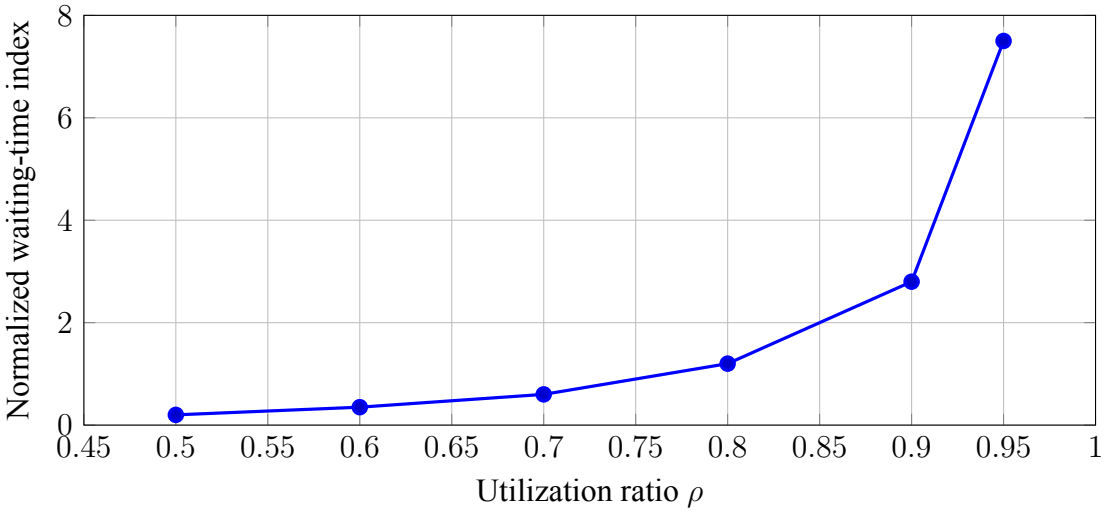

Figure 2: Growth of the waiting-time index as passenger-processing utilization approaches capacity. Author's illustrative calculation based on [17]

In this expression, λ_k is the arrival intensity. When ρ_k approaches unity, even small variations in demand or processing time can cause a disproportionate increase in queues [20].

Demand is uneven by hour, day and season. Airlines seek schedules attractive to passengers, which often produces peaks at convenient departure times or coordinated hub banks. Airports must either provide resources for peak flows, manage demand through slot allocation and pricing, or accept congestion and lower service quality. The planning task is to balance utilization with a reserve for uncertainty. Maximum theoretical utilization is rarely a suitable operational objective because it leaves no capacity to absorb variability [20].

Reliability is consequently a central product characteristic. Passengers value not only the planned duration but also the probability of arriving by a required time. A schedule with insufficient turnaround or transfer margins may appear efficient while generating recurrent delay, missed connections and baggage mishandling. Robust planning uses realistic process times, protects critical connections and defines recovery options before disruption occurs [12].

On-time performance for a delay threshold τ is given by formula (10) [1]:

$$OTP_{\tau} = \frac{N(\Delta t \leq \tau)}{N_{op}} \times 100\%, \tag{10}$$

Here, OTP_{τ} is on-time performance at threshold τ, Δt is actual delay, $N(\Delta t \leq \tau)$ counts flights within the threshold, N_{op} is the number of operated flights, and 100% converts the ratio to percent.

This percentage measures the share of operated flights whose delay does not exceed the selected threshold. The calculation requires the actual delay of every operated flight and a clearly defined threshold, such as fifteen minutes. Raising the threshold normally increases the reported result, so comparisons are valid only when the same definition is used. A high percentage indicates schedule reliability but does not describe the severity of delays outside the threshold. The measure is used for operational monitoring, service-level agreements, benchmarking, and passenger-performance reporting. In this expression, N_{op} is the number of operated flights. The more accurate representation of average delay per passenger is given by formula (11) [19]:

$$\overline{D}_p = \frac{\sum_{f=1}^{F} P_f \max(0, \Delta t_f)}{\sum_{f=1}^{F} P_f}, \tag{11}$$

Here, $\overline{D}_p$ is average passenger-weighted delay, F is the number of flights, f is a flight index, P_f is passengers on flight f, Δt_f is its delay, and $\max(0, \Delta t_f)$ excludes early operation from the delay total.

This indicator measures delay while accounting for the number of passengers affected on each flight. Positive flight delay is multiplied by passenger volume, the products are added, and the result is divided by total passengers. A heavily loaded delayed flight therefore influences the result more than a lightly loaded one. Early arrivals are assigned zero delay so that they do not offset the inconvenience caused by late flights. The measure supports passenger-centred punctuality analysis, disruption-cost estimation, and prioritization of recovery actions. In this expression, P_f is the number of passengers affected by flight f [16].

The performance of passenger air transport is measured from several perspectives. Airlines monitor load factor, yield, unit cost, punctuality, completion factor and aircraft utilization. Airports monitor passenger throughput, processing time, queue length, baggage delivery and infrastructure availability. Passengers judge price, convenience, reliability, comfort, information and complaint resolution. Public authorities

focus on safety, security, connectivity, competition, consumer protection and environmental impacts. No single indicator adequately describes the outcome [22].

The available seat-kilometres and revenue passenger-kilometres indicators are given by formula (12) [22]:

$$\begin{aligned} ASK &= \sum_{r=1}^{R} S_r d_r, \\ RPK &= \sum_{r=1}^{R} P_r d_r, \end{aligned} \tag{12}$$

Here, ASK denotes available seat-kilometres, RPK denotes revenue passenger-kilometres, R is the number of routes, and r is a route index.

These two indicators describe offered transport production and the portion actually consumed by paying passengers. For each route, seats or revenue passengers are multiplied by distance and then summed across the network. ASK measures capacity supplied, whereas RPK measures passenger traffic performed. Their comparison shows whether growth results from additional capacity, higher demand, longer routes, or a combination of these factors. The indicators are fundamental for airline planning, productivity analysis, and comparison of networks of different geographical size. In this expression, S_r is offered seating capacity, P_r is the number of revenue passengers, and d_r is route distance. The passenger load factor is given by formula (13) [22]:

$$LF = \frac{RPK}{ASK} \times 100\%. \tag{13}$$

Here, LF is passenger load factor, RPK is revenue passenger-kilometres, ASK is available seat-kilometres, and 100% expresses the ratio as a percentage.

This percentage shows how much of the offered seat-distance capacity is occupied by revenue passengers. It is calculated by dividing passenger traffic performed by capacity supplied and multiplying by one hundred. A rising value usually improves unit-cost recovery, but an extremely high value may leave little capacity for rebooking disrupted passengers. The result must be interpreted together with yield because full aircraft can still be unprofitable when fares are too low. It is used in revenue management, route evaluation, budgeting, and fleet-capacity decisions. This indicator characterizes the use of offered capacity but must be interpreted together with yield, punctuality and the availability of recovery capacity [16].

A high load factor can improve resource efficiency, but it may reduce recovery options during cancellation. High aircraft utilization lowers unit cost, but an overly

tight rotation can transmit delay. Short processing targets can improve flow, but they must not weaken security or assistance. Performance management should therefore use a balanced set of indicators and explicitly identify trade-offs [12].

Aviation creates benefits but also external costs. Aircraft operations generate greenhouse-gas emissions, local air pollutants and noise. Airports occupy land and influence surrounding development and surface traffic. These effects justify technical standards, land-use planning, environmental assessment and economic measures. Environmental policy should evaluate the complete system, including fleet efficiency, operational procedures, sustainable fuels, airport energy use and access transport. It should also avoid shifting impacts from one stage or region to another without reducing the total burden [15].

The public interest in aviation includes safety, equal access, fair competition, territorial cohesion and environmental responsibility. Regulation is necessary because passengers cannot independently verify many safety properties, network infrastructure has monopoly characteristics, and the consequences of failure cross organizational and national boundaries. At the same time, excessive or inconsistent regulation can raise costs, restrict entry and fragment international operations. The role of policy is to establish clear outcomes and accountability while allowing operators to select efficient means of compliance where appropriate [22].

Thus, passenger air transport is simultaneously a commercial service, a safety-critical technological system and an element of public infrastructure. Its effectiveness must be evaluated through the complete journey and through its interaction with the economy, territory, society and environment. This systems view provides the foundation for analysing regulation, service classification and future development in the following sections [22].

1.2. International and national regulation of air transport

The international character of aviation makes legal coordination indispensable. An aircraft may be registered in one state, operated by an airline established in another, leased from a company in a third, crewed by citizens of several states and used to carry passengers between two further jurisdictions. Safety oversight, market access, passenger liability, security, customs, immigration and environmental obligations may therefore arise from different legal sources. Regulation organizes these relationships and defines which authority, operator or service provider is responsible at each stage [4].

The regulatory system is multi-level. International conventions create common principles and obligations between states. Standards and Recommended Practices developed within the International Civil Aviation Organization provide technical and procedural harmonization. Bilateral and multilateral air service agreements allocate market access. Regional law may create common markets and passenger-protection rules. National legislation establishes institutions, certification, enforcement and administrative procedures. Finally, carrier conditions of carriage and airport rules govern contractual and operational details, but they cannot lawfully reduce mandatory rights [10].

The weighted index summarizing an operator's compliance with applicable regulatory requirements is given by formula (14) [28]:

$$K_c = \frac{\sum_{j=1}^{m} w_j c_j}{\sum_{j=1}^{m} w_j}, \qquad 0 \le c_j \le 1, \tag{14}$$

Here, K_c is the weighted compliance index, j identifies a requirement, m is the number of requirements, and the denominator normalizes the weighted result to the interval from zero to one.

This index summarizes compliance across a set of regulatory requirements. Each requirement is assessed on a zero-to-one scale, multiplied by its importance weight, and included in the normalized weighted average. A value close to one indicates strong overall compliance, while a decline shows deterioration or newly identified gaps. Critical findings must still be treated individually because averaging must not neutralize a mandatory safety deficiency. The index supports management review, audit planning, corrective-action monitoring, and allocation of compliance resources. In this expression, c_j is the level of compliance with requirement j and w_j is its weight according to safety, legal or operational significance. The index is useful for internal monitoring, but a high aggregate value cannot compensate for non-compliance with a single critical mandatory requirement [28].

The Convention on International Civil Aviation, signed in Chicago on 7 December 1944, is the constitutional foundation of modern international civil aviation. It recognizes the complete and exclusive sovereignty of every state over the airspace above its territory. Consequently, an international scheduled service cannot operate through or into another state's territory solely on the basis of airline preference. Traffic rights must arise from an applicable agreement or authorization [30].

The Convention distinguishes civil aircraft from state aircraft and establishes principles concerning nationality, registration, documents, customs and immigration

measures, rules of the air, recognition of certificates and investigation of accidents. It also created ICAO as the permanent organization responsible for cooperation in international civil aviation. The Convention seeks the safe and orderly development of international aviation and the operation of services on the basis of equality of opportunity [29].

Traffic rights are conventionally described as freedoms of the air. The first freedom is the right to overfly another state without landing; the second is the right to land for a non-traffic purpose such as refuelling. The third and fourth freedoms concern carrying traffic from the airline's home state to another state and from another state back to the home state. The fifth freedom permits carriage between two foreign states on a service linked to the carrier's home state. Additional commercial freedoms describe more extensive forms of carriage, including services between foreign states and domestic carriage within another state. These later freedoms are analytical concepts and depend on specific agreements; they are not automatically granted by the Chicago Convention [29].

Air service agreements normally regulate routes, designated airlines, traffic rights, capacity, tariffs or tariff procedures, safety and security cooperation, taxation, commercial opportunities and dispute settlement. Traditional agreements were restrictive and closely controlled capacity. Liberal agreements allow airlines greater freedom to determine frequency, aircraft and prices. Liberalization can expand connectivity and competition, but it still requires effective safety oversight, fair competitive conditions and infrastructure capacity [6].

Under the Chicago Convention, ICAO adopts international Standards and Recommended Practices, commonly called SARPs, in Annexes to the Convention. A Standard is a specification whose uniform application is recognized as necessary for safety or regularity, while a Recommended Practice is recognized as desirable. States undertake to collaborate in achieving the highest practicable degree of uniformity. When a state cannot comply in all respects with an international Standard, the Convention provides a mechanism for notification of differences [6].

The Annexes cover fields that collectively make international passenger service possible. Personnel licensing, rules of the air, aircraft operations, airworthiness, air traffic services, aerodromes, accident investigation, security, dangerous goods and safety management directly affect flight safety. Annex 9 on Facilitation addresses the efficient completion of border-control formalities for aircraft, passengers, baggage and cargo. Annex 17 establishes the international framework for safeguarding civil aviation

against acts of unlawful interference. Environmental protection is addressed through Annex 16 [10].

SARPs are not self-executing rules for an airline in the same manner as a national regulation. States implement them through legislation, regulations, certification requirements and oversight practices. The quality of implementation is therefore critical. Formal adoption without qualified inspectors, reliable reporting, enforcement capacity and institutional independence does not produce the intended safety outcome [9].

The multiplicative relationship representing implementation effectiveness is given by formula (15) [30]:

$$E_r = H^{\gamma_1} I^{\gamma_2} O^{\gamma_3}, \qquad \gamma_1 + \gamma_2 + \gamma_3 = 1, \tag{15}$$

Here, E_r is regulatory implementation effectiveness; γ_1, γ_2, and γ_3 are non-negative importance exponents whose sum equals one.

This relationship combines harmonization, national implementation, and oversight into one effectiveness measure. Each component is raised to an importance exponent and the resulting factors are multiplied. The multiplicative form means that a very weak component substantially reduces the total result even when the other components are strong. The exponents should be selected through expert assessment or empirical calibration and must sum to one. The measure is useful for comparing regulatory systems and identifying whether legal adoption, implementation, or enforcement requires priority improvement. The sensitivity of the result to implementation conditions is shown in Figure 3.

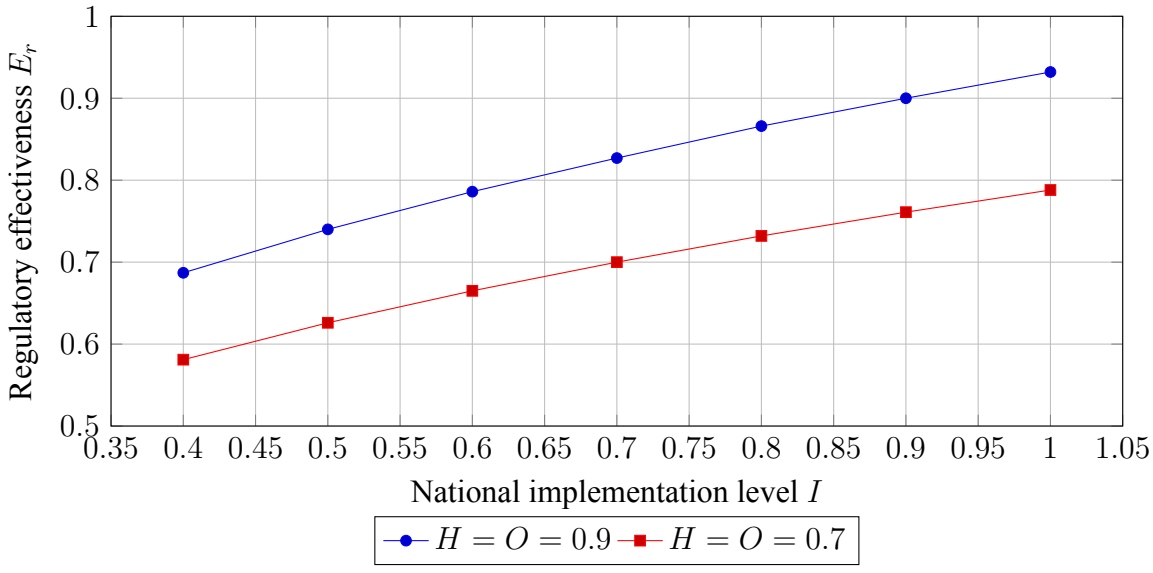

Figure 3: Sensitivity of regulatory effectiveness to national implementation under alternative harmonization and oversight levels. Author's calculation based on [30]

In this expression, H is the level of international harmonization, I is the completeness of national implementation, and O is the effectiveness of oversight and enforcement. The multiplicative form reflects the fact that a very low value of one component limits the result even when the other components are well developed [30].

ICAO also publishes procedures, manuals and guidance material. These documents support consistent interpretation and implementation but must be distinguished from binding national law. Operators should identify the legal status of every requirement in their compliance system. A manual may represent accepted good practice, a contractual standard or an authority's preferred means of compliance even when it is not itself legislation [10].

The coverage of an oversight programme can be assessed as formula (16) [29]:

$$OC = \frac{\sum_{j=1}^{m} w_j a_j}{\sum_{j=1}^{m} w_j} \times 100\%, \tag{16}$$

Here, OC is oversight coverage in percent, j is an oversight area, m is the number of areas, w_j is its importance weight, and a_j is its inspection-status indicator.

This percentage measures how much of the required oversight programme has been completed. Each oversight area is weighted, multiplied by its completion indicator, and included in the normalized total. High-priority areas therefore influence the result more than routine areas. A value below the annual target indicates that inspections, audits, or surveillance activities remain overdue. The indicator is used by aviation authorities and internal compliance departments to schedule oversight work and report programme execution. In this expression, a_j equals one when oversight area j has been examined within the required cycle and zero otherwise. The closure rate for identified findings is given by formula (17) [28]:

$$CR = \frac{N_{closed}}{N_{due}} \times 100\%. \tag{17}$$

Here, CR is the finding-closure rate, N_{closed} is the number of findings closed by the reporting date, N_{due} is the number due for closure, and 100% converts the ratio to percent.

This percentage measures the rate at which due oversight findings have been closed. The number of findings closed by the reporting date is divided by all findings whose closure date has arrived. A value of one hundred percent means that no due corrective action remains formally open. The indicator should be supplemented by

a quality review because closure is valid only when evidence demonstrates that the underlying cause has been removed. It is used to monitor corrective-action discipline and the responsiveness of regulated organizations [10].

Table 2: Levels of regulation relevant to passenger air transportation

Level	Principal instruments	Operational effect
International	Chicago Convention, Montreal Convention and other treaties	Common principles, state obligations, liability and jurisdiction
ICAO	Annexes, procedures, manuals and guidance	Harmonized safety, security, facilitation and environmental framework
Intergovernmental market access	Bilateral and multilateral air service agreements	Routes, designation, traffic rights and commercial conditions
Regional	Regulations and agreements of regional organizations	Common market, competition and passenger-protection rules
National	Air code, aviation regulations and authority decisions	Certification, licensing, oversight, enforcement and sanctions
Contractual and operational	Conditions of carriage, airport rules and handling agreements	Detailed allocation of service obligations within mandatory law

The contract of carriage connects the regulatory system with the individual passenger. It is evidenced by the ticket and associated reservation records, although electronic documentation has replaced the traditional paper ticket in most operations. The contract identifies the itinerary and carrier and incorporates fare rules and conditions of carriage. Mandatory legislation prevails over contractual terms where the two conflict [30].

The Convention for the Unification of Certain Rules for International Carriage by Air, adopted in Montreal in 1999, provides a modern uniform regime for carrier liability in international carriage. It addresses passenger death or bodily injury, delay and damage to or loss of baggage and cargo. It also recognizes electronic documentation and defines jurisdictional rules. Liability limits expressed in Special Drawing Rights are subject to periodic review under the Convention's mechanism, which allows their real value to be adjusted without renegotiating the entire treaty [6].

The liability regime should be distinguished from standardized passenger rights during disruption. The Montreal Convention concerns proven damage within its scope and establishes defences and limits. Regional rules, such as those of the European Union, may additionally require fixed compensation, care, reimbursement or rerouting when specified conditions are met. A single event can therefore engage more than

one legal instrument, but double recovery for the same damage is generally not the objective [6].

For planning purposes, the expected financial exposure associated with passenger claims may be estimated as formula (18) [28]:

$$L_e = \sum_{s=1}^{n} p_s \min(D_s, L_s), \tag{18}$$

Here, L_e is expected financial exposure, s is a claim-scenario index, n is the number of scenarios, and $\min(D_s, L_s)$ selects the smaller of assessed damage and the applicable liability limit.

This relationship estimates the average financial exposure created by possible passenger claims. For every scenario, the payable amount is limited to the smaller of assessed damage and the applicable legal ceiling and is then multiplied by scenario probability. Adding these probability-weighted amounts gives the expected exposure for budgeting purposes. The calculation must use current liability limits and realistic probabilities based on operational history. It supports insurance planning, financial reserves, risk mitigation, and comparison of alternative passenger-service procedures. In this expression, p_s is the probability of claim scenario s, D_s is the assessed damage, and L_s is the applicable legal limit where such a limit exists. This is an operational budgeting expression and does not replace the legal assessment of an individual case [10].

Baggage is a frequent source of legal and operational claims. The passenger must receive clear information about allowances, prohibited articles, special items, declaration of value and reporting deadlines. Checked baggage becomes part of a controlled handling chain, yet the carrier remains the principal contractual contact for the passenger. Handling agreements between airlines and airports or service providers allocate operational tasks but do not automatically transfer statutory responsibility toward the passenger [29].

Safety regulation manages risks arising from the technical and operational performance of aviation. It includes certification of aircraft and organizations, licensing of personnel, operational approvals, maintenance, air traffic management, aerodrome requirements, occurrence reporting and safety-management systems. Contemporary oversight increasingly combines prescriptive rules with performance- and risk-based methods. Prescriptive minimums remain essential, while risk-based oversight directs attention toward activities and organizations with the greatest potential consequences [10].

The conventional quantitative representation of operational risk is given by formula (19) [30]:

$$R = \sum_{i=1}^{n} p_i I_i, \tag{19}$$

Here, R is aggregate expected risk, i is a hazardous-event index, n is the number of events, and $\sum$ adds the probability-weighted consequences.

This expression calculates expected risk as the sum of probability-weighted consequences. Each hazardous event is assigned a likelihood and a consequence value using a consistent scale or monetary unit. Rare events with catastrophic consequences can therefore remain significant even when their probability is low. The result is sensitive to the quality of occurrence data and consequence assumptions, so uncertainty should be documented. The measure supports safety assessment, prioritization of hazards, and comparison of proposed risk controls. In this expression, p_i is the probability of hazardous event i and I_i is the magnitude of its consequences. When several control measures are introduced, residual risk can be approximated by formula (20) [29]:

$$R_{\text{res}} = R_0 \prod_{j=1}^{m} (1 - \eta_j), \tag{20}$$

Here, R_{res} is residual risk, R_0 is initial risk, j is a control index, m is the number of controls, η_j is control effectiveness, and $\prod$ denotes multiplication across controls.

This relationship estimates the risk remaining after several controls are applied. The initial risk is multiplied by the unmitigated fraction associated with every control. A more effective control has a larger η_j and therefore leaves a smaller residual fraction. The expression assumes independent control effects, so common failures or dependencies require a more detailed model. It is used to test whether planned barriers reduce risk to an acceptable level and to compare alternative control packages. In this expression, R_0 is initial risk and η_j is the effectiveness of control j. In practice, dependencies between controls must be considered because their effects are not always independent [30].

Aviation security addresses intentional acts such as unlawful seizure, sabotage and attacks on passengers, aircraft or infrastructure. Security responsibilities are distributed among states, airport operators, airlines, screening providers, police and intelligence services. Measures include access control, screening of passengers and baggage, protection of aircraft, background checks, staff training and response planning.

Security must be effective while remaining compatible with facilitation, privacy, non-discrimination and operational continuity [28].

Facilitation concerns the efficient movement of passengers and baggage through administrative controls. It covers travel documents, entry and departure procedures, inadmissible persons, deportees, public-health measures and assistance to persons with disabilities. Advance passenger information and passenger-name records allow authorities to assess certain risks before arrival, but their use requires a lawful purpose, data minimization, security and retention controls [6].

Safety, security and facilitation should not be managed as isolated fields. A new control measure can create queues that increase crowding and reduce terminal resilience. A rapid self-service process can create identity or cybersecurity vulnerabilities if assurance is weak. Regulation must therefore be translated into an integrated process design, supported by testing, monitoring and contingency procedures [29].

Passenger-protection law responds to information asymmetry and the practical vulnerability of travellers during disruption. Core principles include transparent prices and conditions, non-discrimination, assistance for persons with reduced mobility, timely information, complaint mechanisms and remedies for denied boarding, cancellation, long delay or baggage problems. The exact scope depends on the applicable jurisdiction, departure point, destination and operating carrier [28].

The expected cost of passenger assistance and compensation over a planning period is given by formula (21) [28]:

$$EC = \sum_{s=1}^{S} p_s N_s (c_s + a_s + r_s), \tag{21}$$

Here, EC is expected disruption-related passenger cost, s is a scenario index, S is the number of scenarios, and the product $p_s N_s$ is the expected number of affected eligible passengers in scenario s.

This calculation estimates the expected cost of passenger obligations during disruption. For each scenario, compensation, assistance, and rerouting cost per passenger are added and multiplied by the expected number of eligible passengers. The scenario results are then summed to obtain the planning-period total. Accurate calculation requires separate probabilities and eligibility rules for cancellation, delay, denied boarding, and missed connection events. The result supports contingency budgeting, schedule-robustness decisions, insurance analysis, and evaluation of disruption-

prevention investments. In this expression, p_s is the probability of disruption scenario s, N_s is the number of eligible passengers, c_s is compensation per passenger, a_s is assistance cost, and r_s is the expected cost of reimbursement or rerouting [1].

Regulation (EC) No. 261/2004 remains a central element of the European passenger-rights framework. It establishes rules on compensation and assistance in cases of denied boarding, cancellation and long delay. Its application has been extensively interpreted by the Court of Justice of the European Union. Reform proposals have sought to clarify thresholds, extraordinary circumstances, rerouting and enforcement; operators must therefore distinguish enacted law from proposals or negotiating positions at any particular date [6].

Competition law complements passenger protection. It addresses collusion, abuse of dominant position, merger effects and state aid. Airline alliances, code sharing and joint ventures can provide network benefits, but they may also reduce competition on overlapping routes. Airport charges and slot allocation affect entry conditions. Transparent and non-discriminatory access to essential infrastructure is particularly important where capacity is scarce [1].

The Herfindahl–Hirschman index describing market concentration on route r is given by formula (22) [30]:

$$HHI_r = \sum_{i=1}^{n} s_{ir}^2, \tag{22}$$

Here, HHI_r is the Herfindahl–Hirschman index for route r, i is an airline index, n is the number of airlines, and s_{ir} is airline i's percentage market share on route r.

This index measures how concentrated airline capacity or traffic is on a route. Each airline's percentage share is squared and the squared shares are added. Squaring gives greater influence to large airlines and makes the index rise when traffic is controlled by fewer competitors. The same basis, such as seats, passengers, or frequencies, must be used for every airline and period. The indicator supports competition analysis, merger assessment, and monitoring of market entry or exit. In this expression, s_{ir} is airline i's market share expressed as a percentage. A change associated with a merger or alliance is given by formula (23) [29]:

$$\Delta HHI = HHI_{post} - HHI_{pre}. \tag{23}$$

Here, ΔHHI is the change in market concentration, while HHI_{post} and HHI_{pre} are the post-transaction and pre-transaction index values.

This difference measures how a transaction or structural change alters market concentration. The pre-transaction index is subtracted from the post-transaction index using the same route definition and market-share basis. A positive value indicates increased concentration, while a negative value indicates a more dispersed market. The magnitude must be interpreted together with the resulting absolute concentration level and relevant competition rules. It is used to screen mergers, alliances, code-sharing arrangements, and major capacity changes [1].

National law converts international obligations into enforceable rules and establishes the competent civil aviation authority. Typical functions include registration of aircraft, certification of operators and aerodromes, licensing, approval of training and maintenance organizations, safety oversight, enforcement and investigation arrangements. Other public bodies remain responsible for border control, customs, public health, competition, consumer protection and national security [10].

In Ukraine, the Air Code forms the legislative basis for the use of airspace and civil aviation activity. It operates together with aviation rules, international treaties binding on Ukraine and related legislation. The organization of passenger transport must therefore account for operator certification, market authorization, safety and security rules, consumer obligations and the allocation of authority among public institutions [4].

National implementation is not static. Rules must be updated when international Standards change, technology develops or operational experience reveals a gap. Approximation with regional frameworks may also require institutional and procedural reform. Effective implementation needs consultation with operators and passengers, impact assessment, realistic transition periods, inspector training and digital tools for oversight [6].

For an airline or airport, compliance should be managed as a controlled cycle. The organization identifies applicable requirements, assigns an owner, translates rules into procedures, trains personnel, records performance, reports occurrences, audits implementation and corrects nonconformities. Changes in law must be monitored centrally and communicated before they affect operations. Contractors should be included because outsourcing a process does not eliminate the certificate holder's accountability [29].

The composite priority score for corrective action j is given by formula (24) [28]:

$$P_j = S_j\, O_j\, D_j\, U_j, \tag{24}$$

Here, P_j is the corrective-action priority score and j identifies the action; multiplication means that a high value of any severity, occurrence, detection, or urgency component raises priority.

This multiplicative score ranks corrective actions according to their operational and legal importance. Each action is rated for severity, occurrence, detection difficulty, and urgency using the same predefined scale. Multiplying the ratings highlights actions that are simultaneously serious, likely, difficult to detect, and time-critical. The rating criteria must be documented to prevent inconsistent scoring between auditors or departments. The result supports corrective-action sequencing, assignment of responsible managers, and allocation of limited compliance resources. In this expression, S_j is the severity of possible consequences, O_j is the likelihood of occurrence, D_j reflects difficulty of detection before harm occurs, and U_j represents legal or time urgency. Higher values indicate actions that should receive earlier managerial attention [4].

The regulatory framework is therefore not an external administrative burden added to transportation. It is part of the architecture that allows passengers to cross borders with a predictable level of safety, security and legal protection. Its effectiveness depends on international harmonization, competent national implementation and disciplined operational compliance [4].

1.3. Classification of passenger air services and forms of flight organization

Classification is required because the term passenger air service covers operations with different markets, schedules, legal conditions, aircraft and production processes. A useful classification should support a decision: the selection of a regulatory regime, network structure, fleet, sales method, airport process or service standard. One flight can belong to several categories simultaneously. For example, it may be international, scheduled, short-haul, point-to-point, low-cost and seasonal [1].

The most fundamental distinction is between domestic and international carriage. Domestic carriage takes place between points within one state under its national market and operational rules. International carriage includes an agreed stopping place in another state and engages traffic rights, border formalities and international liability rules. The commercial presentation of an itinerary is not always sufficient to determine its legal character; the contract and agreed stopping places must be considered [11].

A scheduled service is operated according to a published timetable or with a regularity that makes it recognizably systematic. Seats are normally sold individually to the public through the carrier's distribution channels. Schedule stability, slot coordination, minimum service levels and consumer expectations are therefore important. Airlines plan scheduled networks for a season, then continuously adjust capacity, frequency and prices as demand becomes clearer [18].

The coefficient of variation used to assess route schedule regularity is given by formula (25) [8]:

$$CV_h = \frac{\sigma_h}{\overline{h}}, \tag{25}$$

Here, CV_h is the coefficient of variation of departure headways, σ_h is their standard deviation, and $\overline{h}$ is their arithmetic mean.

This indicator measures the regularity of intervals between successive departures. The standard deviation of the headways is divided by their mean, producing a dimensionless value. A low value indicates evenly distributed departures, while a high value shows clustering or long gaps. The calculation should cover a representative service period and exclude intervals created by airport closure unless they are part of normal operation. It is used to evaluate timetable convenience, connection opportunities, and the temporal quality of route service. In this expression, $\overline{h}$ is the mean headway and σ_h is its standard deviation. A value close to zero indicates an evenly spaced timetable. The average offered daily capacity is given by formula (26) [8]:

$$Q_d = \sum_{f=1}^{F_d} S_f, \tag{26}$$

Here, Q_d is daily offered seat capacity, F_d is the number of flights operated during the day, f is a flight index, and S_f is seats offered on flight f.

This expression calculates the total number of seats offered on a route or at an airport during one day. The seating capacity of every operated flight is added without regard to whether the seats are sold. The result changes with frequency, aircraft type, and configuration. Comparing it with daily passenger demand reveals expected spare capacity and supports load-factor estimation. It is used in schedule planning, terminal-flow forecasting, and analysis of competitive capacity. In this expression, S_f is the number of seats offered by daily flight f [13].

Non-scheduled services are performed outside a regular published programme. Charter carriage is the most common commercial form. A tour operator, company,

public institution, sports organization or other customer contracts for all or a substantial part of the aircraft capacity. Seats may then be included in a package or distributed to a defined group. Charter operations can respond efficiently to concentrated seasonal demand, special events, workforce movement, evacuation or ad hoc travel [21].

The distinction affects risk allocation. In scheduled service, the airline generally bears the demand risk for individual seats. In a full charter, the charterer commits to the aircraft capacity under the charter contract, although the detailed allocation depends on the agreement. Operational responsibility for safe conduct of the flight remains with the licensed operator and cannot be transferred merely through commercial contracting [24].

Charters may be inclusive-tour, affinity-group, single-entity or special-purpose operations, depending on national terminology and the relationship between the charterer and passengers. Regulatory systems differ in how they authorize and supervise these services. The planner must verify market access, consumer responsibility, financial protection and documentation rather than relying only on the commercial label "charter" [11].

Services are commonly classified as short-, medium- and long-haul. There is no universal distance threshold because flight time, aircraft capability, crew rules and regional practice differ. The classification is nevertheless operationally useful. Short-haul flights have a high proportion of turnaround, climb and descent in the total cycle and compete more directly with surface modes. Long-haul flights require greater fuel planning, crew-rest arrangements, catering, baggage capacity and disruption recovery resources [11].

Routes can also be described by their function in a network. A local route connects an origin and destination primarily for direct demand. A feeder route brings passengers from a smaller market to a hub. A trunk route connects major centres with high frequency or capacity. A regional service links communities within a defined area, while an intercontinental service connects different continental markets. Thin routes have limited demand and may require smaller aircraft or lower frequency; dense routes can support several operators and differentiated schedules [13].

The origin–destination concept is essential. Flight-leg statistics count every boarded passenger on each segment, whereas origin–destination statistics identify the actual journey between the passenger's starting point and final destination. A transfer passenger contributes traffic to several legs but represents one journey. Network planning based only on leg counts can therefore misinterpret the market [13].

The relationship between origin–destination demand and leg traffic may be expressed as formula (27) [8]:

$$P_l = \sum_{o=1}^{n} \sum_{d=1}^{n} a_{odl} D_{od}, \tag{27}$$

Here, l identifies a physical flight leg, o and d identify origins and destinations, n is the number of airports, and the double sum aggregates all origin–destination flows using leg l.

This model converts origin–destination demand into traffic on individual flight legs. For every origin and destination pair, demand is included only on the legs used by the selected itinerary. Summing these assigned flows gives the passenger volume that each physical leg must carry. The accuracy depends on itinerary choice, connection rules, and the representation of competing routes. The calculation is used in network planning, fleet assignment, hub analysis, and forecasting of transfer baggage and terminal flows. In this expression, P_l is passenger traffic on flight leg l, D_{od} is demand between origin o and destination d, and a_{odl} equals one when itinerary od uses leg l and zero otherwise. This expression permits transfer flows to be assigned correctly to the physical segments of the network [24].

In a point-to-point network, flights are designed mainly for local demand between two airports. This structure reduces dependence on coordinated connections and can simplify baggage and passenger handling. It is associated with many low-cost operations, although full-service airlines also operate strong point-to-point routes. Its feasibility depends on sufficient local demand to support the desired frequency and aircraft size [24].

A hub-and-spoke network consolidates passengers from multiple origins at a hub and redistributes them to multiple destinations. If m spoke airports are linked only to the hub, the network requires approximately m route links, while the number of links required to connect every pair directly is given by formula (28) [8]:

$$N = \frac{m(m-1)}{2} \tag{28}$$

Here, N is the number of undirected links required to connect every pair of airports, m is the number of airports, and division by two prevents each pair from being counted twice.

This expression counts the direct links needed for a fully connected undirected

network. The number of airports is multiplied by one less than itself because each airport could connect to all others, and the product is divided by two to remove duplicate pairs. Network requirements grow approximately with the square of the number of airports. Comparing this value with the number of hub links illustrates the consolidation advantage of a hub-and-spoke structure. The formula is used in conceptual network design and complexity analysis. links. Consolidation therefore allows service between markets that could not support a nonstop flight. The airline coordinates arrivals and departures in banks so that many connections are possible within an acceptable interval [1].

The benefit is accompanied by complexity. A delay on an inbound flight can affect many outbound connections. Baggage must be sorted accurately within limited transfer time. Gates, security processes and passenger information face concentrated peaks. The hub must balance connection quality against aircraft and terminal congestion. Minimum connecting time is therefore both a commercial promise and an operational design parameter [21].

The feasibility condition for a planned connection between inbound flight i and outbound flight j is given by formula (29) [8]:

$$t_j^{\text{dep}} - t_i^{\text{arr}} \geq MCT_{ij} + b_{ij}, \tag{29}$$

Here, t_j^{dep} is the scheduled departure time of outbound flight j, t_i^{arr} is the scheduled arrival time of inbound flight i, MCT_{ij} is their minimum connecting time, and b_{ij} is the robustness buffer.

This inequality tests whether a passenger has enough scheduled time to make a connection. The inbound arrival time is subtracted from the outbound departure time and compared with minimum processing time plus a reliability buffer. The connection is feasible only when the available interval equals or exceeds the required interval. Different values should be used for domestic, international, terminal-change, and special-assistance connections. The test supports timetable construction, itinerary validation, baggage planning, and protection against recurrent missed connections. In this expression, MCT_{ij} is the applicable minimum connecting time and b_{ij} is an additional robustness buffer. The number of passengers using feasible protected connections can be estimated as formula (30) [8]:

$$P^{\text{conn}} = \sum_i \sum_j x_{ij} p_{ij}, \tag{30}$$

Here, P^{conn} is total feasible connecting demand, i and j index inbound and outbound flights, p_{ij} is demand for connection i–j, and binary variable x_{ij} equals one only when that connection is feasible.

This expression calculates the passenger volume associated with feasible protected connections. Demand for every inbound–outbound flight pair is multiplied by a binary feasibility decision and the products are summed. Infeasible or unprotected connections contribute zero to the result. The calculation can be repeated under different minimum times and buffers to examine the trade-off between connectivity and reliability. It supports hub-bank design, gate planning, baggage-resource allocation, and evaluation of schedule changes. In this expression, p_{ij} is connecting demand and x_{ij} equals one for a feasible connection and zero otherwise [24].

Multi-hub and hybrid networks combine these principles. An airline group may use several hubs for different geographical flows, while operating direct services in dense markets. Network structure changes with demand, alliances, airspace constraints, airport costs and fleet availability. It should be understood as a portfolio of route functions rather than a rigid label [21].

For a network represented by adjacency matrix $A = [a_{ij}]$, the normalized degree centrality of airport i is given by formula (31) [8]:

$$C_i^{deg} = \frac{\sum_{j=1}^{n} a_{ij}}{n-1}. \tag{31}$$

Here, C_i^{deg} is normalized degree centrality of airport i, a_{ij} is one when airports i and j are directly connected and zero otherwise, n is the number of airports, and $n-1$ is the maximum possible number of neighbours.

This indicator measures the proportion of all possible airports directly connected to a selected airport. The number of observed direct neighbours is divided by the maximum possible number, which is one less than the network size. A value near one indicates a broadly connected airport, while a low value describes a peripheral node. The measure does not account for frequency or passenger volume, so it should be combined with weighted connectivity indicators. It is used to compare network positions and identify hubs, gateways, and regional endpoints. The share of passengers transferring at hub h is given by formula (32) [3]:

$$TS_h = \frac{P_h^{transfer}}{P_h^{total}} \times 100\%. \tag{32}$$

Here, TS_h is the transfer share at hub h, $P_h^{transfer}$ is the number of transfer passengers, P_h^{total} is total passengers handled, and 100% expresses the result in percent.

This percentage shows how strongly an airport depends on transfer traffic. Transfer passengers are divided by all passengers handled at the hub and the ratio is converted to percent. A high value indicates that coordinated connections and baggage transfers are central to the airport's function. Such airports are especially sensitive to missed connections and disruption propagation. The indicator supports terminal design, schedule banking, minimum-connection policy, and planning of transfer desks and baggage systems. Together, these indicators distinguish airports with many direct links from airports whose function depends strongly on transfer flows [11].

Table 3: Comparison of principal network forms

Criterion	Point-to-point	Hub-and-spoke	Hybrid or multi-hub
Primary demand	Local origin–destination	Combination of local and transfer flows	Different flow types by route
Main advantage	Simple direct journey	Connectivity and traffic consolidation	Flexibility and market coverage
Main vulnerability	Insufficient demand on thin routes	Propagation of delay through connections	Greater planning and fleet complexity
Schedule logic	Market-preferred departure times	Coordinated arrival and departure banks	Selective banking and direct frequency
Baggage process	Predominantly origin to destination	High share of time-critical transfers	Mixed local and transfer handling

A full-service network carrier normally combines several cabin classes, connecting itineraries, interline cooperation, loyalty programmes and a broad range of included or optional services. Its network is often organized around one or more hubs. The product is differentiated by flexibility, schedule, lounge access, priority services and through handling. The model requires sophisticated revenue management and coordination across many passenger categories [23].

A low-cost carrier seeks a structurally low unit cost. Common features include high aircraft utilization, dense seating, simplified fleets, direct distribution, rapid turnaround and unbundled services. However, the term does not define a single product. Low-cost airlines may operate primary airports, connections, assigned seating or long-haul flights. Classification should therefore be based on actual cost and process characteristics rather than stereotypes [13].

An ultra-low-cost model extends unbundling and operational standardization,

with the basic fare covering a narrowly defined transport service and a high share of revenue generated by optional products. A leisure carrier aligns capacity with tourism demand and may cooperate closely with tour operators. A regional airline uses aircraft and schedules suited to smaller markets and may operate under its own brand or a capacity-purchase agreement for a larger airline. A hybrid carrier combines elements of several models [24].

For a given route, the break-even load factor can be calculated as formula (33) [1]:

$$LF_{BE} = \frac{C_f}{S\,y\,d}, \tag{33}$$

Here, LF_{BE} is the break-even load factor, C_f is total flight cost, S is offered seats, y is revenue per passenger-kilometre, and d is route distance.

This indicator determines the passenger load needed for flight revenue to equal flight cost. Total flight cost is divided by the maximum fare revenue obtainable from all offered seat-kilometres. A lower value indicates that the route can cover cost with fewer occupied seats. The calculation assumes a representative average yield and should be repeated when fares, distance, aircraft type, or operating cost changes. It supports route-launch decisions, pricing, capacity selection, and assessment of commercial sustainability. In this expression, C_f is total flight cost, S is the number of seats, y is average revenue per passenger-kilometre, and d is route distance. If ancillary revenue per passenger is a, the expression is given by formula (34) [3]:

$$LF_{BE} = \frac{C_f}{S(yd + a)}. \tag{34}$$

Here, LF_{BE} is the break-even load factor after ancillary revenue is included and a is average ancillary revenue per passenger; C_f, S, y, and d retain the meanings defined above.

This modified indicator includes ancillary products in the break-even calculation. Fare revenue over the route and average ancillary revenue are added for each carried passenger before comparison with total cost. Higher baggage, seat-selection, catering, or other ancillary revenue lowers the load factor required to break even. The ancillary value must be based on actual passenger purchasing behaviour rather than the maximum possible charge. The measure is useful for comparing bundled and unbundled business models and for evaluating changes in optional-service policy [18].

Business-model choice determines passenger expectations and operational de-

sign. A service included in one fare may be optional in another. The decisive requirement is transparency before purchase and consistent delivery at the airport. Unbundling can improve consumer choice and prevent all passengers from paying for services they do not use, but excessive complexity can make meaningful comparison difficult [13].

A nonstop flight operates between two airports without an intermediate landing. A direct flight may retain one flight number while making an intermediate stop, possibly with a change of aircraft. A connecting itinerary requires the passenger to transfer between flights. These terms should be used precisely in schedules and sales information because they imply different journey times and risks [13].

Connections can be online, involving the same airline, or interline, involving different airlines under arrangements that support ticketing, baggage transfer and settlement. A self-connection is assembled by the passenger from separate contracts. It may provide a lower price or additional route options, but through protection during disruption and baggage transfer may be absent. The passenger must understand whether the itinerary is one protected journey or several independent journeys [11].

Code sharing allows one flight operated by an airline to be marketed under the designator and flight number of another. It expands the apparent network and can simplify booking. The operating carrier performs the flight and is central to operational and many passenger-rights obligations, while the marketing carrier has sales and information responsibilities. The identity of the operating carrier must be disclosed accurately [21].

Interline agreements, alliances and joint ventures create deeper forms of cooperation. They may coordinate schedules, fares, loyalty benefits and revenue. Cooperation improves connectivity and recovery options, but regulators evaluate its competitive effects. Operationally, shared services require aligned data, ticketing, baggage, accessibility and disruption procedures. A seamless commercial itinerary must be supported by a seamless process, not merely a shared flight number [11].

Passengers may be classified by journey purpose, fare product, cabin class, group status or special service requirement. Business and leisure are broad demand categories with different price sensitivity and schedule preferences, although individual behaviour is more varied than the labels imply. Transfer passengers require connection management; transit passengers continue through an intermediate point under arrangements defined by the itinerary and local rules [24].

Cabin products commonly include economy, premium economy, business and first class. Differences may include seat space, flexibility, baggage allowance, catering,

priority and ground services. Cabin class is not identical to booking class. Booking classes are inventory categories used for fare and revenue control, and several can exist within one physical cabin [11].

The revenue of a multi-class cabin can be represented as formula (35) [8]:

$$R = \sum_{k=1}^{K} n_k y_k + R_a, \tag{35}$$

Here, R is total cabin revenue, k is a booking-class index, K is the number of booking classes, n_k is passengers in class k, y_k is average fare in that class, and R_a is ancillary revenue.

This expression calculates total passenger-related cabin revenue across booking classes. Passenger numbers are multiplied by the average fare in each class, the class revenues are added, and ancillary revenue is included. The model shows how revenue depends on both occupancy and the distribution of passengers among fare classes. Two flights with the same load factor can therefore produce very different revenue. The calculation supports inventory control, fare-class allocation, revenue forecasting, and evaluation of cabin-product changes. In this expression, n_k is the number of passengers in booking class k, y_k is the average fare of that class, and R_a is ancillary revenue. The cabin load factor is given by formula (36) [3]:

$$LF_c = \frac{\sum_{k=1}^{K} n_k}{S_c} \times 100\%, \tag{36}$$

Here, LF_c is cabin load factor, k indexes booking classes, K is their number, n_k is passengers in class k, S_c is available cabin seats, and 100% converts the ratio to percent.

This percentage measures occupancy of the physical cabin across all booking classes. Passenger counts from every class are added and divided by seats available for sale. The result describes capacity use but does not reflect differences in fare or revenue contribution. It should be calculated separately for cabins when economy, business, and other products have different capacities and demand patterns. The indicator supports overbooking control, cabin configuration, service provisioning, and operational reporting. In this expression, S_c is the number of installed seats available for sale [18].

Special handling categories include infants, children, unaccompanied minors, passengers requiring mobility assistance, passengers with medical conditions, deportees or inadmissible persons, groups and passengers carrying special baggage. Classification enables the correct process but should not become a substitute for individual

assessment. Assistance information is sensitive personal data and should be accessible only to personnel who need it for safe service delivery [23].

Services can be classified by aircraft capacity and propulsion category: regional turboprop, regional jet, narrow-body jet and wide-body jet are common commercial groupings. Fleet choice depends on range, payload, runway performance, demand, frequency, airport compatibility, acquisition and operating cost. A larger aircraft reduces unit cost only if demand supports acceptable utilization and load factor [18].

The required weekly flight frequency for directional demand D_w may be estimated by formula (37) [3]:

$$F_w = \left\lceil \frac{D_w}{S\, LF_t} \right\rceil , \tag{37}$$

Here, F_w is required weekly frequency, D_w is weekly directional demand, S is aircraft seating capacity, LF_t is target load factor as a fraction, and $\lceil \cdot \rceil$ rounds upward to a whole flight.

This calculation determines how many weekly flights are needed to carry forecast directional demand. Effective passenger capacity per flight is obtained by multiplying aircraft seats by the target load factor, and demand is divided by that value. The result is rounded upward because a fraction of a flight cannot be scheduled. A lower target load factor increases frequency and creates more reserve, while a higher target reduces frequency but increases disruption exposure. The formula supports preliminary schedule design and aircraft-size selection. The calculated frequency curves are presented in Figure 4.

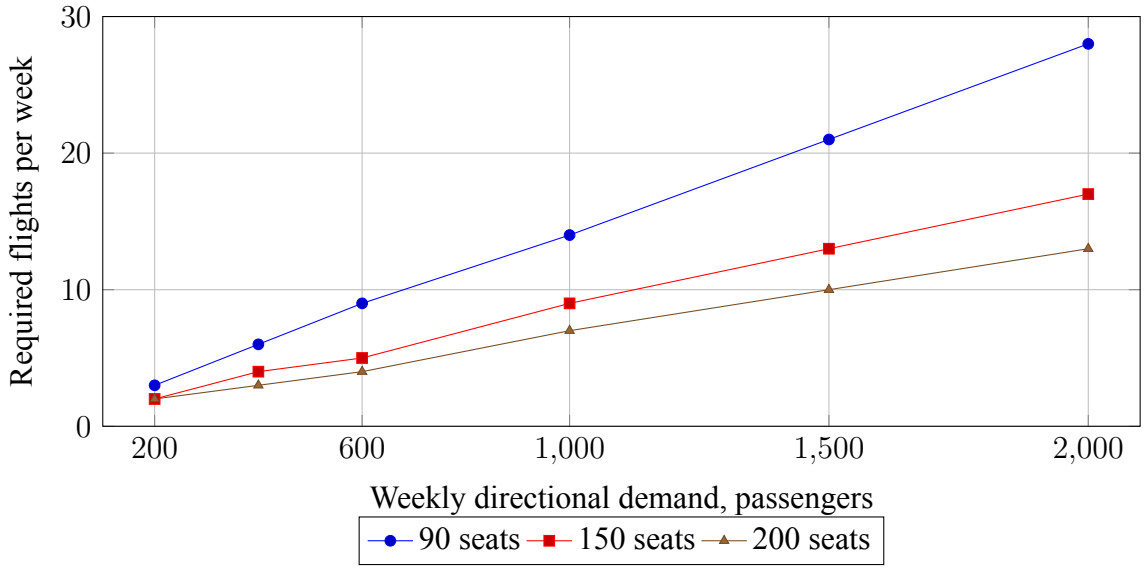

Figure 4: Required weekly frequency for different aircraft capacities at a target load factor of 0.82. Author's calculation based on [18]

In this expression, S is aircraft seating capacity and LF_t is the target load factor expressed as a fraction. Fleet assignment can be formulated as formula (38) [3]:

$$\min Z = \sum_{r=1}^{R} \sum_{a=1}^{A} C_{ra} x_{ra}, \tag{38}$$

Here, Z is total assignment cost, $r = 1, \ldots, R$ indexes routes, $a = 1, \ldots, A$ indexes aircraft types, C_{ra} is the cost of assigning type a to route r, and x_{ra} is the corresponding number of flights.

This objective function selects a fleet assignment with the lowest total operating cost. For each route and aircraft type, unit assignment cost is multiplied by the number of flights and all products are summed. The minimization must be subject to demand coverage, aircraft availability, range, runway, maintenance, and schedule constraints. Changing a constraint can alter the economically preferred aircraft even when its direct flight cost is unchanged. The model supports seasonal fleet planning, aircraft swaps, and evaluation of leasing requirements. subject to demand, range, airport and aircraft-availability constraints, where x_{ra} is the number of flights by aircraft type a on route r [18].

An airline may operate flights with its own aircraft and crew or obtain capacity through leasing and commercial arrangements. In a dry lease, the aircraft is provided without crew and is operated under the lessee's operational system, subject to applicable approvals. In a wet lease, aircraft, crew, maintenance and insurance are supplied by the lessor, while the commercial use of capacity is arranged with the lessee. Code sharing, franchising and capacity-purchase agreements create further combinations of brand, sales and operation. Passengers must be told who actually operates the flight [24].

Average daily aircraft utilization is given by formula (39) [3]:

$$U_a = \frac{\sum_{f=1}^{F} BH_f}{N_a D}, \tag{39}$$

Here, U_a is average daily utilization per available aircraft, F is the number of flights, f is a flight index, BH_f is block hours of flight f, N_a is available aircraft, and D is operating days.

This indicator measures how many block hours each available aircraft produces per operating day. Block time from all flights is added and divided by the product of fleet size and days. Higher utilization can reduce fixed cost per flight but leaves less time for maintenance and recovery from delay. The calculation should exclude aircraft

that are not contractually or technically available during the period. It supports fleet sizing, rotation planning, leasing analysis, and comparison of operational productivity. In this expression, BH_f is the block time of flight f, N_a is the number of available aircraft, and D is the number of operating days. The technical availability coefficient is given by formula (40) [3]:

$$K_a = \frac{H_{calendar} - H_{maintenance} - H_{failure}}{H_{calendar}}, \tag{40}$$

Here, K_a is technical availability, $H_{calendar}$ is total calendar hours, $H_{maintenance}$ is hours unavailable for planned maintenance, and $H_{failure}$ is hours unavailable because of failures.

This coefficient measures the share of calendar time during which an aircraft is technically available. Planned-maintenance and failure-related downtime are subtracted from total calendar hours, and the remainder is divided by calendar hours. A value near one indicates high availability, while a decline signals maintenance burden or reliability problems. Consistent definitions are required for waiting time, spare-parts delays, and administrative downtime. The coefficient supports maintenance planning, spare-aircraft decisions, reliability programmes, and fleet-capacity forecasts. In this expression, unavailable hours due to planned maintenance and failures are deducted from total calendar hours [21].

Regular operations are planned within a seasonal schedule. Additional sections can be added when demand exceeds the capacity of a planned flight. Positioning flights move an aircraft without normal revenue passengers to the location required for its next task. Ferry and test flights have technical purposes. These movements consume aircraft, crew, slots and fuel and must be included in production planning even though they do not directly generate passenger revenue [18].

Classification therefore connects market design with operational responsibility. It enables planners to select the appropriate network, aircraft, schedule, contract and passenger process. Because contemporary airlines combine categories, analysis should identify the characteristics of the particular service instead of assigning it a single permanent label [13].

1.4. Current trends and directions in the development of passenger air transport

Passenger aviation develops under the simultaneous influence of demand, technology, regulation, energy policy and geopolitical conditions. The recovery of global traffic after the COVID-19 shock demonstrated both the strength of mobility demand and the vulnerability of tightly connected networks. By the middle of the 2020s, development is no longer described adequately as a return to previous practice. Airlines and airports are redesigning processes around digital identity, operational resilience, environmental constraints and more selective investment [26].

The direction of development differs by market. Mature regions seek to manage congestion, renew fleets and decarbonize operations, while rapidly growing regions require new capacity and skilled personnel. Some communities depend on restoring basic connectivity. Airspace closures and longer routings affect fleet productivity and cost in certain corridors. The common challenge is to expand useful connectivity without weakening safety, affordability or environmental responsibility [7].

Long-term demand is supported by population, income, urbanization, tourism, migration and international business. Growth is not uniform. It is concentrated in metropolitan regions and expanding middle-income markets, while remote and low-density routes may remain commercially fragile. Forecasts should therefore be disaggregated by origin–destination pair, purpose, season and passenger segment [7].

Under a constant average growth assumption, passenger demand after t periods is given by formula (41) [18]:

$$D_t = D_0(1+g)^t, \tag{41}$$

Here, D_t is demand after t periods, D_0 is base-period demand, g is average growth per period, and t is the number of compounding periods.

This compound-growth model projects passenger demand from a known base value. The base demand is multiplied by one plus the periodic growth rate raised to the number of periods. Positive growth produces an accelerating trajectory, while a negative rate represents contraction. The model assumes the same proportional growth in every period and therefore should be supplemented by scenarios when market conditions are uncertain. It is used for long-term fleet, airport-capacity, and workforce planning. In this expression, D_0 is base-period demand and g is the average growth

rate. When initial and final demand are known, the compound annual growth rate is given by formula (42) [21]:

$$g = \left(\frac{D_t}{D_0}\right)^{1/t} - 1. \tag{42}$$

Here, g is compound average growth per period, D_t is final demand, D_0 is initial demand, t is the number of periods, and the exponent $1/t$ takes the corresponding geometric root.

This calculation derives the constant compound rate connecting initial and final demand. Final demand is divided by initial demand, the geometric root corresponding to the number of periods is taken, and one is subtracted. The result is an average rate and does not reproduce fluctuations within the interval. Both demand observations must use the same traffic definition and geographical scope. The rate supports historical trend comparison, benchmarking of markets, and preparation of baseline forecast scenarios. For short-term updating, the exponential smoothing expression is given by formula (43) [21]:

$$\widehat{D}_{t+1} = \alpha D_t + (1-\alpha)\widehat{D}_t, \qquad 0 < \alpha < 1. \tag{43}$$

Here, $\widehat{D}_{t+1}$ is the forecast for the next period, D_t is observed demand in the current period, $\widehat{D}_t$ is the current forecast, and α is the smoothing coefficient between zero and one.

This forecasting method updates the next-period estimate using the latest observation and the previous forecast. The smoothing coefficient determines how much weight is assigned to new information. A high value reacts quickly to changes but produces a more variable forecast, while a low value gives a smoother but slower response. The coefficient can be selected by minimizing forecast error on historical data. The method is useful for short-term passenger, baggage, staffing, and resource forecasts when strong seasonality has been treated separately [7]. Alternative long-term demand trajectories are compared in Figure 5.

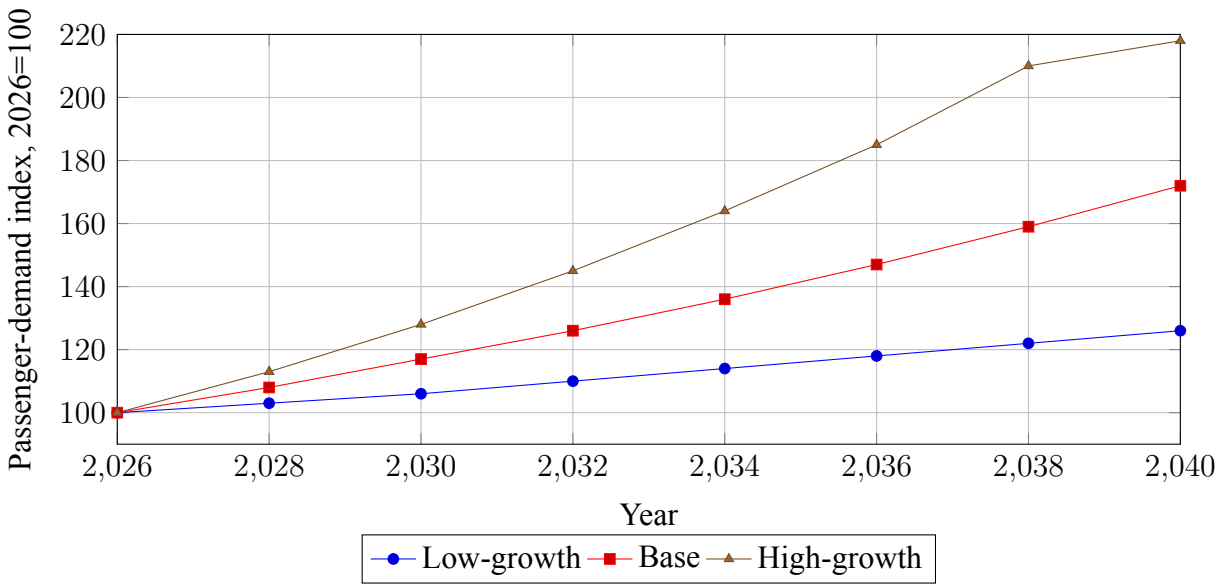

Figure 5: Illustrative scenarios of passenger-demand development for 2026–2040. Author's scenario calculation based on [21]

Passengers increasingly expect continuous control over the journey through a mobile device. They compare total price, receive notifications, store documents, select seats, purchase baggage and seek alternatives during disruption. At the same time, reliance on digital channels can exclude passengers without suitable devices, connectivity or confidence. Development should preserve accessible human assistance and provide equivalent information through more than one channel [12].

Flexibility has become a product attribute. Travellers pay closer attention to change conditions, refund time, health or entry requirements and the reliability of connections. Corporate travel policies combine cost, time, emissions and remote-meeting alternatives. Leisure demand is more willing to use secondary destinations and travel outside traditional seasons when price incentives are strong [25].

Digitalization is moving from isolated self-service machines toward an integrated passenger identity and order-management environment. Online and mobile check-in, electronic boarding passes, self-service bag drop, automated border gates and real-time notifications are already established at many airports. The next development stage connects these processes so that passengers do not repeatedly present the same information [7].

A composite digital-maturity index can be calculated as formula (44) [9]:

$$DMI = \frac{\sum_{j=1}^{m} w_j d_j}{\sum_{j=1}^{m} w_j}, \qquad 0 \le d_j \le 1, \tag{44}$$

Here, DMI is the digital-maturity index, j identifies a digital capability, m is the number of capabilities, d_j is maturity on a zero-to-one scale, and w_j is its importance weight.

This index summarizes the maturity of several digital capabilities in one normalized value. Every capability is scored, multiplied by its importance weight, and included in the weighted average. A high value indicates broad digital development, but the component scores remain necessary for identifying specific weaknesses. The scoring scale should cover technology, data quality, integration, governance, cybersecurity, and user adoption. The result supports digital roadmaps, investment prioritization, and comparison of airports or airlines. In this expression, d_j is the maturity level of digital capability j and w_j is its operational significance. The share of passengers using automated processing is given by formula (45) [9]:

$$K_{auto} = \frac{P_{auto}}{P_{total}} \times 100\%. \tag{45}$$

Here, K_{auto} is the automated-processing share, P_{auto} is passengers using automated channels, P_{total} is all processed passengers, and 100% expresses the share in percent.

This percentage measures passenger adoption of automated service channels. The number of passengers using automated processing is divided by all processed passengers. Growth in the value may indicate successful digitalization, but it can also reflect reduced availability of staffed alternatives. The indicator should therefore be analysed together with completion rate, error rate, accessibility, and passenger satisfaction. It supports planning of kiosks, bag drops, gates, staff assistance, and communication campaigns. If average manual and automated processing times are t_m and t_a, total time saved is given by formula (46) [17]:

$$\Delta T = P_{auto}(t_m - t_a). \tag{46}$$

Here, ΔT is aggregate processing time saved, P_{auto} is the number of automated transactions, t_m is average manual-processing time, and t_a is average automated-processing time.

This expression estimates the total processing time saved by automation. The time difference between manual and automated processing is multiplied by the number of automated transactions. A positive result indicates a reduction in total passenger-processing time, while a negative result signals that the automated process is slower. Measurements should include failed transactions and the staff time required to resolve exceptions. The result supports business cases for automation, capacity estimation, and

evaluation of process redesign [19].

Biometric identification can associate a passenger with a verified travel document and use facial comparison at selected checkpoints. Potential benefits include shorter transaction time and reduced document handling. However, biometric data are highly sensitive. A lawful deployment requires purpose limitation, informed communication, security, retention controls, accuracy testing, procedures for mismatches and a non-biometric alternative. Efficiency cannot be treated as automatic authorization for unlimited data collection [4].

Airline retailing is shifting from legacy records and message exchanges toward modern offer and order concepts. The objective is a consistent digital record of the customer's purchase and fulfilment status. Implementation must address interoperability with airports, border authorities, travel sellers, payment providers and partner airlines. During transition, old and new systems coexist, creating reconciliation risks that must be managed [9].

Artificial intelligence is being applied to demand forecasting, disruption prediction, customer communication, turnaround monitoring, baggage analysis and resource allocation. Its value depends on the quality and representativeness of data. Decisions affecting price, accessibility, security or passenger rights require governance, explainability appropriate to the risk, human review and monitoring for bias. An automated recommendation remains part of the organization's accountable decision process [15].

The mean absolute percentage error used to monitor forecast quality is given by formula (47) [9]:

$$MAPE = \frac{100\%}{n} \sum_{t=1}^{n} \left| \frac{D_t - \widehat{D}_t}{D_t} \right|, \tag{47}$$

Here, $MAPE$ is mean absolute percentage error, t is an observation-period index, n is the number of periods, D_t is actual demand, and $\widehat{D}_t$ is predicted demand.

This percentage measures the average relative size of forecast errors. For each period, the absolute difference between actual and predicted demand is divided by actual demand, and the period values are averaged. Lower values indicate more accurate forecasts. The measure can become unstable when actual demand is zero or very small, so alternative errors should be used in such cases. It supports model selection, parameter tuning, and monitoring of forecasting performance. In this expression, D_t and $\widehat{D}_t$ are actual and predicted demand. For classification systems, precision and recall are

given by formula (48) [9]:

$$Precision = \frac{TP}{TP + FP}, \qquad Recall = \frac{TP}{TP + FN}, \tag{48}$$

Here, $Precision$ is the fraction of predicted positives that are correct, $Recall$ is the fraction of actual positives detected, TP is true positives, FP is false positives, and FN is false negatives.

These indicators evaluate the quality of a binary prediction or detection system. Precision measures how many positive alerts are correct, whereas recall measures how many actual positive cases are detected. Increasing one measure can reduce the other when the decision threshold changes. The preferred balance depends on whether false alarms or missed events create greater operational cost. The indicators support evaluation of baggage-risk models, disruption alerts, security screening, and predictive-maintenance systems. In this expression, TP, FP and FN denote true positives, false positives and false negatives [12].

Table 4: Development priorities and associated management requirements

Direction	Expected benefit	Required control
Integrated digital identity	Faster and more convenient processing	Privacy, cybersecurity, accuracy and alternative channels
Data-driven operations	Earlier prediction and better resource allocation	Data quality, governance and human accountability
Fleet renewal	Lower fuel use, emissions and maintenance burden	Capital planning, training and infrastructure compatibility
Sustainable aviation fuel	Reduction of life-cycle carbon intensity	Verified sustainability, supply expansion and cost management
Intermodal integration	Better door-to-door connectivity	Timetable, ticketing, baggage and disruption coordination
Resilience programmes	Faster recovery from irregular operations	Scenario planning, reserves, communication and joint exercises

Airports, airlines, ground handlers and air navigation providers cannot optimize performance independently. A late aircraft, unavailable stand, baggage-system failure or airspace restriction changes the plan for several participants. Collaborative decision-making creates a common operational picture and agreed milestones for arrival, turnaround and departure. Shared estimates allow resources and slots to be adjusted before the disturbance becomes critical [7].

The aircraft turnaround is becoming more visible through sensors, mobile ap-

plications and event data. Fuelling, catering, cleaning, boarding, baggage loading and technical actions can be monitored against the plan. The purpose is not simply to pressure each activity to work faster. It is to identify dependencies, protect safety barriers and intervene where delay threatens the critical path [7].

If turnaround activities are represented as a precedence network, the total turnaround time determined by the critical path is given by formula (49) [14]:

$$T_{turn} = \max_{p \in \mathcal{P}} \sum_{i \in p} t_i, \tag{49}$$

Here, T_{turn} is total turnaround duration, $\mathcal{P}$ is the set of feasible precedence paths, p is one path, i is an activity on that path, t_i is its duration, and $\max$ selects the longest path.

This expression determines turnaround duration from the longest dependent sequence of ground activities. Durations are added along every feasible precedence path, and the maximum path total is selected. Activities on this critical path directly affect departure time because they have no usable time reserve. Reducing a non-critical activity may not shorten the turnaround unless it becomes part of the critical path. The calculation supports turnaround scheduling, real-time milestone control, delay prevention, and allocation of ground-handling resources. In this expression, $\mathcal{P}$ is the set of feasible activity paths and t_i is the duration of activity i. The time reserve of a non-critical activity is given by formula (50) [14]:

$$S_i = LS_i - ES_i, \tag{50}$$

Here, S_i is time reserve or slack for activity i, LS_i is its latest permissible start, and ES_i is its earliest permissible start.

This value measures how long a non-critical activity may be delayed without affecting the planned completion time. The earliest permissible start is subtracted from the latest permissible start. Zero slack identifies a critical activity, while a positive value provides operational flexibility. Slack should be recalculated when an earlier task is delayed or when the departure target changes. The measure helps dispatchers decide which activities require immediate intervention and where resources can be temporarily reassigned. In this expression, LS_i and ES_i are its latest and earliest permissible start times [25].

Predictive operations use weather, traffic flow, maintenance, crew, passenger

and airport data to estimate disruption. A useful prediction must lead to an operational choice: holding a connection, swapping an aircraft, changing a gate, rebooking passengers or adding staff. Decision support should display uncertainty, because a false impression of precision can produce unstable interventions [12].

The future network control centre integrates operations control, crew control, maintenance control and customer recovery. Passenger consequences are evaluated alongside aircraft recovery. Cancelling one flight may restore the timetable but leave passengers stranded where accommodation or alternatives are limited. A balanced recovery objective includes completion, delay, downstream disruption, passenger value, special needs, baggage and legal obligations [25].

Recent crises have emphasized resilience: the ability to prepare for, absorb, recover from and adapt to disturbance. Aviation faces severe weather, epidemics, conflict, airspace closure, cyber incidents, infrastructure failure, supplier interruption and sudden demand change. Traditional efficiency programmes often reduce spare aircraft, staffing and time buffers. Resilience requires identifying where reserve capacity has greater value than its apparent idle cost [12].

Business-continuity plans should specify critical functions, dependencies, alternative facilities, minimum staffing, communication and recovery priorities. Plans must be tested through exercises involving all relevant organizations. Contact lists and procedures that are not rehearsed are unlikely to perform well under pressure. Lessons from real events should lead to controlled changes in training, contracts and system architecture [26].

The resilience index combining the retained level of service and recovery speed is given by formula (51) [14]:

$$RI = \frac{1}{T_r} \int_0^{T_r} \frac{Q(t)}{Q_0}\, dt, \tag{51}$$

Here, RI is the resilience index, Q_0 is normal capacity, $Q(t)$ is capacity at time t after disruption, T_r is recovery duration, dt is the integration increment, and the integral measures normalized service retained during recovery.

This index measures both the depth of service loss and the speed of recovery after disruption. Available capacity is expressed as a fraction of normal capacity and integrated over the recovery interval. Dividing by recovery time produces the average proportion of service retained. A value close to one indicates limited degradation or rapid restoration, while a low value indicates severe or prolonged loss. The index sup-

ports comparison of contingency plans, reserve strategies, infrastructure alternatives, and recovery performance after real incidents. In this expression, Q_0 is normal service capacity, $Q(t)$ is capacity available after disruption, and T_r is the time required to restore the target operating state. A larger value indicates a smaller loss of service and faster recovery [12].

Passenger communication is a resilience resource. Accurate early information reduces unnecessary queues and allows travellers to make decisions. Messages should state what is known, what remains uncertain, when the next update will be issued and what options are available. Consistency across application, website, airport display, call centre and staff is essential. Silence or contradictory instructions transforms an operational disturbance into a loss of trust [15].

Environmental policy is a defining long-term driver. The principal climate effect of current passenger aviation arises from fuel combustion, together with non-carbon effects at altitude. Development therefore requires action on technology, fuel, operations, infrastructure and demand. No single measure is sufficient [5].

Fleet renewal provides immediate efficiency gains because newer aircraft and engines generally use less fuel per seat-kilometre under comparable conditions. Benefits depend on seating, load factor, mission length and actual operation. Operational measures include improved flight planning, reduced unnecessary weight, efficient taxiing, continuous climb and descent where possible, and better airspace routing. These measures are valuable but cannot alone offset unrestricted long-term traffic growth [7].

Fuel efficiency and carbon intensity per passenger-kilometre can be calculated as formula (52) [25]:

$$\begin{aligned} FE &= \frac{F}{P\,d}, \\ EI_{CO_2} &= \frac{F\,k_{CO_2}}{P\,d}, \end{aligned} \tag{52}$$

Here, FE is fuel use per passenger-kilometre, EI_{CO_2} is carbon-dioxide intensity per passenger-kilometre, F is fuel consumed, P is passengers, d is distance, and k_{CO_2} is emitted carbon dioxide per fuel unit.

These indicators measure fuel use and carbon-dioxide emissions per passenger-kilometre. Fuel consumed is divided by passenger traffic performed, while emissions additionally include the fuel-specific carbon factor. Higher load factor, lower fuel burn, or longer efficient cruise can reduce the values. Comparisons must use consistent treatment of freight payload, diversion fuel, taxi fuel, and route distance. The indicators support aircraft comparison, environmental reporting, route analysis, and assessment

of operational fuel-saving measures. In this expression, F is fuel consumed, P is the number of passengers, d is flight distance, and k_{CO_2} is the carbon-dioxide emission factor. For a fuel portfolio, life-cycle emissions are given by formula (53) [25]:

$$E_{LC} = \sum_{j=1}^{m} F_j e_j, \tag{53}$$

Here, E_{LC} is total life-cycle emissions, j identifies a fuel pathway, m is the number of pathways, F_j is fuel quantity from pathway j, and e_j is its life-cycle emission factor.

This expression calculates total life-cycle emissions from a portfolio of fuel pathways. The quantity of each fuel is multiplied by its verified life-cycle emission factor and the products are summed. A pathway with low direct combustion emissions can still have a significant value when production, transport, or land-use effects are included. Fuel quantities and factors must use compatible energy or mass units. The result supports emissions inventories, sustainable-fuel procurement, regulatory reporting, and comparison of supply scenarios. In this expression, F_j is the quantity of fuel pathway j and e_j is its verified life-cycle emission factor [5].

Sustainable aviation fuels can be used in existing aircraft within approved specifications and offer a pathway to lower life-cycle carbon intensity. Their contribution depends on feedstock, production energy, land-use effects, certification, logistics and additionality. Supply remains limited relative to global jet-fuel demand, and cost is higher than conventional fuel in many markets. Policy must encourage scale while applying credible sustainability criteria and avoiding double counting [25].

For a blend containing a sustainable fuel share x, the weighted life-cycle emission factor is given by formula (54) [5]:

$$e_{blend} = (1 - x)e_{conv} + xe_{saf}. \tag{54}$$

Here, e_{blend} is the blended fuel life-cycle emission factor, x is the sustainable-fuel fraction, $1 - x$ is the conventional-fuel fraction, e_{conv} is the conventional factor, and e_{saf} is the sustainable-fuel factor.

This relationship calculates the life-cycle emission factor of a conventional and sustainable fuel blend. Each component factor is multiplied by its share in the blend and the weighted values are added. Increasing the sustainable share lowers the result only when its verified factor is below the conventional factor. The shares must refer to the same energy or mass basis used by the emission factors. The calculation sup-

ports fuel-blending policy, emissions forecasting, and verification of claimed environmental benefits. The relative reduction compared with conventional fuel is given by formula (55) [5]:

$$RR_{CO_2} = \left(1 - \frac{e_{blend}}{e_{conv}}\right) 100\%. \tag{55}$$

Here, RR_{CO_2} is the relative carbon-dioxide reduction in percent, e_{blend} is the blend emission factor, e_{conv} is the conventional-fuel factor, and 100% converts the fractional reduction to percent.

This percentage expresses the emission reduction achieved by a fuel blend relative to conventional fuel. The blend factor is divided by the conventional factor, the ratio is subtracted from one, and the result is converted to percent. A positive value indicates lower life-cycle emissions, zero indicates no improvement, and a negative value indicates a worse result. The comparison must use the same system boundary and calculation methodology for both factors. It supports reporting of sustainable-fuel performance and comparison of alternative blend shares. The influence of the sustainable-fuel share is visualized in Figure 6.

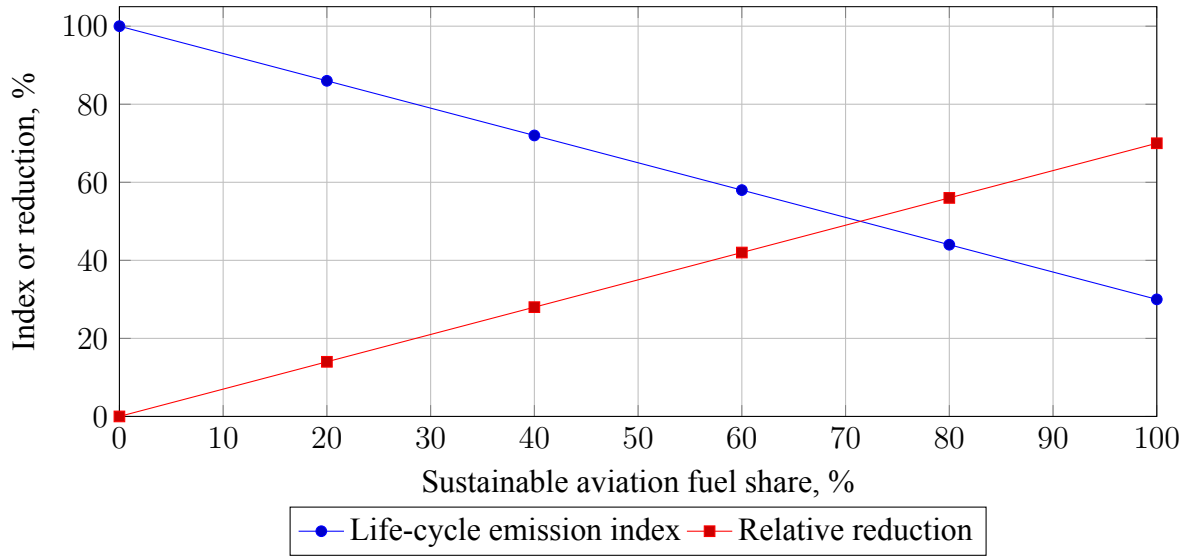

Figure 6: Illustrative effect of sustainable aviation fuel share on life-cycle emissions. Author's calculation based on [25]

The marginal abatement cost is given by formula (56) [5]:

$$MAC = \frac{C_{saf} - C_{conv}}{E_{conv} - E_{blend}}, \tag{56}$$

Here, MAC is marginal abatement cost, C_{saf} and C_{conv} are sustainable and conventional fuel costs, and E_{conv} and E_{blend} are their corresponding life-cycle emissions.

This indicator calculates the additional cost required to avoid one unit of life-cycle emissions. The cost difference between sustainable and conventional fuel is divided by the corresponding reduction in emissions. A lower positive value means that emissions are avoided at a lower incremental cost. A negative value can occur when the cleaner option is also cheaper, while a zero emission difference makes the indicator undefined. The measure supports comparison of decarbonization options, subsidy design, procurement, and investment prioritization. In this expression, the numerator is the additional fuel cost and the denominator is avoided life-cycle emissions [25].

Hydrogen, battery-electric and hybrid-electric propulsion are being researched for particular missions. Battery energy density restricts near-term application mainly to smaller aircraft and shorter ranges. Hydrogen can be used in fuel cells or combustion but requires new aircraft design, storage, airport infrastructure and low-carbon production. These technologies should be assessed by complete life-cycle and system requirements rather than by in-flight emissions alone [26].

Noise and local air quality remain important around airports. Quieter aircraft, operating procedures, restrictions and land-use planning form a balanced approach. Community engagement should provide understandable information and a meaningful process for considering distributional effects. An average reduction does not necessarily protect the neighbourhoods experiencing concentrated exposure [26].

Future traffic cannot be accommodated by runway construction alone. Capacity development includes terminal processes, stands, baggage systems, airspace, surface access, digital infrastructure and staffing. Before expanding physical infrastructure, operators can improve utilization through schedule coordination, common-use systems, automation and more accurate demand forecasts. Expansion remains necessary in some markets, but it should be based on robust scenarios rather than a single growth projection [2].

The net present value used to evaluate the economic feasibility of a digital or infrastructure project is given by formula (57) [5]:

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t}, \tag{57}$$

Here, NPV is net present value, I_0 is initial investment, t is a period index, T is project life, B_t is period benefit, C_t is period cost, and r is the discount rate.

This calculation converts future project benefits and costs into a present mon-

etary value. Initial investment is deducted immediately, while each future net benefit is discounted according to its period and the selected rate. A positive result indicates that discounted benefits exceed discounted costs under the stated assumptions. The outcome is sensitive to project life, demand, operating savings, residual value, and discount rate, so scenario analysis is required. The indicator supports investment decisions for terminals, equipment, information systems, and passenger-processing technologies. In this expression, I_0 is initial investment, B_t and C_t are benefits and operating costs in period t, and r is the discount rate. Under the conventional financial criterion, a project is acceptable when $NPV > 0$, although safety and social effects may require broader appraisal [4].

Airport design is becoming modular and adaptable. Passenger processes change faster than major buildings can be replaced. Flexible spaces, common-use equipment and scalable baggage systems allow terminals to respond to airline changes and new control technologies. Climate adaptation must be included because heat, flooding, storms and sea-level effects can threaten infrastructure and operations [2].

The capacity reserve of terminal subsystem k is given by formula (58) [17]:

$$R_k = Q_k - \lambda_k, \tag{58}$$

Here, R_k is absolute capacity reserve of subsystem k, Q_k is its sustainable capacity, and λ_k is forecast demand in the same unit and time interval.

This value measures the absolute difference between available capacity and forecast demand in a subsystem. Capacity and demand must be expressed in the same unit and peak interval before subtraction. A positive value represents reserve, zero indicates full planned utilization, and a negative value indicates insufficient capacity. The calculation should be repeated for alternative schedules, staffing levels, and disruption scenarios. It supports bottleneck identification, resource planning, and timing of capacity expansion. In this expression, Q_k is sustainable hourly capacity and λ_k is forecast peak demand. The relative reserve coefficient is given by formula (59) [17]:

$$K_{R,k} = \frac{Q_k - \lambda_k}{Q_k} \times 100\%. \tag{59}$$

Here, $K_{R,k}$ is relative reserve of subsystem k, Q_k is sustainable capacity, λ_k is forecast demand, and 100% expresses reserve as a percentage of capacity.

This percentage expresses capacity reserve relative to the subsystem's sustainable capacity. Absolute reserve is divided by capacity and converted to percent. The

normalized form allows comparison of subsystems with different physical scales and units. A small positive value indicates limited ability to absorb variability, while a negative result signals overload. The indicator supports service-level design, resilience planning, and selection of reserve targets for check-in, security, border control, gates, and baggage systems. For a modular expansion with modules of capacity q_m, the required number of additional modules is given by formula (60) [17]:

$$n_m = \left\lceil \frac{\lambda_{future} - Q_{current}}{q_m} \right\rceil . \tag{60}$$

Here, n_m is additional modules required, λ_{future} is forecast future demand, $Q_{current}$ is current capacity, q_m is capacity per module, and $\lceil \cdot \rceil$ rounds upward.

This calculation determines the whole number of capacity modules required to meet future demand. Current capacity is subtracted from forecast demand, the deficit is divided by the capacity of one module, and the result is rounded upward. Rounding upward ensures that the installed capacity is not below the forecast requirement. If current capacity already exceeds demand, the operational interpretation should set the required addition to zero. The expression supports phased terminal expansion, purchase of processing equipment, and planning of modular baggage or gate facilities [5].

Integration with rail and urban transport improves accessibility and can replace inefficient short surface journeys. Effective integration requires more than physical proximity. Timetables, wayfinding, ticketing, minimum connection times, passenger information and disruption responsibility must be coordinated. Through baggage between rail and air is operationally complex but can materially improve the product where volumes justify it [15].

Technology changes work but does not remove the need for competent personnel. Growth and retirement create demand for pilots, technicians, air traffic personnel, ground handlers, security staff, data specialists and managers. Training capacity must expand without reducing standards. Competency-based training, simulation and recurrent assessment help connect qualifications with actual operational performance [4].

The personnel requirement for activity j can be estimated as formula (61) [17]:

$$N_j = \left\lceil \frac{W_j}{H_j K_{prod}} \right\rceil , \tag{61}$$

Here, N_j is employees required for activity j, W_j is its workload in staff-hours, H_j is available hours per employee, K_{prod} is productive-time share, and $\lceil \cdot \rceil$ rounds upward.

This expression estimates the minimum whole number of employees required for an activity. Total workload is divided by the productive time available from one employee and the result is rounded upward. The productive-time coefficient accounts for breaks, administration, training, and other non-processing time. Separate calculations should be made by qualification, shift, and traffic peak because staff are not always interchangeable. The formula supports roster design, recruitment planning, contractor requirements, and evaluation of automation effects. In this expression, W_j is total workload in staff-hours, H_j is available working time per employee, and K_{prod} is the productive-time coefficient. The annual training demand is given by formula (62) [17]:

$$N_{train} = N_{growth} + N_{replacement} + N_{recurrent}, \tag{62}$$

Here, N_{train} is total annual training demand, N_{growth} is training for expansion, $N_{replacement}$ is training to replace departing personnel, and $N_{recurrent}$ is recurrent qualification training.

This identity calculates total annual training demand from three sources. Training required for organizational growth, replacement of departing staff, and recurrent qualification is added. Each component should be estimated separately because it has different timing, course content, and instructor requirements. A rise in turnover increases replacement demand even when the organization is not expanding. The calculation supports training-centre capacity, instructor staffing, simulator scheduling, and annual personnel budgets. which combines expansion, staff replacement and recurrent qualification requirements [2].

Automation shifts tasks from routine transaction processing toward exception management. Staff must understand the system, recognize when its output is unreliable and take control during failure. Human factors are therefore more important, not less. Interfaces, workload, fatigue, communication and organizational culture determine whether technology supports or undermines performance [9].

The strategic development of passenger air transport can be summarized through five linked priorities: safe capacity, passenger-centred digitalization, environmental transformation, operational resilience and international interoperability. Progress in one area must not create unacceptable risk in another. For example, automation should not exclude passengers; capacity growth should not exceed infrastructure or environmental limits; and cost reduction should not remove essential recovery resources [2].

Planning should use scenarios rather than a single forecast. Variables include

economic growth, fuel and carbon prices, technology maturity, regulation, airspace availability and passenger preferences. Each scenario should identify trigger points for fleet, infrastructure and workforce decisions. This approach reduces the risk of committing all resources to assumptions that may not materialize [2].

If scenario s has probability p_s and produces outcome $V_s(x)$ for decision x, an expected-value criterion is given by formula (63) [27]:

$$\max_x \; EV(x) = \sum_{s=1}^{S} p_s V_s(x), \qquad \sum_{s=1}^{S} p_s = 1. \tag{63}$$

Here, x is the decision, $EV(x)$ is its expected value, s is a scenario index, S is the number of scenarios, p_s is scenario probability, $V_s(x)$ is the outcome under scenario s, and the probabilities sum to one.

This criterion calculates the probability-weighted outcome of a decision across several scenarios. The outcome in each scenario is multiplied by that scenario's probability and all weighted values are added. Probabilities must be mutually consistent and sum to one. The criterion favours the decision with the highest average outcome but does not independently penalize variability or severe downside cases. It supports fleet, infrastructure, technology, and network choices when scenarios and their probabilities can be reasonably estimated. For risk-averse planning, the criterion including a penalty for variability is given by formula (64) [27]:

$$U(x) = EV(x) - \lambda \sqrt{\sum_{s=1}^{S} p_s \left[V_s(x) - EV(x)\right]^2}, \tag{64}$$

Here, $U(x)$ is the risk-adjusted utility of decision x, $EV(x)$ is expected value, λ is risk aversion, s and S index scenarios, p_s is scenario probability, and the square-root term is outcome standard deviation.

This criterion adjusts expected outcome for uncertainty by subtracting a variability penalty. Scenario dispersion is calculated as a probability-weighted standard deviation and multiplied by the risk-aversion coefficient. A larger coefficient gives greater preference to stable decisions and a smaller coefficient places more emphasis on average outcome. The decision maker should test several coefficient values because risk preference is not directly observable. The criterion supports robust planning where high-return alternatives may also create unacceptable operational or financial volatility. In this expression, λ is the decision maker's risk-aversion coefficient [2].

Finally, development should be measured by useful and reliable connectivity, not only by passenger totals. A mature system delivers safe journeys, understandable conditions, accessible service, predictable recovery and progressively lower environmental impact. The direction of passenger aviation is therefore toward an integrated mobility service in which physical flight, digital information, legal protection and coordinated ground processes are designed as one system [2].

CHAPTER 2

PARTICIPANTS AND INFRASTRUCTURE OF PASSENGER AIR TRANSPORT

Passenger air transportation is produced by a network of organizations rather than by an airline acting alone. Airlines, airports, ground handling companies, air navigation service providers, public authorities, security organizations, concessionaires and surface transport operators contribute separate resources and decisions to one passenger journey. Their activities are technologically interdependent, while their legal status, commercial objectives and planning horizons differ. Effective organization therefore requires clear allocation of functions, continuous information exchange and procedures for resolving conflicts between local efficiency and system-wide performance [46].

Airport infrastructure provides the physical environment in which these interactions occur. Runways, taxiways, aprons, stands, passenger terminals, baggage systems, access roads, utilities and information networks form a single production complex. A capacity increase in one element is useful only when connected elements can process the resulting flow. Terminal design must reflect passenger categories, border-control requirements, security rules, aircraft mix, baggage technology, transfer patterns and demand variability [56].

The preparation and operation of a flight links strategic planning with minute-by-minute control. Long-term decisions determine fleet, terminal configuration, contracts and staffing, whereas day-of-operation control coordinates gates, crews, fuel, catering, cleaning, boarding, baggage and air traffic restrictions. Delayed or inaccurate information can convert a local deviation into missed connections, baggage failures and disruption of later aircraft rotations [52].

Ground handling is the operational interface between aircraft, airport and passenger service. It includes arrival servicing, passenger stairs or bridges, unloading and loading, cleaning, catering, water and lavatory service, fuelling coordination, push-back and departure preparation. These processes must be completed within a limited turnaround interval and under strict safety constraints [48].

Airport performance cannot be assessed by passenger volume alone. Throughput, queue time, punctuality, service quality, safety, resource productivity, environmental impact and resilience describe different dimensions of the result. A balanced

evaluation combines technical capacity with passenger experience and recognizes that high utilization can reduce the ability to recover from disturbance [43].

The passenger journey provides a practical basis for integrating the work of all participants. From access to the airport and check-in to security control, boarding, flight, arrival and baggage reclaim, each successive operation depends on the completion and quality of the preceding one. A failure at an early stage can create queues, missed departure milestones or additional workload in later stages. For this reason, infrastructure and services should be planned as an end-to-end chain rather than as isolated facilities. Process ownership must remain clear at every transfer point, while common operational information must be available to the organizations responsible for the next stage [36, 43].

The capacity of an airport is consequently determined by the weakest element of the technological chain under the conditions of a particular traffic peak. Additional check-in positions do not increase effective capacity if security screening, passport control, gate areas or baggage systems remain constrained. Similarly, increasing the number of aircraft stands may have limited value when apron routes, buses, boarding bridges or terminal corridors cannot accommodate the associated flow. Functional zoning should therefore separate incompatible flows while minimizing unnecessary movement, repeated control and passenger uncertainty. The resulting layout must also preserve reserve capacity for delayed flights, irregular operations and seasonal concentration of demand [39, 42].

Institutional coordination is inseparable from passenger rights and service quality. Although a passenger normally purchases transportation from an airline, many decisive service events occur in infrastructure managed by an airport or through processes performed by contractors and public authorities. The division of legal and operational responsibility must not produce gaps in information, assistance or complaint handling. Common service standards, escalation procedures and communication channels are needed so that passengers receive consistent instructions during normal operations and disruptions. Particular attention is required for persons with reduced mobility, unaccompanied minors, transfer passengers and travellers affected by cancellation, denied boarding or baggage irregularities [31, 32, 46].

Digital systems increasingly connect organizational and physical infrastructure. Airport operational databases, departure-control systems, resource-management platforms, baggage reconciliation, biometric identification and passenger-information channels create a shared digital representation of the flight process. Automation can

shorten processing time and improve data accuracy, but it also increases dependence on interface compatibility, cybersecurity, data quality and fallback procedures. A digital solution is effective only when employees understand how to interpret its output and can continue critical operations during partial system failure. Technology should therefore support accountable decisions rather than obscure responsibility behind automated messages or fragmented software platforms [33, 37, 53].

Operational resilience depends on the availability of time, space, personnel and equipment reserves that can be activated when actual conditions differ from the schedule. Excessive utilization may appear economically efficient during stable demand but can cause disproportionate delay propagation when an aircraft arrives late, a stand becomes unavailable or passenger processing takes longer than expected. The organization of resources should combine planned productivity with predefined recovery actions, alternative allocations and authority to make rapid joint decisions. This approach links daily operational control with longer-term infrastructure planning because recurring disruptions often reveal structural bottlenecks that cannot be eliminated by local instructions alone [38, 41, 50].

The mathematical expressions in this chapter are authorial adaptations of methods and indicators described in the cited literature [34, 43, 53]. A citation placed before each expression identifies its conceptual or methodological basis rather than verbatim reproduction. The formulas translate organizational relationships into measurable quantities for planning, operational control and infrastructure decisions. They are used to compare responsibility allocation, information latency, resource utilization, terminal capacity, turnaround performance and service quality. Their results should be interpreted together with operational constraints and qualitative evidence because a single indicator cannot represent the entire passenger transport system [38].

2.1. Airlines, airports, ground handling companies and public authorities

The airline is contractually responsible for transporting the passenger according to the itinerary and conditions of carriage. It plans the network, schedule, fleet, crew and commercial product and coordinates disruption recovery. Even when passenger service or ramp work is outsourced, the carrier must ensure that contracted processes meet applicable safety, security and service requirements [37].

The airport operator provides and manages common infrastructure, including movement areas, terminals, stands, utilities, common-use systems and emergency capability. Ground handling companies transform the airline schedule into physical passenger, baggage and ramp services. Public authorities establish certification, safety, border, customs, security, competition and consumer-protection requirements [37].

The completeness of responsibility allocation is evaluated by formula (65) [53]:

$$RC = \frac{\sum_{j=1}^{m} w_j r_j}{\sum_{j=1}^{m} w_j} \times 100\%. \tag{65}$$

Here, RC is responsibility coverage, j is a required function, m is the number of functions, w_j is criticality weight, and r_j equals one when an accountable owner is assigned. The indicator checks whether every important activity has an identifiable decision maker. Functions are listed, weighted and tested for formal ownership. A high percentage indicates clear allocation, while a low value signals gaps or overlapping authority. The result supports contracts, operational manuals and emergency planning.

Coordination depends on the speed and accuracy of information exchange. Shared operational data should include aircraft status, estimated arrival and departure times, stand, gate, connections, baggage progress, crew limitations and infrastructure restrictions [57].

Coordination quality is summarized by formula (66) [47]:

$$CI = \sum_{k=1}^{K} \alpha_k z_k, \qquad \sum_{k=1}^{K} \alpha_k = 1. \tag{66}$$

Here, CI is the coordination index, z_k is normalized performance criterion k, α_k is its weight and K is the number of criteria. Criteria can include message timeliness, milestone accuracy, response time and closure of joint actions. Every criterion is nor-

malized before weighting. Higher values indicate more reliable cooperation. The index supports service reviews and contractor management.

The relationship between communication delay and coordination performance is shown in Figure 7.

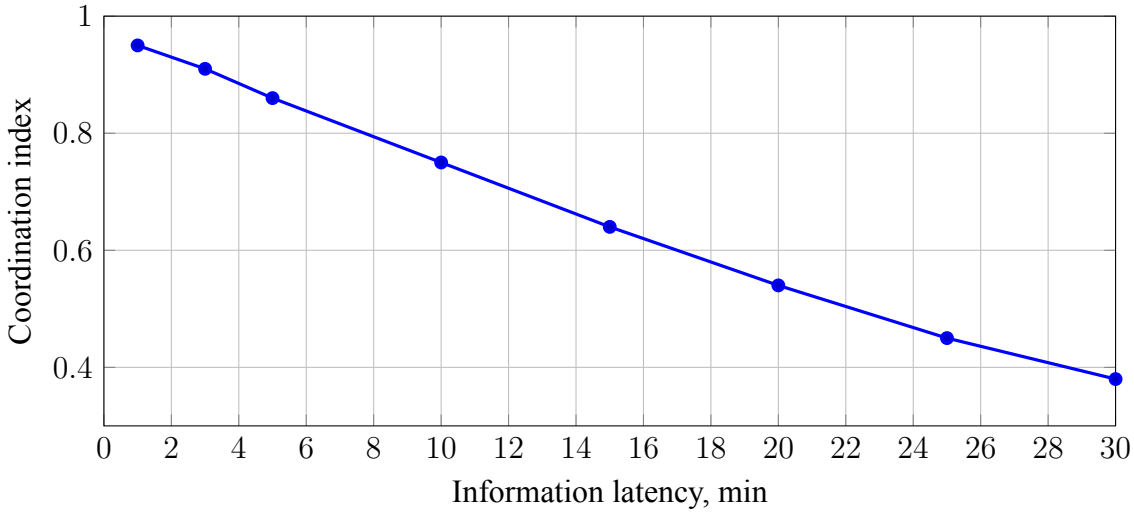

Figure 7: Illustrative influence of information latency on coordination [53]

Description of the graph. The curve demonstrates a persistent decline in the coordination index as information latency increases. With a delay of one minute, the index is approximately 0.95, indicating that participants receive almost current operational data. At ten minutes, it decreases to about 0.75, which substantially reduces the time available for joint corrective action. Delays exceeding twenty minutes correspond to an index below 0.55 and indicate fragmented coordination. The graph therefore confirms that rapid information exchange is a critical prerequisite for synchronized airport operations.

Joint decisions often require compromise among punctuality, passenger service, cost and operational risk. Alternatives should be evaluated transparently so that one participant does not transfer consequences to another [40].

The organizational model of an airport depends on ownership, traffic structure, regulation and the extent of outsourcing. At some airports the operator directly performs terminal, ramp or security functions, while at others it mainly coordinates specialized companies. Direct provision can simplify command and standardization, whereas outsourcing can provide specialist expertise and flexible capacity. The decisive requirement is that passengers experience one coherent process even when several legal entities deliver it. Interfaces must be documented at the level of tasks, information fields, response times and escalation procedures [43].

Commercial relationships influence operational behaviour. A handling contract based exclusively on the lowest unit price may encourage minimum staffing and reduce reserve during peaks or disruption. Conversely, a contract without measurable productivity requirements can preserve inefficient routines. Balanced agreements combine safety and quality thresholds with punctuality, baggage, staffing, reporting and improvement indicators. Incentives should reward sustained system performance rather than isolated speed that transfers delay or risk to another participant [46].

Average information latency is given by formula (67) [46]:

$$L_I = \frac{1}{n} \sum_{i=1}^{n} \left(t_i^{rec} - t_i^{gen} \right). \tag{67}$$

Here, L_I is mean information latency, n is the number of messages, t_i^{gen} is generation time and t_i^{rec} is receipt time. The indicator measures delay in the information chain. Lower latency increases the time available for gate changes and resource reassignment. Percentiles should supplement the average because a few late messages can have serious consequences. The result supports data integration and collaborative decision-making.

Table 5: Distribution of principal responsibilities among air transport participants [32]

Participant	Principal responsibilities	Critical coordination interfaces
Airline	Schedule, aircraft, crew, passenger contract, load control and disruption recovery	Airport slots, handler tasks, passenger information and air traffic restrictions
Airport operator	Common infrastructure, terminal flows, stands, emergency coordination and utilities	Airlines, authorities, concessionaires and surface transport
Ground handler	Check-in, boarding, baggage, ramp services and turnaround execution	Airline operations, airport control and equipment providers
Public authorities	Safety, security, border, customs, health and consumer oversight	Process design, information requirements and enforcement
Air navigation provider	Air traffic services, flow management and restrictions	Airline dispatch, airport capacity and departure sequencing

Public authorities must coordinate their own requirements. Security, border, customs and public-health measures can create conflicting demands for space, information and process sequence. A change introduced by one authority may increase queues or require modification of airline and airport systems. Regulatory impact should therefore be assessed at the complete passenger-process level. Joint working groups,

controlled trials and transition periods reduce the risk that individually reasonable rules create an inefficient combined process [31].

The utility of alternative a is given by formula (68) [36]:

$$U_a = \sum_{j=1}^{m} \beta_j x_{aj} - \sum_{q=1}^{Q} \gamma_q p_{aq}. \tag{68}$$

Here, U_a is utility, x_{aj} is benefit criterion j, β_j is its weight, p_{aq} is penalty q, and γ_q is the penalty weight. Benefits and penalties are normalized before summation. The highest admissible value identifies the preferred alternative. Sensitivity analysis is needed because weights affect ranking. The method supports gate allocation, connection protection and disruption recovery.

Operational governance needs several levels. Strategic committees address investment and long-term service standards; tactical groups prepare seasonal schedules, staffing and contingency plans; operational centres manage the current day. Decisions should move to the lowest level possessing sufficient information and authority. Escalation is required when consequences cross organizational boundaries or exceed agreed tolerance. A common action register prevents recurring issues from being discussed repeatedly without implementation [53].

Human factors remain central despite automation. Employees from different organizations may use different terminology, priorities and reporting cultures. Joint training creates shared understanding of hazards, passenger needs and operational objectives. Exercises should include normal peaks as well as aircraft changes, evacuation, system failure and mass disruption. After-action reviews should focus on interface weaknesses rather than individual blame [47].

The quality of stakeholder interaction ultimately becomes visible to passengers. Contradictory announcements, repeated document checks, unclear responsibility for assistance and long complaint transfers indicate organizational fragmentation. A passenger-centred approach assigns one accessible contact for each stage and ensures that internal transfers of responsibility do not require the passenger to restart the process. Satisfaction and loyalty depend on the combined airline and airport experience. Inter-organizational coordination is therefore a component of commercial competitiveness [36].

Information ownership is as important as process ownership. A data field should have an authoritative source, update rule, quality threshold and retention period. Du-

plicate manual entry creates inconsistent versions of aircraft, passenger and baggage status. Interface agreements should define what happens when data are missing or contradictory. Audit trails allow organizations to reconstruct which information supported a decision and improve both accountability and learning [53].

Financial settlement mechanisms should not dominate operational cooperation. Disputes about delay codes, exclusions or additional services are best reviewed after immediate passenger and safety needs have been resolved. Operational staff require authority to deploy reasonable resources without waiting for commercial approval in every exceptional case. Pre-agreed limits and evidence requirements protect both cost control and response speed. This separation between immediate control and later settlement reduces hesitation during disruption [40].

Service-level compliance is calculated by formula (69) [40]:

$$SLC = \frac{N_{met}}{N_{app}} \times 100\%. \tag{69}$$

Here, SLC is compliance, N_{met} is events meeting the target and N_{app} is all applicable events. The calculation excludes only formally agreed exceptions. A high result shows consistent delivery but not the severity of failures. Critical processes should therefore be monitored separately. The indicator supports contractor review and corrective action.

Continuous improvement converts performance data into redesigned procedures. Joint teams should identify recurring interface losses, test a modified process, measure the result and standardize successful changes. Improvement portfolios need prioritization because organizations cannot implement every proposal simultaneously. Actions with large passenger, safety or punctuality effects should receive priority. Shared benefits encourage participation when savings or revenue improvements would otherwise accrue to only one organization [32].

Performance accountability should distinguish responsibility for cause from responsibility for response. An airport may not cause adverse weather, and a handler may not cause a late inbound aircraft, but each organization remains responsible for timely mitigation within its control. Reports should therefore identify the initiating event, controllable response time and final passenger consequence. This approach prevents external causes from becoming blanket exclusions and encourages effective recovery. It also provides a fairer basis for contractual incentives and joint improvement [40].

2.2. Airport infrastructure and functional zoning of terminals

Airport infrastructure is divided into airside, landside and interface areas. Airside includes runways, taxiways, aprons, stands and restricted roads. Landside includes access transport, parking, public halls and commercial areas. The terminal connects these domains while maintaining security separation [39].

Functional zoning distinguishes departing, arriving, transfer, domestic and international flows. Additional separation may be required for screened and unscreened passengers, border categories, persons requiring assistance, staff and service deliveries [44].

The area required for processing zone j is given by formula (70) [36]:

$$A_j = \lambda_j t_j s_j. \tag{70}$$

Here, A_j is required area, λ_j is peak arrival rate, t_j is dwell time and s_j is area standard per passenger. Flow is converted into the simultaneous passenger population and then into floor area. All units must be compatible. Higher dwell time increases space requirements even when throughput is unchanged. The formula supports sizing of check-in, security, holding and reclaim areas.

Passenger accumulation is given by formula (71) [42]:

$$N_j(t) = N_j(0) + \int_0^t \left[\lambda_j(\tau) - \mu_j(\tau)\right] d\tau. \tag{71}$$

Here, $N_j(t)$ is passengers in zone j, $N_j(0)$ is the initial number, λ_j is arrival rate and μ_j is departure rate. When arrivals exceed departures, accumulation grows. Time-dependent rates represent flight banks and temporary failures. The result supports simulation and dynamic opening of channels. It also helps test evacuation and crowding conditions.

The relationship between peak flow and area is shown in Figure 8.

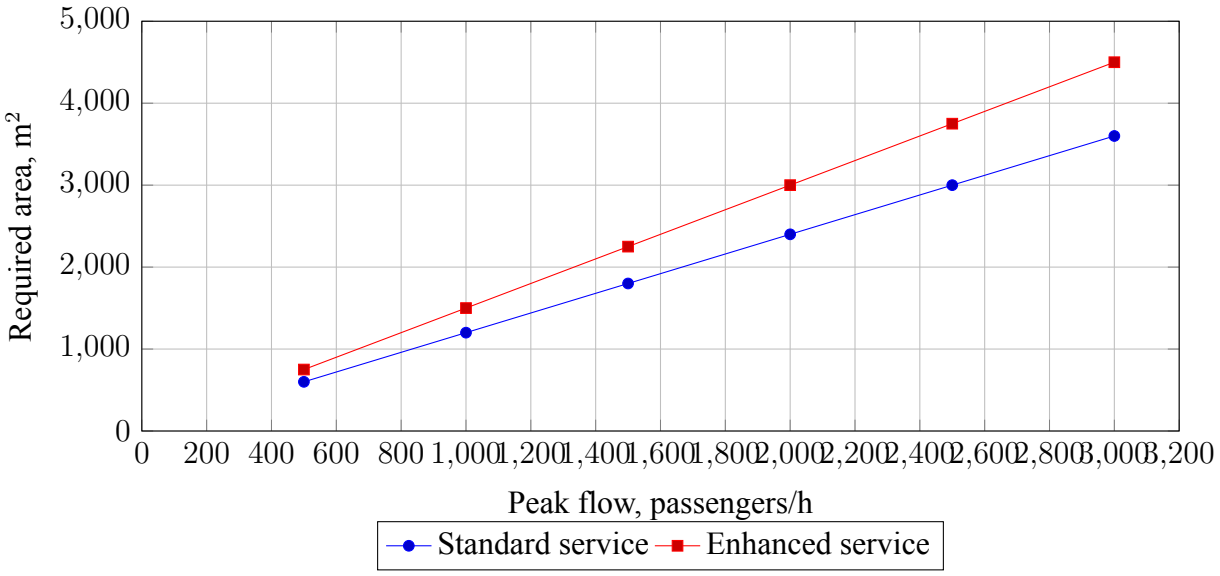

Figure 8: Illustrative terminal-area requirement [43]

Description of the graph. Both curves show that the required terminal area increases in direct proportion to the peak passenger flow. The enhanced-service scenario consistently requires more space than the standard-service scenario. At a flow of 1,000 passengers per hour, the respective requirements are approximately 1,500 and 1,200 m^2. At 3,000 passengers per hour, the difference reaches 900 m^2, which becomes significant for investment planning. The graph illustrates how the selected service standard affects terminal dimensions at every level of demand.

Airport master planning links forecast demand with staged infrastructure development. The plan should define the ultimate spatial concept while preserving the ability to build modules as demand materializes. Premature construction creates underused capital assets, whereas delayed investment produces congestion and operational workarounds. Scenario analysis is preferable to one deterministic forecast. Land reservation and protected utility corridors often determine long-term flexibility more strongly than the architectural form of the first terminal stage [43].

Airside layout influences capacity and turnaround reliability. Taxiway geometry, stand orientation, pushback procedures and service-road crossings determine how aircraft and ground vehicles interact. Contact stands shorten passenger movement but occupy terminal frontage, while remote stands increase bus and equipment movements. Stand allocation should account for aircraft wingspan, passenger category, turnaround duration, towing and adjacent-stand restrictions. Flexible stands improve adaptability but require reliable markings and operational controls [42].

The number of processing positions is given by formula (72) [35]:

$$n_j = \left\lceil \frac{\lambda_j t_{s,j}}{\rho_j^*} \right\rceil . \tag{72}$$

Here, n_j is positions, $t_{s,j}$ is service time, ρ_j^* is target utilization and $\lceil \cdot \rceil$ rounds upward. Arrival rate multiplied by service time gives workload. Dividing by target utilization creates reserve for variability. A lower target requires more positions but reduces queues. The formula supports check-in, security, border and self-service sizing.

Table 6: Functional zones of a passenger terminal and principal planning criteria [43]

Zone	Main processes	Principal planning criteria
Departure hall	Check-in, bag drop, information and distribution	Peak profile, processing technology, queue space and accessibility
Security and border control	Screening and document verification	Lane capacity, separation, privacy and alarm resolution
Airside departure area	Waiting, retail, gate processing and boarding	Dwell time, seating, walking distance and gate flexibility
Transfer area	Connection routing, re-screening and assistance	Connection time, vertical circulation and passenger recovery
Arrival and reclaim	Immigration, baggage reclaim and customs	Belt capacity, delivery time and landside exit capacity

Terminal passenger flows should be intuitive and observable. Excessive changes of level, long corridors and crossing streams increase travel time and make assistance difficult. Wayfinding combines architectural visibility, signs, lighting, colour, audio information and staff support. Digital navigation cannot replace a legible physical environment because passengers may lack connectivity or familiarity. Universal design reduces ambiguity and provides step-free, well-proportioned routes [36].

Baggage infrastructure requires its own spatial logic. Conveyors, screening machines, sorters, make-up areas, early-bag storage and reclaim belts must accommodate origin, transfer and arrival flows. The system should provide alternative routing around failed equipment and access for maintenance without prolonged closure. Capacity depends on bags per hour, destination distribution, transfer peaks and screening alarms. Baggage corridors and equipment rooms therefore require protection in the master plan [39].

Technology changes the use of terminal space. Online check-in reduces demand for conventional counters, while self-service bag drop and biometric processing create

equipment and supervision requirements. Space released by one process may be needed for exception handling or identity resolution. Automation is most effective when the physical process is redesigned rather than when machines are inserted into an unchanged layout. Common-use and relocatable equipment improves adaptability [37].

Commercial facilities contribute revenue and passenger experience but must not obstruct transport functions. Retail placement should respect sightlines, circulation width, emergency routes and flight information. Dwell time creates commercial opportunity, yet forcing long routes through retail areas disadvantages passengers with limited mobility or short connections. Seating, water, sanitary facilities, charging points and quiet areas are part of operational quality. The terminal should support efficient movement and comfortable waiting [44].

The weighted zoning cost is given by formula (73) [54]:

$$ZC = \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} d_{ij} + \sum_{i=1}^{n} \sum_{j=1}^{n} M_{ij} v_{ij}. \tag{73}$$

Here, ZC is zoning cost, F_{ij} is flow, d_{ij} is distance, M_{ij} is an incompatibility indicator and v_{ij} is separation penalty. The first term measures movement burden and the second penalizes unsafe adjacency. Candidate layouts use the same flow matrix. Lower values indicate a more efficient admissible configuration. The method supports master planning and renovation comparison.

Infrastructure resilience begins with physical redundancy and maintainability. Critical power, data, security, baggage and passenger-information systems require backup arrangements and tested restoration procedures. Flooding, heat, snow and wind must be incorporated into design standards. Modular partitions, mobile counters and common-use networks can shorten recovery time. Resilience investments should be evaluated against passenger and network consequences rather than only direct repair cost [56].

Surface access is part of airport infrastructure performance. Road congestion, unreliable public transport and insufficient interchange capacity can cause passengers to miss flights even when terminal processes operate correctly. Access planning should evaluate door-to-door time, passenger origin zones, employee travel and the operating hours of early and late flights. Rail and bus stations require protected walking routes and clear information inside the terminal. Coordination with urban and regional authorities expands the effective airport catchment area [57].

Maintenance planning must preserve infrastructure capacity over its life cycle. Floors, bridges, baggage conveyors, screening equipment, lifts, lighting and utilities deteriorate under intensive use. Preventive work should be scheduled around demand peaks and supported by temporary routing. Asset registers need condition, failure history, spare-parts and replacement information. Life-cycle planning reduces emergency closure and avoids concentrating renewal needs in one financial period [35].

Terminal expansion should be evaluated from the passenger perspective before construction. Temporary corridors, remote gates, noise, dust and changed wayfinding can reduce service quality for several years. Phasing plans need safe separation of construction, staff and passengers. Communication should explain route changes before arrival and at decision points. A well-managed construction phase can preserve airport choice and satisfaction even when the final capacity benefit has not yet become available [44].

The minimum number of stands is given by formula (74) [33]:

$$G = \left\lceil \frac{\sum_{f=1}^{F} t_f^{stand}}{T \eta_g} \right\rceil . \tag{74}$$

Here, G is required stands, F is flights, t_f^{stand} is occupancy time, T is the planning interval and η_g is target utilization. Total stand-hours are divided by productive time from one stand. The utilization target provides reserve for variation. Compatibility and simultaneous peaks must be checked separately. The result supports apron planning and gate allocation.

The functional zoning of a terminal must also account for changes in passenger status. A departing passenger may move from a publicly accessible landside area to a security-restricted airside zone, while an international transfer can require document control, security screening or temporary entry into another processing stream. These transitions must be physically clear and legally controlled without creating unnecessary backtracking. Doors, lifts, corridors and vertical circulation elements should prevent accidental mixing of screened and unscreened passengers. At the same time, the layout must permit authorized staff to redirect flows rapidly when a gate, checkpoint or baggage facility becomes unavailable [31, 42].

2.3. Interaction of participants during flight preparation and operation

Flight preparation begins before aircraft arrival. The airline operations centre, airport, handler and air navigation provider update estimates, assign resources and identify restrictions. Milestones require an owner, planned time, predicted time and actual time [51].

Milestone deviation is given by formula (75) [58]:

$$\Delta t_i = t_i^{act} - t_i^{plan}. \tag{75}$$

Here, Δt_i is deviation, t_i^{act} is actual completion and t_i^{plan} is planned completion. Positive values mean delay. Common timestamp sources prevent disagreement. The sequence reveals where delay began and propagated. The indicator supports real-time control and review.

Prediction accuracy is measured by formula (76) [38]:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left| t_i^{est} - t_i^{act} \right|. \tag{76}$$

Here, MAE is mean absolute error, n is observations, t_i^{est} is prediction and t_i^{act} is actual time. Absolute errors cannot cancel. Lower values indicate better forecasts. The metric can be evaluated at different time horizons. It supports model and data-provider assessment.

Turnaround progress is shown in Figure 9.

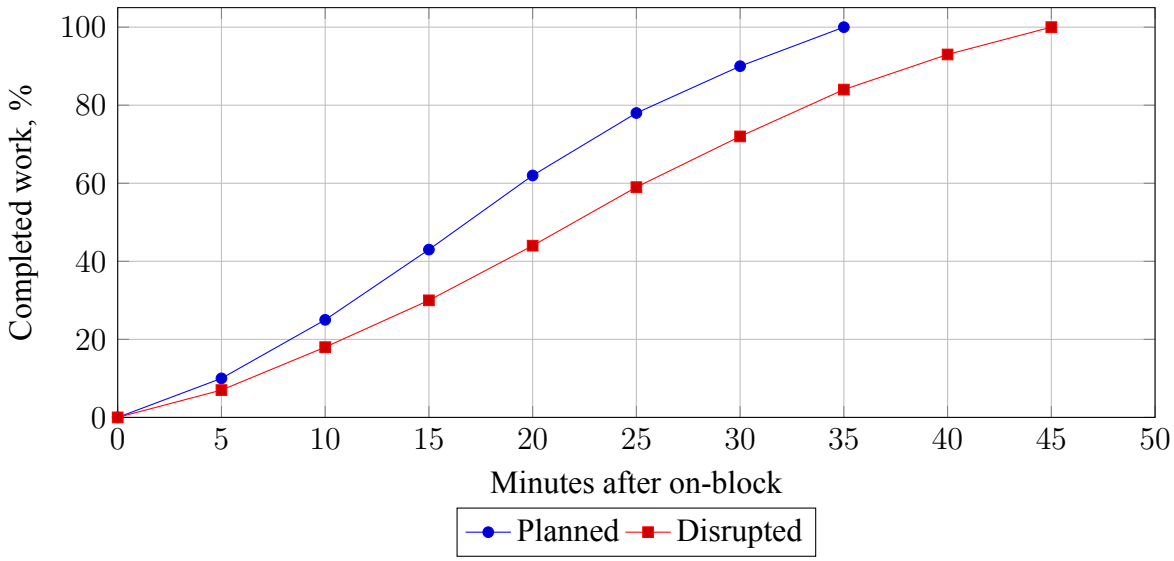

Figure 9: Illustrative turnaround progress [50]

Description of the graph. The planned curve reaches full task completion approximately 35 minutes after the aircraft arrives on stand. Under disrupted conditions, progress is slower throughout the turnaround and completion shifts to about 45 minutes. The largest practical separation between the curves occurs during the middle stage, when several passenger, baggage and aircraft-service tasks operate simultaneously. The delayed curve indicates that early deviations are not fully recovered during subsequent operations. The graph emphasizes the need to detect emerging delays before they affect the critical departure milestones.

Seasonal coordination begins when airlines submit schedules and expected aircraft types. Airports test stand, gate, terminal and baggage demand against available capacity, while handlers translate the programme into shifts and equipment requirements. Concentrated peaks are more important than daily totals. Construction work, curfews, border staffing and special events should be included in the same planning dataset. Early identification of infeasible periods allows adjustment before commercial commitments become difficult to change [42].

Collaborative decision-making requires common definitions. Estimated landing, in-block, target off-block and take-off times must be generated according to agreed rules and updated when evidence changes. Participants should know whether a time is a target, prediction or confirmed event. Data quality includes completeness, timeliness, consistency and traceability. Automatic exchange reduces calls but still requires monitoring because technically delivered data can be operationally wrong [53].

Table 7: Key milestones in coordinated flight preparation [38]

Milestone	Responsible participants	Main use
Estimated landing and in-block time	Airline, air navigation provider and airport	Stand, gate and arrival-resource planning
Aircraft ready for service	Flight crew, maintenance and handler	Start of turnaround tasks and technical decisions
Boarding start and completion	Airline, gate agent and cabin crew	Passenger control and departure-readiness forecast
Load-sheet completion	Load control, baggage and flight crew	Final mass, balance and loading confirmation
Target off-block time	Airline, airport, handler and air traffic services	Pushback sequencing and flow management

Daily operational briefings should focus on deviations from the normal plan. Weather, airspace restrictions, unserviceable infrastructure, staff shortages, special passengers, large groups and tight connections require joint attention. The briefing should result in decisions and owners rather than only information exchange. Short update cycles are preferable during rapidly changing conditions. Digital logs ensure that later shifts understand why a decision was made [50].

Resource assignment is formulated by formula (77) [42]:

$$\min C = \sum_{r=1}^{R} \sum_{f=1}^{F} c_{rf} x_{rf}, \qquad \sum_{r=1}^{R} x_{rf} = 1. \tag{77}$$

Here, C is cost, r indexes resources, f indexes flights, c_{rf} is assignment cost and x_{rf} is binary. Cost may include travel distance, lateness and incompatibility. Each flight receives the required resource. Overlapping use is prohibited by additional constraints. The model supports buses, tugs, stairs and teams.

Passenger communication must be synchronized with operational control. Information should state current status, available options, responsible contact and time of the next update. Premature certainty creates repeated corrections, while excessive caution leaves passengers unable to plan. Displays, applications, announcements, call centres and front-line staff should use a consistent source. Special attention is required for transfer passengers and persons needing assistance [31].

Irregular operations require predefined decision rights. The airline decides commercial recovery and aircraft rotation, the airport manages common infrastructure, the handler controls assigned resources, and authorities determine legal restrictions. The

practical solution often requires a joint decision. An aircraft change can affect gate compatibility, boarding, baggage, crew and seating simultaneously. Scenario playbooks accelerate response but must allow adaptation [49].

Post-operation analysis should separate primary cause, contributing factors and propagated consequences. A late inbound aircraft may be visible, while unrealistic schedules, delayed information or equipment shortages explain why recovery failed. Reviews should use common timestamps and avoid incompatible reports. Corrective actions need an owner, deadline, verification method and expected effect. Trend analysis across many flights is more useful than blame focused on one event [41].

Performance meetings should combine punctuality with passenger and baggage outcomes. An on-time departure may still involve left-behind baggage or unsafe work pressure. Conversely, a justified short delay may prevent greater downstream disruption. Balanced evaluation encourages decisions that improve the network rather than one timestamp. Measures should be segmented by airline, handler, stand type, period and cause [58].

Downstream delay is given by formula (78) [51]:

$$D_j = \max\left(0, D_i - B_{ij}\right) + D_j^{loc}. \tag{78}$$

Here, D_j is downstream delay, D_i is incoming delay, B_{ij} is schedule buffer and D_j^{loc} is local delay. The buffer absorbs part of incoming delay. Excess delay propagates. Local delay is then added. The relationship supports robust scheduling and recovery.

Connection management links the turnaround plan with passenger itineraries. Operations control needs the number, location and remaining time of connecting passengers, together with the availability of alternatives. Holding a departure is justified only when protected passengers and downstream consequences outweigh the delay imposed on the aircraft and local passengers. Decisions should be consistent across similar cases while allowing exceptions for vulnerable passengers or limited route frequency. Recording the assumptions supports later evaluation [58].

Crew legality creates hard operational constraints. Flight and cabin crews have duty, rest and qualification limits that cannot be solved by faster ground handling once exceeded. Early prediction of legality risk allows reserve crew, aircraft swaps or schedule changes. Airport and handler decisions should consider how gate changes or passenger delays consume the remaining duty margin. Protecting a few minutes during the turnaround can prevent a cancellation when the crew margin is small [50].

Maintenance decisions also interact with passenger operations. A technical defect may permit dispatch under approved conditions, require repair or make aircraft substitution necessary. The time estimate should include diagnosis, parts, access, testing and documentation. Passenger information must reflect uncertainty without promising an unsupported completion time. Close coordination among maintenance, operations, gate staff and load control reduces repeated boarding or baggage changes [49].

Weather response should be planned by threshold rather than improvised after capacity deteriorates. Wind, visibility, lightning, heat, snow and de-icing requirements affect runway, ramp and passenger processes differently. Predetermined actions can include staff recall, equipment positioning, revised connection protection and schedule reduction. The operational picture must distinguish forecast uncertainty from confirmed restrictions. Early conservative action may reduce the much larger cost of uncontrolled disruption [42].

The end of the operating day requires structured handover. Open technical issues, delayed baggage, unaccompanied passengers, equipment status and expected morning constraints must pass to the next shift. Verbal handover alone is vulnerable to omission, especially during high workload. A concise digital record with priority and ownership supports continuity. The quality of handover should be audited as a process milestone rather than treated as an informal staff habit [51].

Decision support should present uncertainty rather than one apparently precise estimate. A predicted off-block time may depend on boarding rate, late bags, maintenance and air traffic restrictions. Providing a range and confidence level helps participants choose proportional actions. Frequent unstable updates can be as harmful as late updates because they cause repeated resource movement. Prediction systems should therefore balance responsiveness and stability and explain the main factors driving a change [41].

The passenger-weighted disruption score is given by formula (79) [31]:

$$DS = \sum_{f=1}^{F} \left(P_f D_f + \omega M_f + \psi C_f \right). \tag{79}$$

Here, DS is disruption score, P_f is passengers, D_f is delay, M_f is missed connections, C_f is cancellations and ω, ψ are weights. Passenger-delay minutes form the base effect. Connections and cancellations receive penalties. Recovery alternatives are compared using the same weights. The lowest feasible score is preferred.

2.4. Technological processes of ground handling of aircraft

Ground handling begins when the aircraft approaches the stand and ends when it safely leaves. Arrival guidance, chocking, disembarkation, unloading, servicing, boarding, loading and pushback form a coordinated production cycle [45].

Turnaround duration is given by formula (80) [55]:

$$T_{ta} = \max_{p \in \mathcal{P}} \sum_{i \in p} t_i. \tag{80}$$

Here, T_{ta} is turnaround duration, $\mathcal{P}$ is precedence paths, p is one path and t_i is task duration. Durations are added on each path. The longest path determines departure. Non-critical task reduction has no effect until slack is exhausted. The model supports process redesign and real-time control.

Ground task completion is presented in Figure 10.

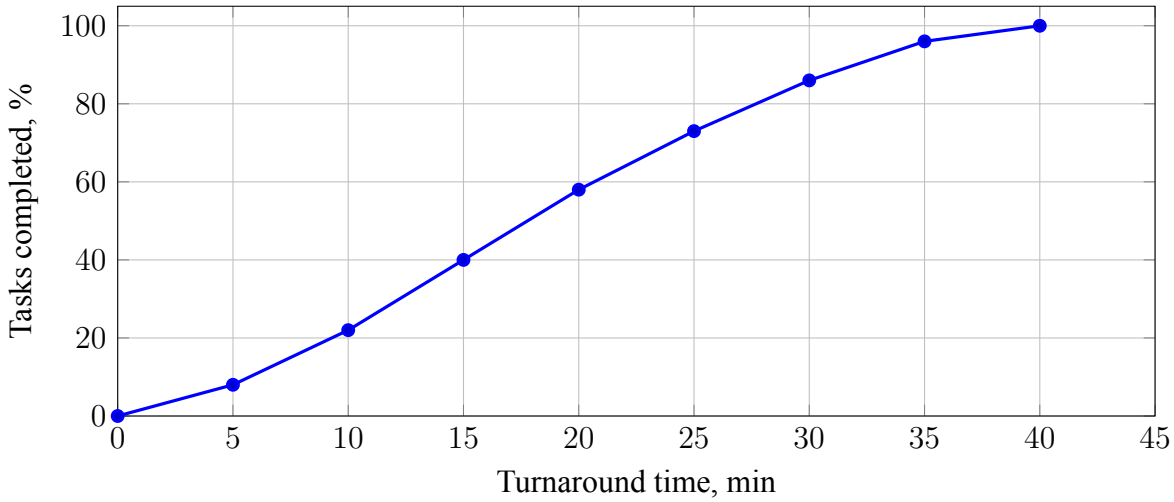

Figure 10: Illustrative ground-handling task completion [50]

Description of the graph. The graph presents the cumulative completion of ground-handling tasks during a forty-minute turnaround. Progress is initially slow because equipment positioning and preparatory safety actions must precede the main service operations. The completion rate accelerates between 10 and 30 minutes as compatible tasks are performed in parallel. Approximately 86% of the work is completed by minute 30, while the remaining tasks determine final departure readiness. The curve shows why control of late critical activities is more important than the average progress percentage alone.

The turnaround plan must distinguish tasks that can run in parallel from tasks requiring separation. Fuelling may be compatible with boarding only under defined

procedures, emergency access and communication conditions. Catering, cleaning and passenger movement can compete for doors and aisles. Baggage loading depends on reconciliation, load control and final passenger status. A graphical task network identifies critical dependencies and prevents nominal time savings from creating unsafe interference [38].

Stand safety begins before equipment approaches the aircraft. The area must be inspected for foreign objects, markings and obstructions, and vehicles must follow defined paths and speed limits. Equipment is positioned only after chocks, beacons and engine status permit access. Damage prevention relies on trained guidance, functional brakes, proximity controls and communication. Near-miss reporting reveals weak conditions even when no damage occurs [49].

Table 8: Typical ground-handling tasks and operational dependencies [50]

Task	Principal inputs	Main dependencies
Passenger disembarkation	Bridge or stairs, cabin crew and arrival route	Safe stand, door opening and terminal readiness
Baggage unloading/loading	Belt loader, teams, carts and load instruction	Hold access, reconciliation and final load plan
Cabin cleaning and catering	Service teams, supplies and waste removal	Passenger flow, door allocation and security control
Fuelling and ground power	Provider, bonding, power equipment and monitoring	Aircraft status, safety zone and crew communication
Pushback	Tug, headset operator, clearance and trained team	Door closure, equipment removal and apron clearance

Labour productivity is given by formula (81) [41]:

$$LP = \frac{N_{fl}}{H_{lab}}. \tag{81}$$

Here, LP is flights per labour-hour, N_{fl} is completed handlings and H_{lab} is paid labour-hours. Comparable service packages must be used. High productivity should not be achieved through omitted tasks. Safety and delay indicators are reviewed alongside it. The result supports staffing and benchmarking.

Passenger boarding is a major source of turnaround variability. Boarding time depends on load factor, cabin layout, carry-on baggage, passenger groups and compliance with sequence. Early gate processing can remove document and baggage problems before passengers enter the bridge. Strategies should be adapted to aircraft and passen-

ger characteristics rather than applied universally. Real-time progress metrics allow support before the departure target becomes unattainable [41].

Baggage operations require reconciliation between passenger status and loaded items. Transfer bags are prioritized according to remaining connection time and onward aircraft location. Container and cart planning should minimize rehandling and protect delivery sequence. Scanning at handover points increases traceability, but exception processes are needed when tags are unreadable or networks fail. Performance should include transfer success and delivery time [39].

Equipment utilization is given by formula (82) [41]:

$$U_e = \frac{H_e^{work}}{H_e^{avail}} \times 100\%. \tag{82}$$

Here, U_e is equipment utilization, H_e^{work} is productive hours and H_e^{avail} is available hours. Low utilization may indicate excessive fleet size. Very high utilization leaves little reserve. Travel and waiting time should be tracked separately. The result supports procurement and maintenance.

Ground support equipment dispatch resembles a vehicle-routing problem with time windows. Equipment travels between stands, completes service, recharges or refuels, and remains compatible with aircraft type. Central pooling can improve utilization but requires accurate demand information and dispatch discipline. Electric equipment also requires charging infrastructure and energy planning. Telematics supports location tracking, maintenance and analysis of idle time [45].

Staffing plans should reflect qualifications and task concurrency. A sufficient total number of workers does not guarantee feasibility if too few are certified for pushback, load control or dangerous-goods functions. Shift handovers must protect unfinished tasks and information. Fatigue, weather exposure and repeated peaks affect performance and safety. Cross-training increases flexibility, but competency must be maintained through recurrent assessment [50].

Contingency procedures are required for equipment failure, extreme weather, health measures and unavailable stands. Mobile replacement assets and agreements between handlers shorten recovery. During exceptional events, normal task duration and safe capacity assumptions must be revised rather than simply demanding faster work. The plan should define which services can be simplified and which safety controls are inviolable. Exercises reveal whether spare equipment and decision rights are genuinely usable [55].

Successful baggage delivery probability is given by formula (83) [49]:

$$P_{bag} = \prod_{j=1}^{m}(1 - p_j). \tag{83}$$

Here, P_{bag} is delivery probability, p_j is failure probability and m is process stages. Each stage contributes its success probability. More stages or higher failure rates reduce the product. Independence is a simplifying assumption. The model supports baggage risk assessment.

Environmental improvement should be integrated with turnaround performance. Fixed electrical ground power reduces auxiliary-power use, while optimized dispatch reduces vehicle travel and idle running. Electric equipment lowers local emissions but may introduce charging constraints. Environmental indicators should be evaluated with reliability and life-cycle cost. A measure that reduces emissions but creates recurrent delay may require different infrastructure or scheduling [45].

Load control integrates passenger, baggage, cargo and fuel data into the aircraft mass-and-balance decision. Late passenger changes or baggage removals require timely updates to loading teams and flight crew. Communication errors can create departure delay or an unacceptable loading condition. Electronic systems reduce calculation time but require controlled interfaces and fallback procedures. Final documentation must correspond to the actual aircraft configuration and loaded items [38].

Fuelling requires coordination of quantity, timing, safety zone and passenger status. Delayed fuel orders can place the task on the critical path, while early fuelling may be affected by later payload changes. Procedures for fuelling with passengers on board need trained staff, communication and unobstructed evacuation routes. Spillage or bonding failure requires immediate stop and response. Performance assessment should never reward duration reduction that weakens safety checks [50].

Aircraft cleaning influences both passenger perception and turnaround time. The cleaning standard should reflect flight length, aircraft condition and health requirements. Teams need access to cabin zones without conflicting with catering or boarding. Waste removal and replenishment should be organized to minimize repeated movement through narrow aisles. Quality sampling after departure is ineffective, so supervisors require rapid inspection before boarding begins [51].

Winter operations add de-icing, snow removal and contamination inspection to the ground process. Treatment effectiveness depends on weather, fluid, holdover time

and departure sequence. An aircraft treated too early may require repetition, while treatment too late can miss the flow-management slot. Airport, airline, handler and air traffic services must coordinate capacity assumptions. Seasonal training and equipment tests should be completed before the first severe event [49].

Turnaround improvement should use observed task data rather than a single average duration. Distributions reveal whether variability arises from passenger load, stand type, team, equipment or preceding delay. Video analytics and equipment timestamps can provide detail, subject to privacy and governance controls. Pilot changes should compare a baseline with the modified process across sufficient flights. Sustainable improvement reduces both mean time and variability without increasing safety events or staff workload [41].

Ground-service emissions are given by formula (84) [49]:

$$E_g = \sum_{k=1}^{K} F_k e_k + E_{APU}. \tag{84}$$

Here, E_g is emissions, F_k is energy consumed, e_k is emission factor, K is equipment categories and E_{APU} is auxiliary-power emissions. Consumption is multiplied by its factor. Electricity factors reflect the selected boundary. The model compares diesel, electric and fixed-power scenarios. It supports environmental reporting and investment.

Process standardization should define the required result while allowing justified local adaptation. Aircraft configuration, stand equipment and weather can make one fixed sequence inefficient or unsafe. Teams need clear rules for selecting an approved alternative sequence and recording the reason. Standard work provides a baseline for training and measurement, while controlled flexibility supports real operations. Uncontrolled variation, by contrast, makes performance unpredictable and weakens investigation [38].

Service providers should measure first-time-right performance. A task completed quickly but repeated because of incorrect quantity, position or documentation consumes more time and can compromise departure readiness. Examples include baggage reloading, catering correction, repeated cabin checks and revised load sheets. Quality-at-source assigns verification to the team performing the work and provides rapid feedback. Reducing rework improves punctuality without requiring staff to perform the original task faster [50].

2.5. Throughput capacity and quality of airport infrastructure operation

Airport throughput is the sustainable flow processed under defined conditions. It differs from a short exceptional maximum because it includes staffing, reliability, service standards and demand variability [39].

System throughput is given by formula (85) [47]:

$$Q_{sys} = \min\left(Q_{ci}, Q_{sec}, Q_{bor}, Q_{bag}, Q_{gate}\right). \tag{85}$$

Here, Q_{sys} is throughput and the remaining terms are capacities of check-in, security, border, baggage and gates. The minimum identifies the bottleneck. All capacities use the same interval. After improvement, the calculation is repeated. It supports targeted investment.

The utilization–quality relationship is shown in Figure 11.

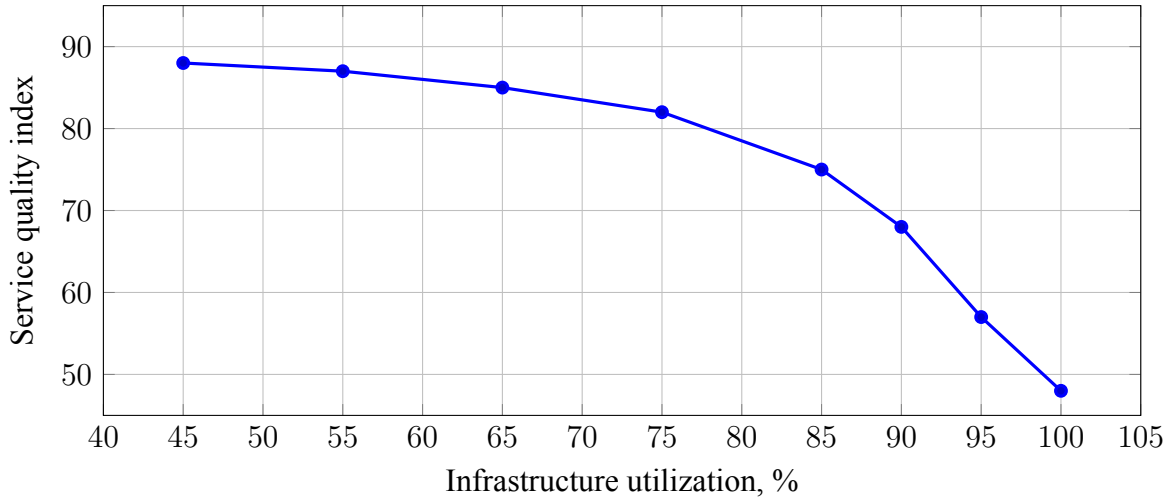

Figure 11: Illustrative relationship between utilization and service quality [44]

Description of the graph. The curve shows that service quality remains relatively stable while infrastructure utilization is moderate. Once utilization rises above approximately 75–80%, the quality index begins to decline more rapidly. At 90% utilization, the index falls to about 68, reflecting longer queues and reduced operational flexibility. Near full utilization, even small demand fluctuations can produce a disproportionate deterioration in passenger service. The graph supports maintaining an operational reserve instead of planning airport facilities for continuous maximum loading.

Infrastructure management should integrate capacity, quality, efficiency and re-

silience. Decisions based on only one dimension can create congestion, fragile operations or poor passenger experience [34].

Capacity must be defined for specific operating conditions. Runway configuration, weather, aircraft mix, security regime, staffing and passenger composition can change sustainable flow. Declared capacity should include its assumptions and not be treated as a permanent physical constant. Practical capacity is lower than theoretical maximum because service quality and recovery margin must be preserved. Analysis should use distributions and scenarios rather than one average value [42].

Demand management complements physical expansion. Schedule coordination, slot allocation, differentiated charges and collaborative planning can shift traffic away from congested periods. These measures should reflect airline network needs and avoid unusable schedules. When demand consistently exceeds capacity, administrative allocation cannot remove the need for investment or redesign. Transparent rules are essential because scarce capacity affects competition and connectivity [48].

Average passengers in a process are given by formula (86) [32]:

$$L = \lambda W. \tag{86}$$

Here, L is passengers in the system, λ is throughput rate and W is average time. Stable flow and consistent units are required. Any third value follows from the other two. Longer time increases terminal occupancy. The relationship supports queue monitoring and space sizing.

Table 9: Balanced indicators of airport infrastructure performance [34]

Dimension	Representative indicators	Management purpose
Capacity	Passengers per hour, movements per hour and reserve	Identify bottlenecks and expansion requirements
Efficiency	Cost per passenger, productivity and equipment utilization	Compare resource use and process design
Service quality	Waiting, satisfaction, walking and baggage delivery	Protect passenger experience
Reliability	Punctuality, availability and completion factor	Monitor consistency and disruption exposure
Resilience	Retained capacity, recovery time and alternatives	Prepare for failures and exceptional demand

Productive efficiency is given by formula (87) [34]:

$$PE = \frac{\sum_{r=1}^{R} u_r y_r}{\sum_{i=1}^{I} v_i x_i}. \tag{87}$$

Here, PE is efficiency, y_r is output, u_r is output weight, x_i is input and v_i is input weight. Weighted output is divided by weighted input. Definitions must be consistent across airports. The ratio identifies resource productivity. Quality and safety remain separate constraints.

Queue simulation is needed when arrivals are peaked, service times vary or passenger categories use different channels. Analytical averages may underestimate the tail of the waiting-time distribution. Discrete-event models reproduce individual arrivals, routing, service and equipment states. Scenarios should test normal peaks, delayed flight banks, lane failure and staff shortage. Validation requires comparison with observed queues and timestamps [39].

Passenger quality should be interpreted across the whole journey. Short security waiting does not compensate for confusing wayfinding or late baggage delivery. Satisfaction is shaped by expectations, perceived fairness, staff behaviour and recovery. Surveys should combine ratings with objective data. Segment analysis reveals different priorities among business, leisure, transfer, family and reduced-mobility passengers [46].

Airport efficiency is influenced by external conditions. Traffic structure, regional income, tourism, regulation and ownership affect the relationship between resources and outputs. Benchmarking should compare similar airports or control for the operating environment. A low score may result from process weakness, public-service obligations or temporary excess capacity built for growth. Interpretation requires quantitative models and institutional knowledge [56].

Financial sustainability depends on aeronautical and commercial revenue, operating cost and investment obligations. Passenger collapse demonstrated that high fixed costs can rapidly weaken airport finances. Charge changes may support recovery but can affect airline capacity and regional connectivity. Long-term planning should test traffic, inflation, energy and financing scenarios. Essential maintenance must be protected when expansion is postponed [48].

Airport and regional development are interdependent. Connectivity can support tourism, labour access and investment, while regional economic growth generates air demand. The direction and strength of causality vary between markets. Appraisal

should distinguish direct airport productivity from wider economic benefits and avoid double counting. Coordinated land-use and surface transport planning increases the value of airport capacity [57].

Airport service quality is given by formula (88) [35]:

$$ASQ = \frac{\sum_{j=1}^{m} w_j s_j}{\sum_{j=1}^{m} w_j}. \tag{88}$$

Here, ASQ is quality, s_j is passenger rating, w_j is importance weight and m is attributes. Ratings are weighted and normalized. Higher values indicate better perceived service. Passenger segments should be analysed separately. The index supports service improvement and terminal investment.

Self-connectivity and independent transfers create flows that may not be visible to airlines as protected connections. These passengers expand route combinations but face higher risk during delay and may need to reclaim baggage. Airports can support them through information, suitable minimum times and transfer services. Capacity models should account for additional circulation and processing. Passenger behaviour can therefore change infrastructure demand without a formal airline network decision [58].

Performance targets should be linked to the time scale of decisions. Real-time indicators support lane opening and resource dispatch, daily indicators reveal operational deviations, and monthly indicators support staffing and investment review. Combining all purposes in one dashboard can hide urgent conditions among strategic measures. Each indicator needs an owner, update frequency, threshold and defined response. Measurement creates value only when a deviation triggers an appropriate action [43].

Data comparability is necessary for benchmarking. Airports may define passengers, delays, available area, staff hours and costs differently. Before comparison, the analyst should harmonize scope, accounting period, transfer treatment and outsourced resources. Peer groups should reflect traffic scale, international share, hub function and regional conditions. Transparent definitions prevent incorrect conclusions and allow practices to be transferred responsibly [35].

Quality and capacity investments should be evaluated after implementation. Actual passenger time, satisfaction, throughput, reliability and operating cost are compared with the baseline and business-case assumptions. Benefits can be delayed while staff learn the new process, so evaluation should include stabilization time. If expected re-

sults are not achieved, the review should distinguish design weakness from incomplete implementation. Post-project evaluation improves later forecasts and strengthens accountability [46].

Capacity control should also account for the interaction between landside and airside constraints. A terminal may possess sufficient processing positions while access roads, kerb space, public transport platforms or parking payment points create arrival peaks that reach the building in concentrated waves. On the airside, runway acceptance rates may remain adequate while stand occupancy prevents arriving aircraft from reaching the terminal. An integrated capacity review therefore maps demand from the regional access network through passenger processing to aircraft departure. This prevents investment in a visible local bottleneck from merely transferring congestion to the next element of the journey [42, 57].

Operational thresholds are more useful when they trigger predetermined responses. For example, a security queue threshold can activate staff redeployment, opening of reserve lanes and revised passenger messaging; a baggage-system threshold can initiate manual encoding positions and priority routing for short connections. Thresholds should include both a warning level and a critical level so that action begins before service failure becomes unavoidable. Their values must be calibrated from observed demand, processing variability and the time required to mobilize additional resources. Regular review is necessary because technology, passenger behaviour and traffic composition change the relationship between an indicator and the resulting operational risk [39, 43].

Infrastructure resilience is given by formula (89) [32]:

$$K_{res} = \alpha \frac{Q_{dist}}{Q_0} + (1 - \alpha) \frac{T_0}{T_{rec}}. \tag{89}$$

Here, K_{res} is resilience, Q_{dist} is retained capacity, Q_0 is normal capacity, T_{rec} is recovery time, T_0 is target time and α is the continuity weight. The first term rewards continued operation. The second rewards rapid restoration. The weight reflects management priorities. The coefficient supports contingency investment and post-incident assessment.

Maintenance planning is an essential part of usable capacity. Equipment that is nominally installed but frequently unavailable cannot be counted at its full design rate. Airports should combine preventive maintenance, condition monitoring, spare-parts policy and restoration targets for screening lanes, baggage conveyors, boarding

bridges, lifts, information systems and utilities. Planned closures should be coordinated with the flight schedule and communicated to operational units in advance [48].

CHAPTER 3

FORMATION OF PASSENGER FLOWS BETWEEN CITIES, COUNTRIES AND CONTINENTS

Passenger flows are the observable result of decisions made by travellers, airlines, airports and public authorities. They arise from the spatial distribution of population and economic activity, the generalized cost of travel, available frequencies, network structure, visa and border conditions, service quality and the capacity of competing transport modes. A passenger flow is therefore not a fixed quantity attached to a route but a time-dependent response to the opportunities and constraints of the complete transport system [59, 61].

The analysis of flows requires several spatial scales. At the city-pair level, the principal questions concern trip generation, destination choice and modal competition. At the national level, the analyst studies the hierarchy of airports, domestic accessibility and the effect of economic structure. At the intercontinental level, direct links, hub connections and airline alliances determine how demand is distributed among alternative paths. The same passenger can appear as local traffic at one airport and transfer traffic at another, which makes consistent definitions essential [62, 68].

Forecasting connects observed demand with decisions about routes, fleets, terminals and personnel. Short-term forecasts support resource allocation, while medium- and long-term forecasts support schedule development and investment. Reliable analysis combines statistical data, network models, behavioural assumptions and scenarios. It also recognizes structural breaks caused by economic crises, pandemics, geopolitical restrictions or the entry of a new transport competitor [65, 74–76].

3.1. Factors shaping demand for passenger air transport

Demand for passenger air transport is derived from the need to perform an activity at another location. Business, tourism, education, labour migration, family visits, medical travel and participation in events create different trip purposes and different sensitivities to fare, time and reliability. The volume of potential journeys depends on population, income, economic specialization, cultural links and the attractiveness of destinations. Actual air demand emerges only when a feasible itinerary is available at a generalized cost acceptable to the traveller [59, 60].

The trip-generation potential of city i may be represented by formula (90) [59]:

$$O_i = \alpha P_i^{\beta_1} Y_i^{\beta_2} B_i^{\beta_3}, \tag{90}$$

where O_i is the number of generated air trips, P_i is population, Y_i is income or gross regional product per capita, B_i is an index of business and tourism activity, and $\alpha, \beta_1, \beta_2, \beta_3$ are calibrated parameters. The multiplicative form allows elasticities to be interpreted directly. A one-percent change in an explanatory variable changes demand approximately by the corresponding exponent, other conditions remaining constant. Calibration requires observations covering cities of different size and economic structure.

Income influences both the ability to pay and the value assigned to travel time. At low income levels, discretionary journeys are highly sensitive to fare. As income increases, passengers may travel more frequently and choose faster or more flexible products. Business demand is often less price-elastic than leisure demand, although corporate travel policies and digital communication can alter this relationship. Aggregate models should therefore distinguish passenger segments whenever data permit [61].

Fare elasticity is calculated by formula (91) [61]:

$$\varepsilon_p = \frac{\Delta Q / Q}{\Delta p / p}, \tag{91}$$

where Q is passenger demand and p is the relevant fare. A negative value reflects the usual inverse relationship between price and quantity demanded. The magnitude depends on journey purpose, distance, advance-purchase period, market concentration and the availability of substitutes. Elasticity should be estimated over a clearly defined range because a single coefficient may not describe both normal pricing and extreme disruption.

Economic growth affects demand through employment, household expenditure, investment and trade. Airport development can also influence regional activity by improving accessibility, although causality may operate in both directions. Evaluation must distinguish demand generated by existing regional growth from activity attracted by improved connectivity. Evidence from regional airports shows that the effect depends on complementary infrastructure and the capacity of local firms and tourism organizations to use the new accessibility [60, 68].

Population alone does not determine market size. The airport catchment area depends on surface-access time, competing airports, border conditions and traveller familiarity. A large city can divide its demand among several airports, whereas one regional airport can serve many small settlements. Catchment boundaries are probabilistic because passengers may select a more distant airport to obtain a lower fare, a direct flight or a more convenient departure time.

The probability that passenger n selects airport or itinerary k can be expressed by the logit model and is presented in formula (92) [61]:

$$P_{nk} = \frac{\exp(V_{nk})}{\sum_{j \in \mathcal{C}_n} \exp(V_{nj})}, \qquad V_{nk} = \theta_1 p_{nk} + \theta_2 t_{nk} + \theta_3 f_{nk} + \theta_4 q_{nk}, \tag{92}$$

where $\mathcal{C}_n$ is the passenger's choice set, p_{nk} is price, t_{nk} is total travel time, f_{nk} is frequency and q_{nk} is a service-quality variable. Parameters describe the marginal effect of each attribute. The model converts itinerary utility into choice probabilities and can be aggregated to forecast market shares. Correct specification of the choice set is essential because passengers cannot select alternatives they do not know or cannot access.

Tourism demand is affected by destination image, accommodation capacity, season, climate, exchange rates and event calendars. Visiting-friends-and-relatives traffic reflects migration and diaspora links and can remain strong even when business demand weakens. Educational and labour flows may concentrate at the beginning and end of terms or work rotations. These differences explain why annual totals are insufficient for designing schedules and airport resources.

The seasonal index for month m is given by formula (93):

$$S_m = \frac{Q_m}{\overline{Q}}, \qquad \overline{Q} = \frac{1}{12} \sum_{m=1}^{12} Q_m. \tag{93}$$

An index above one identifies a month with demand above the annual monthly average. The profile supports seasonal fleet assignment, staffing and marketing. It should be

calculated separately for origin–destination and transfer passengers because their peaks can differ. Several years of data are preferable so that an exceptional event does not become a permanent seasonal factor.

Figure 12 illustrates a typical nonlinear relationship between regional income and air-trip generation.

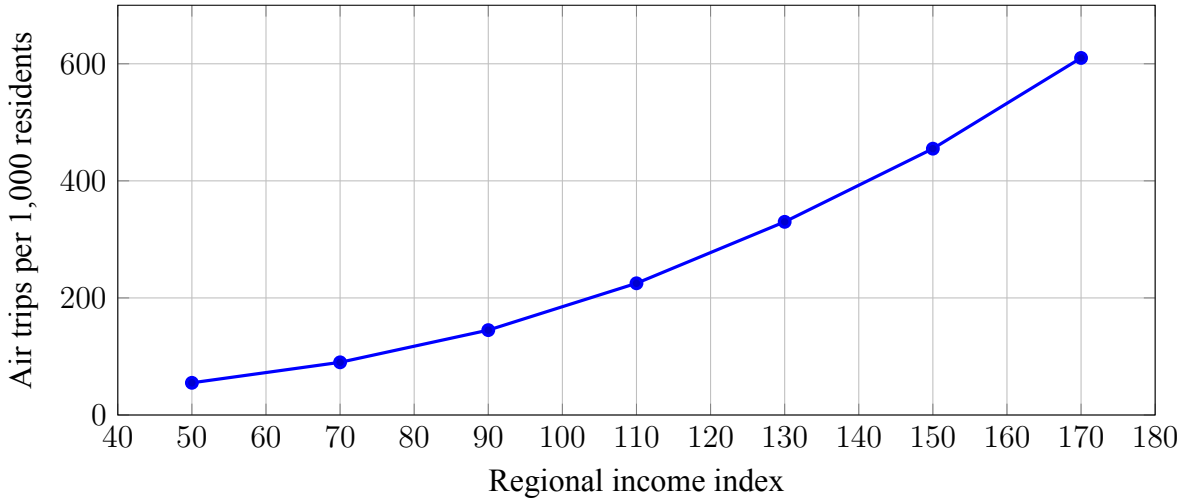

Figure 12: Illustrative relationship between regional income and air-trip generation. Author's calculation based on [60, 68]

Description of the graph. The curve indicates that air-trip generation increases faster after the regional income index passes approximately 100. At lower income levels, most additional resources are directed toward essential consumption and the increase in air travel is moderate. Higher income expands discretionary tourism and raises the value of time, making air transport more attractive. The relationship is illustrative and does not imply that income alone causes the observed demand. Population structure, fares, connectivity and destination attractiveness must be included in an empirical model.

Transport competition changes the effective market. High-speed rail can reduce air demand on medium-distance routes while also feeding long-haul flights when schedules and terminals are integrated. Road transport remains important where airports are distant or frequencies are low. The relevant comparison concerns door-to-door time, total cost and reliability rather than line-haul speed alone [65].

The effective demand captured by air transport can be estimated as formula (94):

$$Q_{ij}^{air} = Q_{ij}^{pot} \, P_{ij}^{mode} \, P_{ij}^{airport} \, P_{ij}^{itinerary}, \tag{94}$$

where Q_{ij}^{pot} is the total travel market and the three probabilities describe successive

mode, airport and itinerary choices. The decomposition prevents the potential market from being confused with passengers who will actually use a specific flight. Each probability can be estimated from observed choices or a discrete-choice model. The result supports sensitivity analysis of fares, access improvements and schedule changes [61, 65].

Cross-price elasticity between air service a and competing alternative b is given by formula (95):

$$\varepsilon_{ab} = \frac{\Delta Q_a / Q_a}{\Delta p_b / p_b}. \tag{95}$$

A positive coefficient indicates substitution, whereas a negative value can occur when the services are complementary, as in rail feeding a long-haul airport. The coefficient should be estimated for a specified market and time horizon. It helps predict the redistribution of passengers after a competitor changes its fare or capacity.

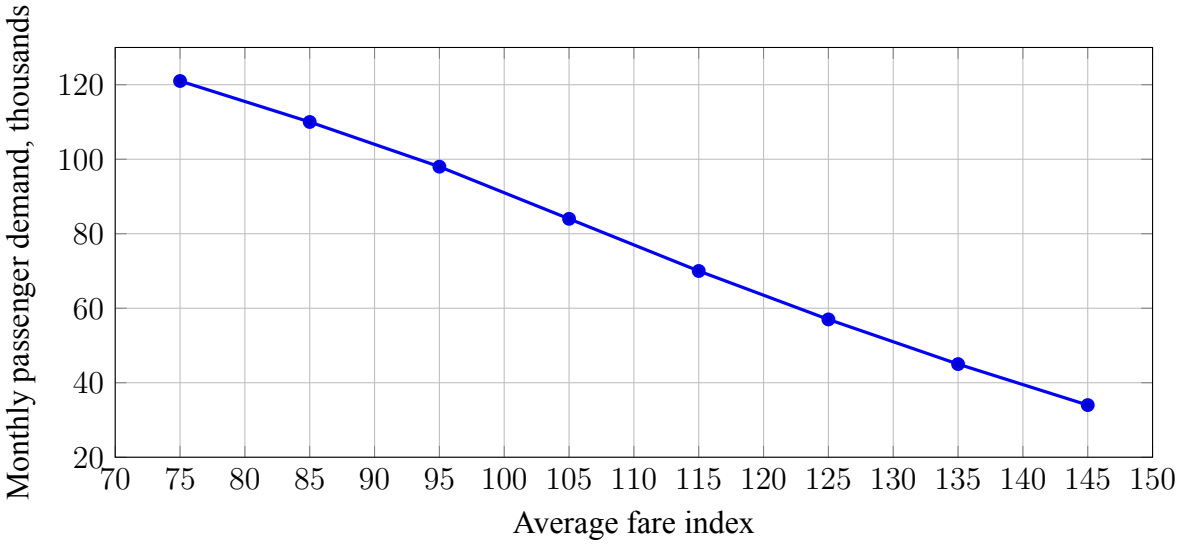

Figure 13: Illustrative relationship between fare level and passenger demand. Author's calculation based on [61]

Description of the graph. Passenger demand declines as the average fare index increases. The slope becomes particularly important in the middle of the observed range, where a moderate fare change produces a substantial traffic response. Demand does not fall to zero because some passengers have limited substitutes or a high value of time. The curve represents an aggregate market and may conceal different elasticities for business and leisure passengers. Practical forecasting should therefore segment demand and test competitor responses.

Table 10: Principal determinants of passenger air-transport demand

Factor group	Representative variables	Expected analytical role
Socio-economic	Population, income, employment and business activity	Determines trip-generation potential
Spatial	Distance, airport access and competing destinations	Defines feasible markets and generalized cost
Service	Fare, frequency, directness, reliability and quality	Influences itinerary and mode choice
Institutional	Visa rules, borders, taxes and traffic rights	Enables or restricts movement
Temporal	Season, events, school terms and shocks	Produces peaks and structural changes

Forecasting demand requires separation of correlation and causality. A high association between passenger traffic and regional output does not show whether aviation generates growth, responds to growth or shares a third cause. Panel data, natural experiments and time-series causality tests improve interpretation. The selected method must correspond to the decision: route launch requires a market forecast, whereas public investment appraisal requires evidence of additional social benefit [60, 68].

3.2. Modeling passenger flows between cities and countries

Passenger-flow modelling translates the characteristics of origins, destinations and transport services into an origin–destination matrix. The matrix records journeys between places rather than aircraft movements between airports. This distinction matters in multi-airport regions and connecting networks because one city pair may use several airports and several flight paths. Models range from aggregate gravity relations to disaggregate itinerary-choice and network-assignment models [59, 61].

The basic gravity model is given by formula (96) [59]:

$$Q_{ij} = K \frac{M_i^{\alpha} M_j^{\beta}}{G_{ij}^{\gamma}}, \tag{96}$$

where Q_{ij} is passenger flow, M_i and M_j are origin and destination masses, G_{ij} is generalized separation, and K, α, β, γ are estimated parameters. Population, income, tourism capacity or composite activity indicators can represent mass. Generalized separation can include fare, elapsed time, frequency and border friction. Logarithmic transformation permits estimation by regression, although count-data models are often preferable when many city pairs have small or zero flows.

International flows require variables that do not appear in a purely domestic model. Common language, historical ties, migration stocks, bilateral trade, visa regimes and exchange rates can materially change demand. A long-distance city pair with strong diaspora links may generate more travel than a closer pair with similar population. Country-level variables should not replace city-level accessibility because national demand is distributed unevenly among metropolitan regions [62, 68].

A constrained origin–destination model preserves known trip totals and is presented in formula (97):

$$Q_{ij} = A_i O_i B_j D_j f(G_{ij}), \tag{97}$$

where O_i and D_j are origin and destination totals, while A_i and B_j are balancing factors. Iterative proportional fitting adjusts the matrix until row and column totals match observed constraints. The method is useful when aggregate departures and arrivals are reliable but individual city-pair observations are incomplete. Its limitation is that the resulting pattern still depends on the selected deterrence function.

Itinerary choice distributes city-pair demand among direct and connecting alternatives. Relevant attributes include fare, departure time, elapsed time, connection

airport, number of stops, airline identity and expected reliability. Price is endogenous because airlines set fares partly in response to demand and competition; ignoring this relationship can bias estimated passenger preferences [61]. Service quality and perceived value also affect behavioural intention and should be incorporated when the forecast concerns market share rather than total trip generation [82, 87, 90].

The passenger flow assigned to itinerary r is given by formula (98):

$$q_{ijr} = Q_{ij} \frac{\exp(V_{ijr})}{\sum_{s \in \mathcal{R}_{ij}} \exp(V_{ijs})}, \tag{98}$$

where $\mathcal{R}_{ij}$ is the set of available itineraries. The sum of assigned itinerary flows equals total city-pair demand. Nested or mixed-logit specifications may be needed when alternatives share flights, airports or airlines and therefore are not independent. Assignment results support frequency planning, connection design and estimates of transfer traffic.

Network representation adds structural information. Airports are nodes and direct services are edges, while frequency, capacity, time or fare form edge weights. Degree measures direct connectivity, centrality identifies strategically positioned airports, and community detection reveals regional subnetworks. The evolution of the Southeast Asian network demonstrates how economic integration and airline strategies can alter network hierarchy over time [62].

The weighted shortest-path impedance is given by formula (99):

$$G^{*}_{ij} = \min_{r \in \mathcal{R}_{ij}} \left(\sum_{a \in r} c_a + \sum_{h \in r} \pi_h \right), \tag{99}$$

where c_a is the cost of flight or surface segment a, and π_h is a transfer penalty at hub h. The minimum identifies the least-generalized-cost path rather than necessarily the shortest geographic path. Capacity constraints can be added so that excessive demand increases cost or is assigned to another route. The model supports evaluation of new links and network disruptions.

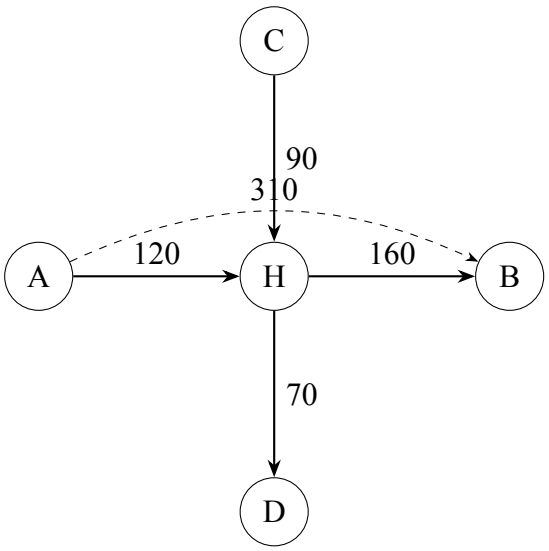

Figure 14: Illustrative assignment of direct and connecting passenger flows in an airport network

Description of the graph. The scheme represents four spoke cities connected through hub H and a direct alternative between A and B. Numbers on the links illustrate generalized impedance rather than geographic distance. The connection through H has a combined link impedance of 280 before the transfer penalty is added. Passengers choose the direct or connecting path according to total utility, schedule and available capacity. The same structure can be expanded to a large weighted graph for national or international flow assignment.

Model validation compares predicted and observed matrices. Aggregate accuracy can hide large errors on strategically important routes, so evaluation should include absolute error, percentage error, rank correlation and spatial residuals. Zero-flow pairs need separate treatment because a percentage error is undefined. Validation should use a later time period or held-out markets rather than the observations used for calibration.

For count-valued passenger flows, the Poisson log-likelihood can be written as formula (100):

$$\ell(\boldsymbol{\theta}) = \sum_{i,j} \left[Q_{ij} \ln \widehat{Q}_{ij}(\boldsymbol{\theta}) - \widehat{Q}_{ij}(\boldsymbol{\theta}) - \ln(Q_{ij}!) \right]. \tag{100}$$

Maximizing this expression estimates parameters without requiring logarithms of zero flows. Overdispersion should be tested because passenger-flow variance often exceeds the Poisson mean. A negative-binomial specification is preferable when unobserved market heterogeneity is substantial [59].

Flow conservation at intermediate airport h requires the condition stated in for-

mula (101):

$$\sum_{a \in \delta^-(h)} q_a + q_h^{orig} = \sum_{a \in \delta^+(h)} q_a + q_h^{dest}, \tag{101}$$

where incoming and outgoing assigned flows are balanced after local origins and destinations are included. The constraint prevents a network model from creating or losing passengers at transfer nodes. Capacity constraints can then limit individual links or processing facilities.

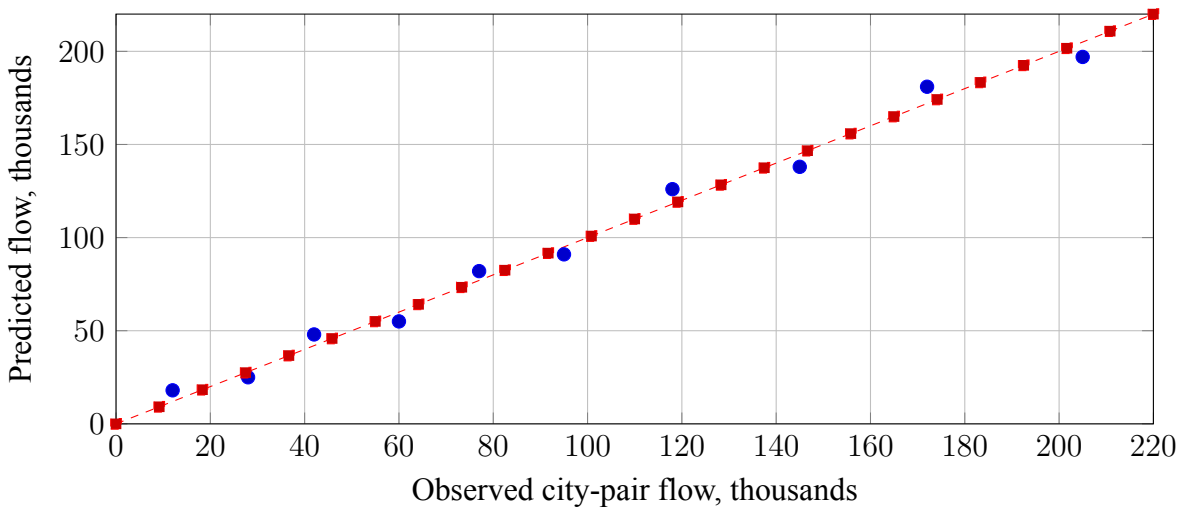

Figure 15: Illustrative comparison of observed and predicted city-pair passenger flows

Description of the graph. Points close to the dashed diagonal indicate accurate predictions. The model performs consistently across most medium- and high-volume markets. Several small markets show larger relative errors even though their absolute deviations remain modest. Systematic placement above or below the diagonal would indicate forecast bias. Validation should combine this visual assessment with numerical metrics and analysis of spatial residuals.

The root mean squared error is given by formula (102):

$$RMSE = \sqrt{\frac{1}{N} \sum_{(i,j)} \left(\widehat{Q}_{ij} - Q_{ij} \right)^2}. \tag{102}$$

Large errors receive greater weight because they are squared. Mean absolute error should be reported alongside RMSE to show whether the result is driven by a small number of major markets. Segment-level validation is required for domestic, international, direct and connecting demand. A model is acceptable only when its accuracy is sufficient for the planning decision.

Table 11: Comparison of passenger-flow modelling approaches

Approach	Principal strength	Principal limitation
Gravity model	Transparent relation between mass and separation	Limited representation of individual choice
Constrained matrix	Preserves known origin and destination totals	Depends on deterrence-function assumptions
Discrete choice	Represents fare, time and service preferences	Requires detailed itinerary and passenger data
Network assignment	Captures alternative paths and capacity	Sensitive to impedance and transfer penalties
Machine learning	Models nonlinear interactions	Can be difficult to interpret outside training data

Uncertainty should be propagated through the model rather than hidden in one forecast. Population, income, fares and service attributes can be represented by distributions or scenarios. Repeated simulation produces a range for each city-pair flow and identifies routes whose business case is robust. Transparent assumptions are especially important for thin markets, where a small absolute change can determine whether a viable frequency can be offered.

3.3. Intercontinental connections, hub airports and transfer flows

Intercontinental networks combine a limited number of long-haul services with regional feeder flows. Hub-and-spoke organization allows an airline to connect many origin–destination markets without operating every city pair directly. The resulting economies of density can support larger aircraft and higher frequencies, but passengers incur transfer time and the network becomes sensitive to disruption at central airports [62, 68].

The theoretical number of directional city pairs connected through a hub with n spokes is given by formula (103):

$$N_{OD} = n(n-1). \tag{103}$$

This value describes connectivity potential rather than actual demand. Useful connections require compatible arrival and departure times, sufficient capacity and acceptable minimum connecting time. A hub with many destinations but poorly coordinated schedules can provide less practical connectivity than a smaller, well-banked network.

Transfer flows are produced by schedule banks. Feeder aircraft arrive within a defined interval, passengers and baggage are processed, and onward flights depart in another interval. Concentrated banks improve connection availability but create peaks at runways, stands, security facilities and baggage systems. More even schedules reduce peaks but may lengthen passenger waiting and weaken the number of feasible connections.

The connection-feasibility indicator is given by formula (104):

$$I_{ab} = \begin{cases} 1, & MCT \le t_b^{dep} - t_a^{arr} \le MCT + W_{max}, \\ 0, & \text{otherwise}, \end{cases} \tag{104}$$

where MCT is minimum connecting time and W_{max} is the maximum acceptable additional waiting interval. Summing I_{ab} across arrival and departure pairs measures schedule connectivity. The minimum time must reflect terminal layout, border and security procedures, baggage transfer and passenger mobility. A published value that cannot be achieved reliably creates missed connections and unstable flows.

Hub choice depends on location, airline network, airport capacity, bilateral rights and total itinerary quality. Passengers can bypass a geographically convenient hub when another offers a lower fare or more reliable schedule. Alliances and joint ventures widen the set of coordinated itineraries, while self-connectivity allows passengers

to combine independent tickets at their own risk. The growth of self-connecting markets changes terminal circulation and may create baggage-reclaim and re-check demand not visible in traditional airline records [62, 73].

The proportion of transfer passengers at airport h is given by formula (105):

$$\tau_h = \frac{P_h^{tr}}{P_h^{loc} + P_h^{tr}} \times 100\%. \tag{105}$$

A high value indicates dependence on connecting flows and airline network strategy. Local and transfer passengers use infrastructure differently, so total volume alone is insufficient for terminal planning. Transfer traffic can be redirected rapidly after schedule restructuring, making a hub more exposed than an airport with a large local catchment.

Intercontinental flows are asymmetric when economic activity, tourism and migration differ between endpoints. Directional imbalance varies by season and can affect seat availability and fares. Airlines use revenue management, schedule timing and connecting traffic to improve load factors in both directions. Cargo revenue may also influence long-haul viability even when the present analysis focuses on passengers.

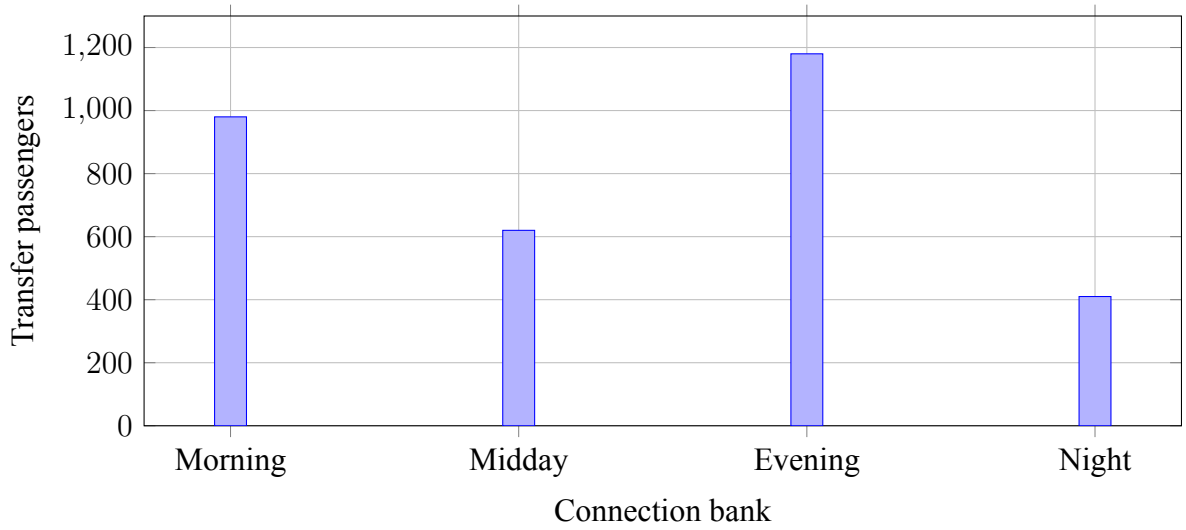

Figure 16: Illustrative distribution of transfer passengers among hub connection banks

Description of the graph. The evening bank contains the largest transfer flow and therefore determines a major part of peak terminal demand. The morning bank is also substantial, while midday traffic is more moderate. A small night bank may still be operationally important when public transport and staffing are limited. Concentration improves the number of possible connections but increases the need for reserve capacity. Schedule evaluation must therefore balance network connectivity with runway, stand, terminal and baggage constraints.

The vulnerability of hub h can be represented by formula (106):

$$V_h = \sum_{f \in \mathcal{F}_h} P_f^{conn} \, \Pr(D_f > MCT_f), \tag{106}$$

where P_f^{conn} is the number of connecting passengers exposed to flight f and the probability term describes a missed-connection risk. The indicator weights operational unreliability by passenger consequences. It supports prioritization of connection protection, reserve gates and rebooking resources.

The weighted connectivity supplied by hub h is given by formula (107):

$$CI_h = \sum_{a \in \mathcal{A}_h} \sum_{b \in \mathcal{D}_h} I_{ab} \, f_a f_b \, e^{-\rho w_{ab}}, \tag{107}$$

where f_a and f_b are arrival and departure frequencies and w_{ab} is passenger waiting time. The exponential term reduces the value of connections with excessive waiting. The parameter ρ reflects passenger sensitivity and can vary by trip purpose. The index supports comparison of alternative bank structures [62, 73].

If arrival delay is normally approximated, the probability of completing connection ab is given by formula (108):

$$P_{ab}^{succ} = \Phi\left(\frac{t_b^{dep} - t_a^{arr} - MCT - \mu_D}{\sigma_D}\right), \tag{108}$$

where Φ is the standard normal distribution function and μ_D, σ_D describe arrival-delay behaviour. Greater schedule buffer increases success probability but also lengthens the itinerary. Empirical delay distributions should replace the normal approximation when they are strongly asymmetric.

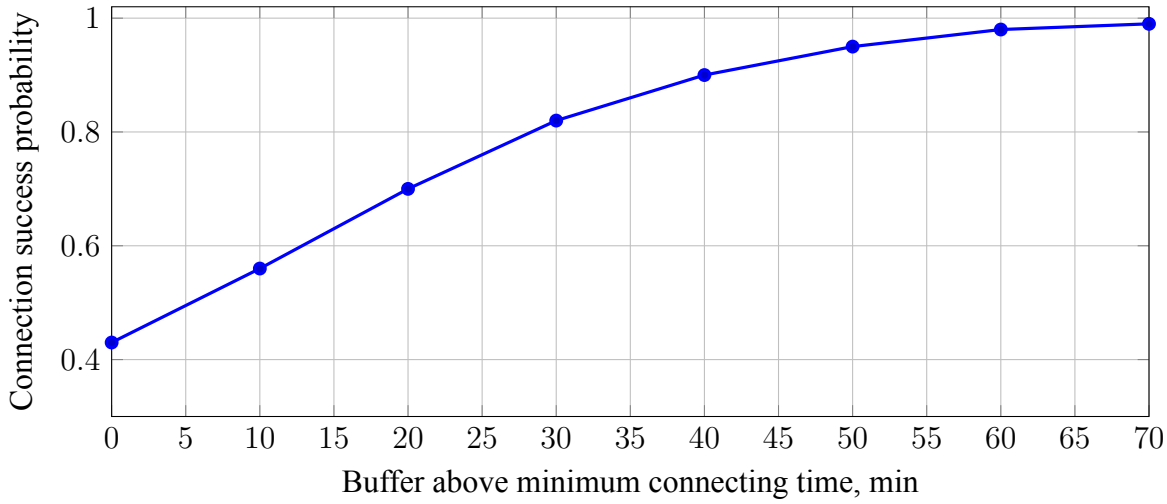

Figure 17: Illustrative influence of schedule buffer on connection reliability

Description of the graph. Connection reliability rises rapidly when the first thirty minutes of additional buffer are introduced. Further increases continue to improve reliability but with diminishing benefit. Very short buffers expose passengers to ordinary arrival variability and baggage-transfer delay. Excessive buffers protect the connection but reduce itinerary attractiveness. Hub scheduling should therefore select a buffer that balances passenger time and missed-connection cost.

Pandemic-related network changes demonstrated that connectivity and traffic can contract unevenly across regions. Central airports may lose a large number of indirect city-pair links even when some direct flights remain. Recovery paths depend on domestic demand, border policy, airline finances and the order in which feeder and long-haul services return [74–76]. Scenario planning should therefore examine network structure rather than restoring only aggregate passenger totals.

Table 12: Advantages and risks of hub-based intercontinental networks

Dimension	Advantage	Risk
Connectivity	Many city pairs with limited direct services	Dependence on timetable coordination
Economics	Concentration supports frequency and aircraft size	High exposure to loss of feeder demand
Passenger service	Broad destination choice on one network	Transfer time and missed connections
Infrastructure	Repeated use of specialized hub facilities	Severe bank peaks and baggage complexity
Resilience	Possibility of rerouting through partner hubs	Disruption propagation across continents

Hub development should not be evaluated solely by transfer share. A sustainable hub requires competitive geographic position, adequate local demand, reliable operations, scalable infrastructure and an airline strategy capable of maintaining coordinated banks. Public investment based on optimistic connecting flows is risky because transfer passengers can change hubs without changing their origin or destination. The strongest business case combines network value with a resilient local market.

3.4. Seasonality, forecasting and spatial distribution of passenger flows

Passenger flows vary by hour, day, month and year. Their temporal pattern reflects work and school calendars, tourism seasons, public holidays, events, airline schedules and weather. Spatial distribution changes simultaneously because different destinations reach their peaks at different times. A forecasting model must therefore preserve both total demand and its allocation among routes, airports and time intervals [66, 68].

An additive time-series decomposition is given by formula (109):

$$Q_t = T_t + S_t + C_t + \varepsilon_t, \tag{109}$$

where T_t is trend, S_t is seasonality, C_t is a cyclical component and ε_t is irregular variation. A multiplicative form is preferable when seasonal amplitude grows with traffic. Decomposition helps distinguish a permanent change from a normal seasonal decline. Operational forecasts require finer intervals than strategic forecasts, but both should use consistent historical definitions.

Classical time-series models use lags of traffic and forecast errors. Explanatory models add income, fare, exchange rate, capacity, events and competing-mode variables. Machine-learning methods can capture nonlinear interactions, while graph-based models represent dependence among airports or routes. No method is universally superior: performance depends on horizon, data volume, structural stability and the cost of forecast error [63, 64, 66, 67].

The one-step autoregressive forecast is given by formula (110):

$$\widehat{Q}_{t+1} = c + \sum_{k=1}^{p} \phi_k Q_{t+1-k} + \boldsymbol{\beta}^{\mathsf{T}} \mathbf{x}_{t+1}, \tag{110}$$

where p is lag order and $\mathbf{x}_{t+1}$ contains known or forecast explanatory variables. Lag selection should avoid both omitted dynamics and excessive parameterization. Residual autocorrelation indicates that useful temporal structure remains unexplained. Rolling-origin validation reproduces the information that would have been available at each historical forecast date.

Spatial dependence arises because neighbouring airports compete, feeder flows support hubs and common shocks affect connected markets. A route forecast made independently can violate network constraints or miss propagation. Graph convolution

and diffusion models treat observations as signals on nodes and use a weighted adjacency matrix to exchange information among related locations [63, 64, 67, 71, 72].

A generic spatial–temporal layer is given by formula (111):

$$\mathbf{H}_t^{(l+1)} = \sigma\left(\sum_{k=0}^{K} \widetilde{\mathbf{A}}^k \mathbf{H}_{t-k}^{(l)} \mathbf{W}_k^{(l)}\right), \tag{111}$$

where $\widetilde{\mathbf{A}}$ is a normalized airport-relation matrix, $\mathbf{H}$ contains traffic features, $\mathbf{W}$ contains learned weights and σ is an activation function. The model combines temporal lags with information from connected nodes. The adjacency matrix may represent direct services, geographic proximity, common passenger markets or empirically learned dependence. Interpretability requires testing whether learned connections correspond to plausible transport relations.

Forecast accuracy must be evaluated at the scale at which decisions are made. A low network-wide error may coexist with an unacceptable error for a constrained hub or a prospective route. Mean absolute error is easy to interpret, RMSE penalizes large deviations and mean absolute percentage error facilitates comparison but behaves poorly near zero. Quantile loss is appropriate when staffing or capacity decisions require upper-demand forecasts.

The symmetric mean absolute percentage error is given by formula (112):

$$sMAPE = \frac{100\%}{N} \sum_{t=1}^{N} \frac{2|Q_t - \widehat{Q}_t|}{|Q_t| + |\widehat{Q}_t|}. \tag{112}$$

The bounded denominator reduces the instability of ordinary percentage error for small values, although zero observations still require attention. Metrics should be reported by horizon, airport size, season and disruption condition. A forecast used for peak resources should also be assessed by its ability to predict threshold exceedance.

A two-sided forecast interval can be approximated by formula (113):

$$\widehat{Q}_{t+h} \pm z_{1-\alpha/2}\widehat{\sigma}_h, \tag{113}$$

where $\widehat{\sigma}_h$ is the forecast-error standard deviation at horizon h. The interval normally widens with the horizon because uncertainty accumulates. Empirical quantiles or bootstrap simulation should be used when forecast errors are non-normal. Capacity decisions may use an upper quantile rather than the central estimate [66, 77].

Spatial autocorrelation of airport forecast residuals is assessed by Moran's statis-

tic and is presented in formula (114):

$$I = \frac{N}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij}(e_i - \bar{e})(e_j - \bar{e})}{\sum_i (e_i - \bar{e})^2}. \tag{114}$$

A positive value indicates that neighbouring or connected airports tend to have errors with the same sign. Such a pattern shows that the model has omitted a spatially shared factor. The weights w_{ij} should represent a meaningful relationship such as direct service or overlapping catchment areas [63, 64].

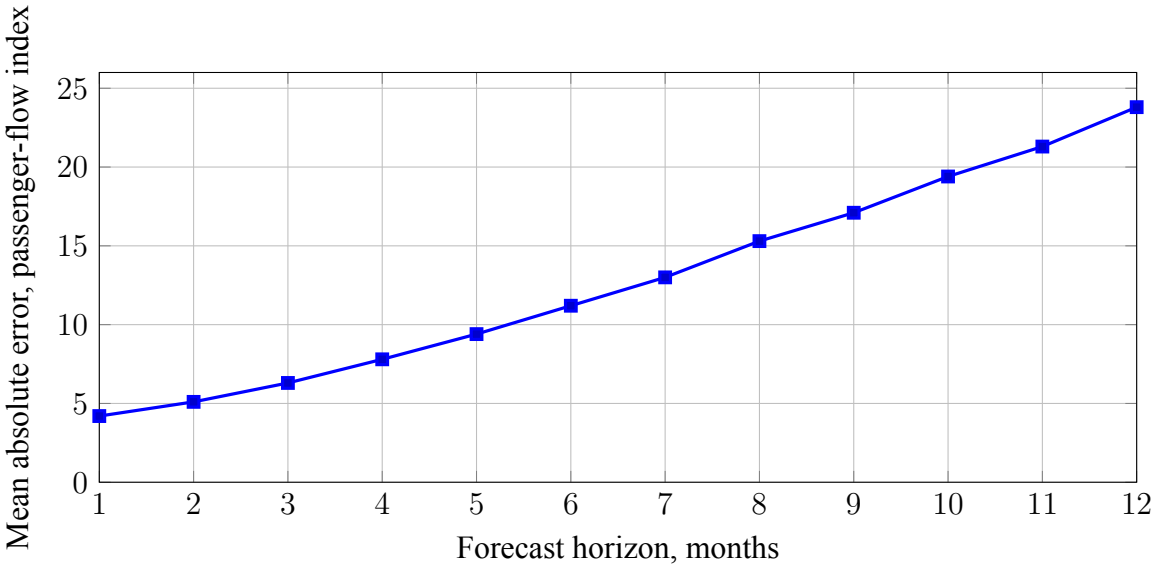

Figure 18: Illustrative growth of passenger-flow forecast error with the forecast horizon

Description of the graph. Forecast error increases steadily as the horizon expands from one to twelve months. Near-term predictions benefit from observed bookings, schedules and recent traffic conditions. Longer horizons depend more strongly on uncertain economic, competitive and seasonal assumptions. The curve justifies using wider prediction intervals for strategic decisions. Forecast accuracy should always be reported separately for each horizon rather than as one combined average.

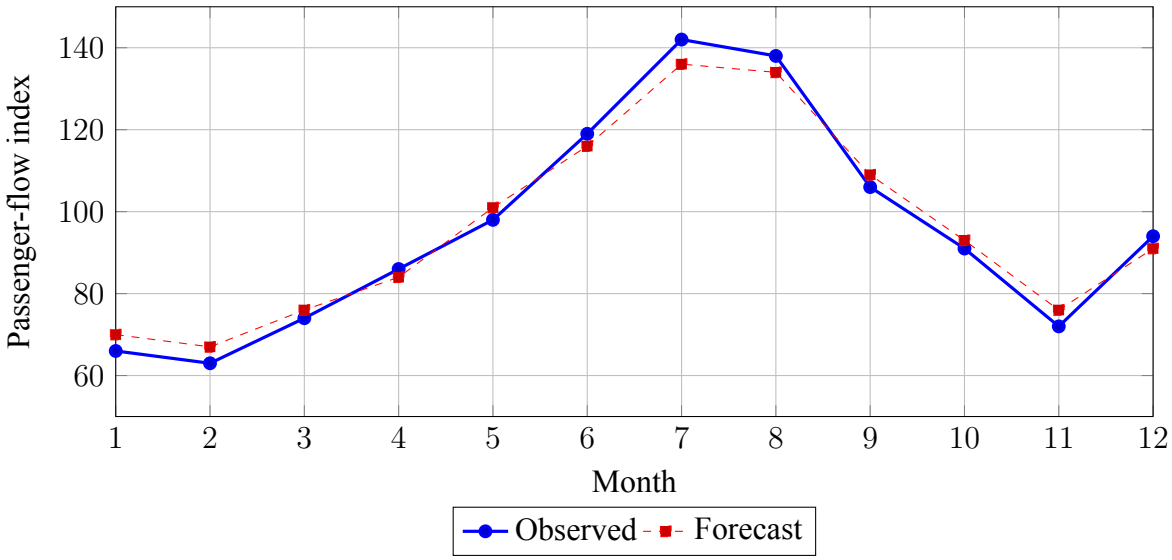

Figure 19: Illustrative seasonal passenger-flow profile and forecast

Description of the graph. The observed series reaches its maximum during July and remains high in August. The forecast reproduces the seasonal shape but slightly underestimates the summer peak. Differences are smaller during shoulder months and increase where demand changes rapidly. Such a forecast may be adequate for annual planning but require a safety margin for peak staffing. Repeated validation determines whether the summer underestimation is systematic or random.

Structural breaks require explicit treatment. The pandemic changed the scale and spatial distribution of the world air network rather than producing an ordinary seasonal residual [74–76]. Models trained only on stable growth can recover slowly after such a break. Analysts can use intervention variables, regime-switching models, scenario ranges and shorter calibration windows. Historical relationships should be re-estimated when passenger behaviour, borders or airline capacity strategies change.

Table 13: Forecasting methods for passenger-flow planning

Method	Suitable use	Required caution
Seasonal decomposition	Transparent baseline and recurring peaks	Weak response to structural breaks
Econometric regression	Causal and scenario interpretation	Requires forecasts of explanatory variables
ARIMA and state space	Short- and medium-term temporal dynamics	Limited spatial representation
Graph neural network	Network-wide nonlinear forecasting	High data and validation requirements
Scenario method	Strategic uncertainty and disruptions	Does not assign objective probabilities automatically

Forecast governance is as important as algorithm selection. Every forecast needs a reference date, data version, horizon, responsible owner and documented assumptions. Operational units should record overrides and later compare them with model output. A forecast that is frequently adjusted can still be useful if human changes add measurable information. Continuous monitoring protects decisions from silent deterioration when the market evolves [77–81].

3.5. Methods of collecting and analysing passenger movement data

Passenger-flow analysis combines administrative, commercial, operational and observational data. Ticket and reservation records describe intended itineraries, while departure-control records describe passengers accepted for a flight. Airport systems record check-in, security, boarding and baggage milestones. Surveys add journey purpose, access mode and satisfaction, and mobile or sensor data can reveal movement through space. No source is complete, so data integration must begin with explicit definitions and quality controls [69, 70].

The completeness of dataset d is given by formula (115):

$$C_d = \frac{N_d^{valid}}{N_d^{required}} \times 100\%. \tag{115}$$

A field can be present but still invalid because of an impossible timestamp, unknown airport code or inconsistent passenger status. Completeness should therefore be evaluated together with accuracy, timeliness, consistency and uniqueness. Critical fields include origin, destination, itinerary, flight date, passenger category and event time.

Booking data represent demand that may later cancel, change or fail to appear. Boarding data represent realized flight use but can hide the passenger's true origin and final destination when tickets are separate. Airport throughput counts include transfer passengers differently depending on the reporting convention. Analysts must distinguish passengers, journeys, flight legs and airport processing events before combining tables.

Trajectory sources such as ADS-B provide aircraft movement rather than passenger counts, yet they help reconstruct operated networks, schedule reliability and travel times. The OpenSky dataset and open aircraft-performance models demonstrate how crowdsourced surveillance data can support reproducible air-transport research [69, 70]. Coverage, receiver density and aircraft equipage create spatial bias, so missing observations must not automatically be interpreted as cancelled flights.

The linkage rate between two systems is given by formula (116):

$$LR = \frac{N_{matched}}{N_{eligible}} \times 100\%. \tag{116}$$

Deterministic linkage uses stable identifiers, while probabilistic linkage combines flight number, date, airport, time and other attributes. False matches can distort connection

and delay analysis. Linkage quality should be tested manually on a sample and reported with the resulting dataset.

Passenger surveys remain necessary when administrative systems do not contain purpose, income, airport-choice reasons or perceived quality. Sampling must cover time periods, airlines, destinations and passenger categories. Online surveys are efficient but may exclude travellers with limited digital access. Stated-preference experiments can evaluate a future route or service attribute that is not yet observable, but hypothetical responses require careful experimental design [82, 87, 90].

Automated border and biometric systems generate high-resolution process timestamps but involve sensitive personal data. Collection should follow purpose limitation, access control, retention and security requirements. Facial-recognition acceptance depends not only on processing speed but also on perceived security, benefits and trust [83]. Research datasets should use aggregation or pseudonymization and should not retain identity fields merely because they are technically available.

Passenger counts can be expanded from a sample by formula (117):

$$\widehat{Q}_{ij} = \sum_{n \in s_{ij}} w_n, \qquad w_n = \frac{1}{\pi_n}, \tag{117}$$

where s_{ij} is the sample of observed passengers and π_n is inclusion probability. Stratification improves precision when traffic varies strongly by period or passenger type. Non-response adjustment is required when participation correlates with travel characteristics. Reported estimates should include confidence intervals rather than only expanded totals.

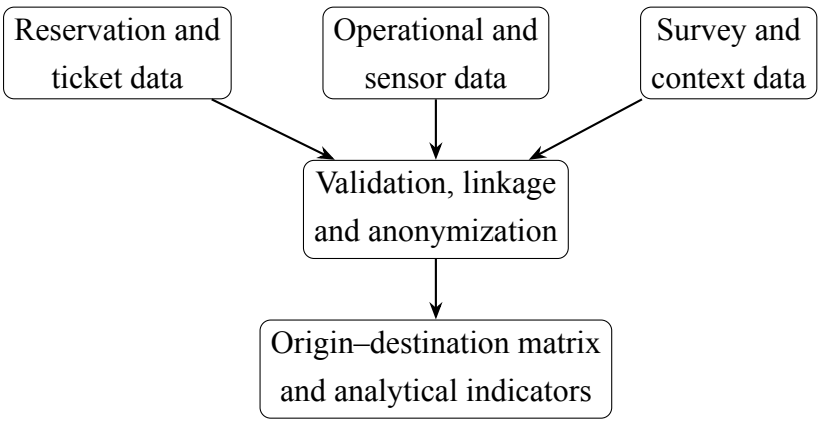

Figure 20: Integrated process for constructing a passenger-flow dataset

Description of the graph. Three source groups enter a common validation and integration stage. Reservation data describe intended travel, operational data record

realized events and surveys provide behavioural context. Linkage resolves common flights or journeys while anonymization limits privacy risk. The resulting dataset supports origin–destination matrices and performance indicators. Quality documentation must remain attached to the output so that later users understand its limitations.

Exploratory analysis begins with distributions, missingness, outliers and temporal coverage. Spatial visualization can reveal impossible movements or airport-code errors. Network analysis identifies central nodes and communities, while clustering groups markets with similar seasonality or growth. Text analysis of reviews can supplement measured behaviour with passenger perceptions, but it should not be treated as a representative traffic sample [87, 90].

The consistency error between ticketed and boarded totals is given by formula (118):

$$E_c = \frac{|Q^{ticket} - Q^{board}|}{\max(Q^{ticket}, Q^{board})}. \tag{118}$$

The indicator flags records requiring investigation but does not specify the cause. Legitimate differences arise from cancellations, no-shows, rebooking and infant-count conventions. Quality rules should therefore combine numerical thresholds with process knowledge.

The standardized anomaly score for observation x_n is given by formula (119):

$$z_n = \frac{x_n - \operatorname{median}(x)}{1.4826\, MAD(x)}, \tag{119}$$

where MAD is the median absolute deviation. The robust denominator is less affected by extreme traffic observations than the ordinary standard deviation. Large absolute scores identify records for investigation rather than automatic deletion. Events, diversions and disruptions can create valid extremes [69].

A composite data-quality index is given by formula (120):

$$DQ = \sum_{k=1}^{K} \omega_k d_k, \qquad \sum_{k=1}^{K} \omega_k = 1, \tag{120}$$

where d_k are normalized completeness, accuracy, timeliness, consistency and uniqueness scores. The aggregate supports monitoring across data deliveries, while individual components reveal the reason for deterioration. Critical safety or privacy failures should remain hard constraints and must not be compensated by strong results in other dimensions.

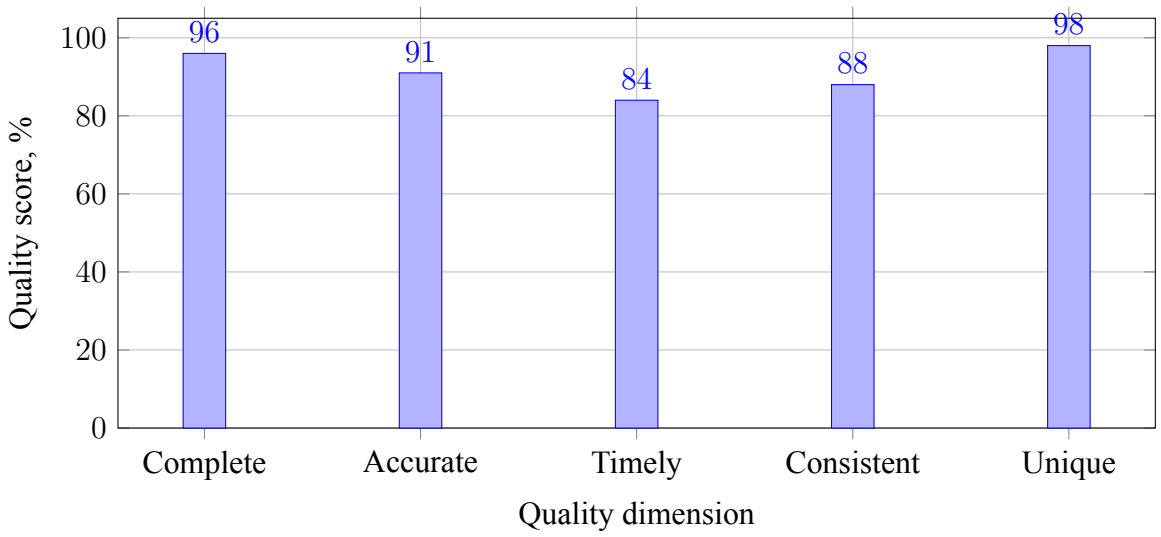

Figure 21: Illustrative quality profile of an integrated passenger-flow dataset

Description of the graph. Uniqueness and completeness have the highest scores in the illustrative dataset. Timeliness is the weakest dimension and may limit real-time operational use. Accuracy and consistency remain acceptable but still require targeted validation. A single average score would conceal the specific delay in data delivery. The profile therefore supports corrective action by the organization responsible for each quality dimension.

Table 14: Passenger-flow data sources and analytical uses

Source	Main information	Typical limitation
Reservations and tickets	Intended itinerary, fare and booking time	Changes, cancellations and separate tickets
Departure control	Accepted and boarded passengers	Limited door-to-door context
Airport process systems	Terminal timestamps and resource use	Fragmented identifiers across organizations
Surveys	Purpose, preferences and access mode	Sampling and response bias
ADS-B and schedules	Operated network and aircraft movement	No direct passenger count

Data stewardship requires a catalogue specifying owner, definition, update frequency, legal basis and quality threshold for every field. Version control is necessary because corrected historical data can change model estimates. Reproducible scripts should transform raw records into analytical tables without undocumented manual steps. These practices allow forecasting results to be audited and updated when new observations become available.

3.6. Scenario forecasting and the development of a prospective route network

A prospective route network is a set of services that can be operated sustainably under future demand, fleet, airport and regulatory conditions. Development begins with market identification but must also test schedule connectivity, aircraft economics, competitive response and network effects. A route with sufficient annual passengers can still fail when demand is highly seasonal or when an acceptable frequency cannot be offered [74, 81].

The unconstrained passenger potential of route i is converted into expected airline demand by formula (121):

$$D_i^{air} = D_i^{market}\, s_i^{airport}\, s_i^{mode}\, s_i^{carrier}, \tag{121}$$

where the three shares represent airport, mode and carrier choice. Each share should be estimated consistently with available alternatives. Multiplying optimistic shares without accounting for correlation can overstate demand. Sensitivity analysis identifies which assumption has the greatest effect on the business case.

Route feasibility depends on revenue exceeding operating and allocated fixed costs. A simplified break-even load factor is given by formula (122):

$$LF_{BE} = \frac{C_f}{S_f \overline{y}_f}, \tag{122}$$

where C_f is flight cost, S_f is offered seats and $\overline{y}_f$ is average net passenger yield. Ancillary and cargo revenue can be included in the denominator or deducted from cost. The estimate must reflect directional and seasonal variation because an annual average can conceal unprofitable periods.

Scenario forecasting avoids dependence on one deterministic future. A baseline scenario can extend central economic and demographic assumptions; an optimistic scenario can combine faster growth and improved connectivity; a constrained scenario can represent recession, regulation, airspace closure or limited fleet availability. Pandemic recovery studies show that the sequence of market reopening and airline response can matter as much as the final macroeconomic level [74–76].

For scenario s, expected flow is given by formula (123):

$$Q_{ij}^{(s)} = Q_{ij}^{0} \prod_{k=1}^{K} \left(1 + g_k^{(s)}\right)^{\eta_k}, \tag{123}$$

where $g_k^{(s)}$ is the scenario change in driver k and η_k is demand sensitivity. The multiplicative form preserves positive flows and makes assumptions transparent. Correlated drivers should be specified coherently; for example, income growth, business activity and fare may not change independently.

Candidate routes compete for aircraft, slots and management attention. Selection is therefore a portfolio problem rather than a sequence of isolated route studies. Criteria can include demand, profitability, strategic connectivity, seasonality, competition, operational complexity and regional benefit. Multi-criteria scoring supports transparent comparison, while mathematical optimization enforces fleet and schedule constraints.

The binary route-selection model is given by formula (124):

$$\max \sum_{r \in \mathcal{R}} \left(\Pi_r + \lambda C_r^{net} + \mu B_r^{reg}\right) x_r, \tag{124}$$

subject to aircraft-hour, slot, budget and risk constraints, where x_r equals one when route r is selected. Π_r is expected profit, C_r^{net} is network-connectivity value and B_r^{reg} is a regional-benefit indicator. Weights should be approved by the decision maker and tested for sensitivity. A public authority and a private airline will normally apply different weights.

Disruption resilience must be included during network design. Integrated recovery research shows that aircraft, passengers and schedules interact after a disturbance [85, 86, 88]. A tightly utilized fleet can produce attractive planned economics but large downstream losses. Prospective schedules should include turnaround, maintenance and connection buffers based on observed variability rather than arbitrary percentages.

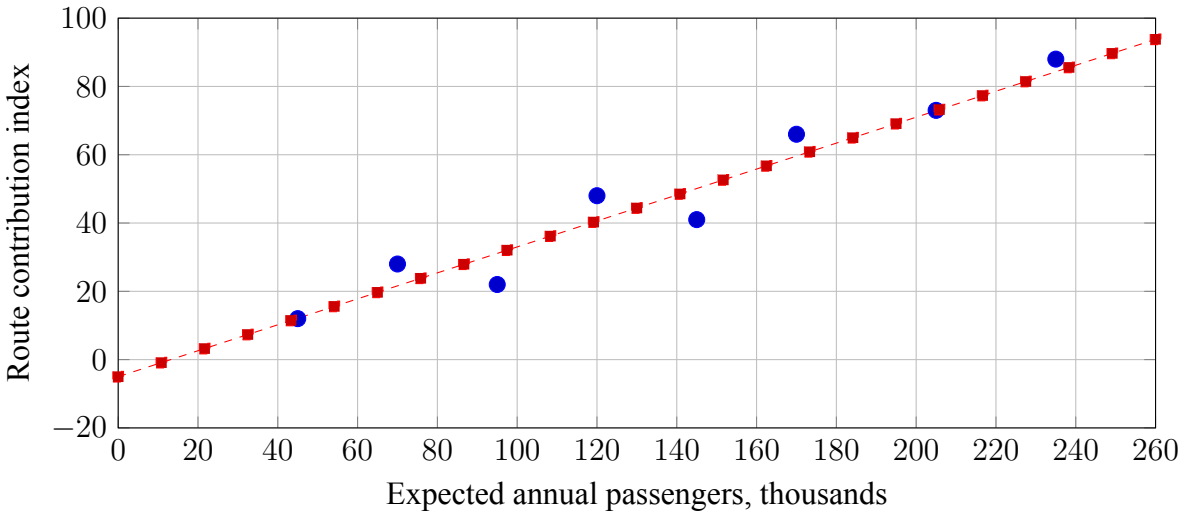

Figure 22: Illustrative screening of prospective routes by demand and contribution

Description of the graph. Each point represents a candidate route with a different combination of annual passengers and expected contribution. The dashed line provides a simplified screening benchmark rather than an automatic decision boundary. Routes above the line may merit detailed schedule and risk analysis. A low-volume route can remain strategically valuable when it provides unique connectivity or regional access. Final selection must therefore combine quantitative screening with network and policy considerations.

New-route forecasts should include ramp-up. Awareness, distribution, corporate agreements and connecting schedules develop over time, so first-year demand may remain below mature potential. Conversely, introductory fares can temporarily inflate bookings. A ramp-up curve should be calibrated from comparable route launches and reviewed after each season.

The maturity adjustment is given by formula (125):

$$Q_{r,t} = Q_r^{mature} \left(1 - e^{-\kappa_r t}\right), \tag{125}$$

where κ_r controls the speed of market development. The expression approaches mature demand gradually. Marketing, frequency and network feed can change the parameter, so it should not be treated as a universal constant.

The net present value of prospective route r is given by formula (126):

$$NPV_r = -I_r + \sum_{t=1}^{T} \frac{R_{r,t} - C_{r,t}}{(1+d)^t}, \tag{126}$$

where I_r is launch expenditure, $R_{r,t}$ is revenue, $C_{r,t}$ is operating cost and d is the dis-

count rate. Positive NPV indicates that the route covers the required return under the selected assumptions. Scenario-specific demand, yield, fuel and exchange-rate inputs should be applied rather than one average case.

A robust portfolio objective can maximize the worst scenario result and is presented in formula (127):

$$\max_{\mathbf{x}} \min_{s \in \mathcal{S}} \sum_{r \in \mathcal{R}} \Pi_r^{(s)} x_r. \tag{127}$$

This criterion favours a network that remains acceptable under adverse conditions. It can be conservative when one scenario is extremely unlikely, so expected-value and regret measures should also be reviewed. The formulation is useful when fleet commitments are difficult to reverse [74–76].

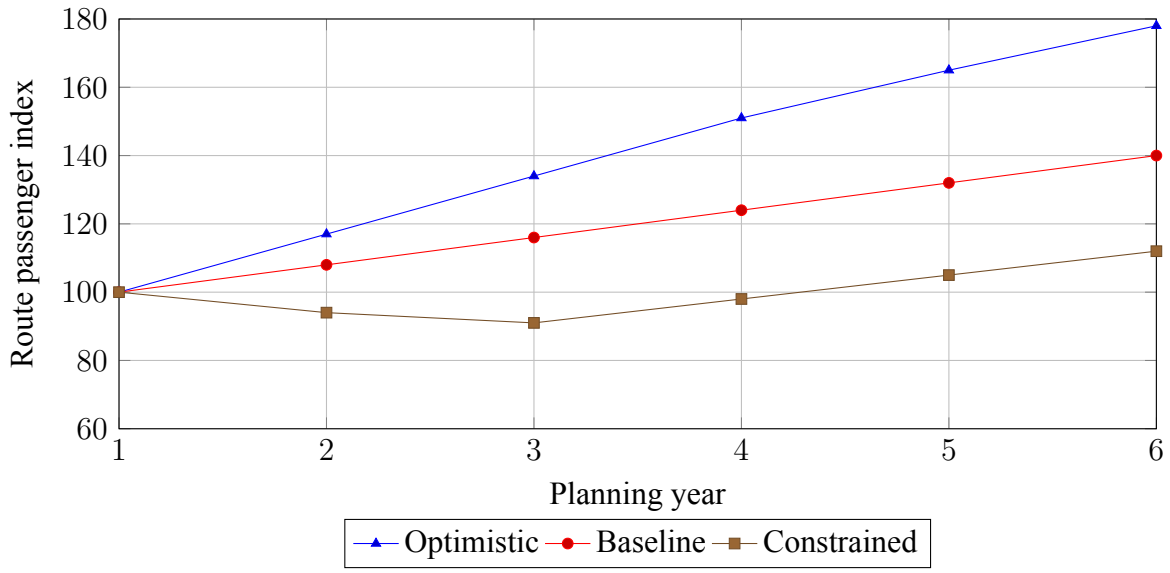

Figure 23: Illustrative scenarios for passenger development on a prospective route

Description of the graph. The optimistic scenario produces rapid and continuous growth over the six-year period. Baseline demand increases more gradually and represents the central planning case. The constrained scenario initially declines before a partial recovery begins. Aircraft and schedule decisions should remain feasible across this range rather than depend only on the optimistic trajectory. Monitoring actual traffic against the scenarios provides an early signal for frequency or marketing adjustment.

Table 15: Stages in developing a prospective air-route network

Stage	Main analysis	Decision output
Market screening	Origin–destination demand and leakage	Long list of candidate routes
Service design	Frequency, timetable, aircraft and connections	Feasible operating concept
Financial appraisal	Yield, cost, ramp-up and scenarios	Route business case
Network appraisal	Feed, cannibalization and strategic value	Portfolio priority
Implementation review	Booking, yield and operational performance	Continue, modify or withdraw

Passenger acceptance also depends on the service delivered after launch. Value for money, reliability and satisfaction influence repeat purchase and word-of-mouth [82, 87, 90]. Boarding design and seat or baggage policies can affect operational performance and perceived quality [84, 89]. Route monitoring should therefore combine bookings and revenue with punctuality, misconnections, complaints and passenger feedback.

The prospective network should be revised as evidence accumulates. Monthly monitoring supports tactical adjustment, seasonal review supports frequency and aircraft changes, and annual review updates the strategic portfolio. Routes should not be retained solely because their original forecast was optimistic, nor withdrawn because of a temporary disturbance without examining recovery potential. A disciplined cycle of forecast, implementation, measurement and revision converts route development into a learning process.

CHAPTER 4

ORGANIZATION OF PASSENGER AND BAGGAGE CARRIAGE

The organization of passenger and baggage carriage converts an airline schedule into a sequence of services experienced by an individual traveller. Reservation, payment, check-in, document control, security screening, boarding, cabin service, arrival and baggage delivery must operate as one continuous process. Each stage has its own resources and legal requirements, but failures are transferred downstream through queues, missed departures, baggage irregularities and inconsistent passenger information [91, 94].

Digital channels have expanded passenger choice and reduced routine transaction time. At the same time, automation transfers some tasks to passengers and creates new requirements for accessibility, identity assurance, cybersecurity and exception handling. A successful process does not merely maximize self-service use; it provides a clear transition to trained personnel when documents, payments, baggage or individual needs cannot be handled automatically [92, 99].

The operational objective is safe and punctual completion of the journey at a predictable level of quality. Productivity indicators must therefore be interpreted together with passenger satisfaction, first-time-right performance and recovery capability. The mathematical models in this chapter formalize capacity, waiting, boarding, baggage traceability and service-quality relationships using the research represented by sources [91]–[105].

4.1. Reservation, ticketing and information services

Reservation begins when a passenger searches for an itinerary and ends when a confirmed transportation document and related service records are created. The process includes availability display, fare selection, passenger-data entry, optional services, payment authorization, ticket issuance and notification. Information must remain consistent across the airline website, mobile application, travel agency, call centre and airport systems. A discrepancy in fare conditions, baggage allowance or schedule can create later disputes even when the flight itself operates normally [91, 98].

The conversion rate from search to confirmed booking is given by formula (128):

$$CR = \frac{N_{book}}{N_{search}} \times 100\%, \tag{128}$$

where N_{search} is the number of eligible itinerary searches and N_{book} is confirmed bookings. The indicator should be segmented by channel, device, market and itinerary type. A low value may indicate uncompetitive price, inconvenient schedule, poor interface design or payment failure. Conversion alone is insufficient because an interface can increase sales while creating later servicing costs.

Seat inventory is controlled by booking class and forecast demand. Accepting a request uses capacity that may otherwise be sold later at a different fare. The airline therefore balances immediate revenue against the opportunity cost of closing future demand. Restrictions such as advance purchase, change conditions and minimum stay separate passenger segments with different willingness to pay.

The expected marginal seat revenue for class c can be written as formula (129):

$$EMSR_c = y_c \Pr(D_c > x_c), \tag{129}$$

where y_c is net yield, D_c is future demand and x_c is the number of seats protected for the class. Capacity is protected while the expected marginal revenue exceeds the revenue available from the next class. Forecast error must be monitored because excessive protection leaves empty seats, while insufficient protection displaces high-value demand.

The booking balance for flight f at time t is given by formula (130):

$$B_f(t) = B_f(0) + R_f(t) - C_f(t) - X_f(t), \tag{130}$$

where R_f is new reservations, C_f is cancellations and X_f is changes transferred to other flights. Net bookings should be analysed by departure horizon because cancellation and

change behaviour varies as departure approaches. A booking curve supports demand monitoring and identifies deviations from comparable flights.

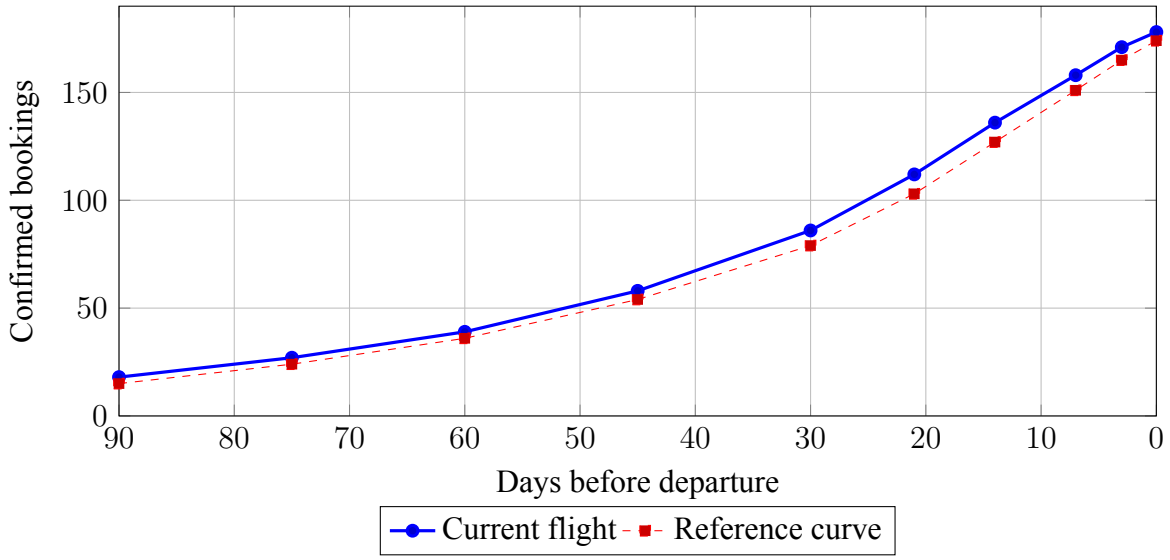

Figure 24: Illustrative booking curve before flight departure

Description of the graph. Confirmed bookings increase gradually during the early sales period and accelerate during the final month. The current flight remains above the reference curve at every observation point. The difference becomes larger between thirty and fourteen days before departure, indicating stronger-than-normal demand. Revenue management can respond by revising availability or fare levels. The final bookings still require adjustment for expected cancellations and no-shows.

Overbooking compensates for passengers who cancel late or fail to appear. The decision must consider denied-boarding cost, passenger rights, reaccommodation capacity and uncertainty. Historical no-show rates should be segmented because behaviour differs by fare, route, season and connection type.

The expected cost of overbooking level b is given by formula (131):

$$EC(b) = c_e \, \mathbb{E}\big[(S - N_b)^+\big] + c_d \, \mathbb{E}\big[(N_b - S)^+\big] \,, \tag{131}$$

where S is seat capacity, N_b is the number of passengers presenting for travel, c_e is the cost of an empty seat and c_d is denied-boarding cost. The preferred booking limit minimizes expected cost subject to legal and service constraints. Passenger volunteers and alternative flights reduce consequences but should not justify systematically aggressive overbooking.

Payment processing must verify authorization, currency, taxes and fraud controls without creating unnecessary abandonment. Failed payments should generate un-

derstandable instructions and preserve the itinerary for a reasonable time. The ticket record must correspond to the confirmed booking, while electronic miscellaneous documents record optional paid services. Audit trails are required when a transaction is corrected or refunded.

The first-attempt payment success rate is given by formula (132):

$$PSR = \frac{N^{(1)}_{approved}}{N^{(1)}_{payment}} \times 100\%. \tag{132}$$

Declines should be divided into insufficient funds, authentication failure, suspected fraud, technical error and passenger abandonment. A high approval rate is not automatically desirable if fraud losses increase. Payment design must balance security, conversion and passenger effort.

Passenger information has operational and commercial value. Before purchase, it supports comparison; after purchase, it supports preparation and compliance. Essential information includes itinerary, local times, terminal, check-in deadline, documents, baggage conditions, accessibility services, change rules and contact channels. Online reviews show that passenger recommendations depend on several interacting service dimensions rather than one isolated event [91, 94, 96, 97].

Information quality can be evaluated by formula (133):

$$IQ = \sum_{k=1}^{K} w_k q_k, \qquad \sum_{k=1}^{K} w_k = 1, \tag{133}$$

where q_k are normalized accuracy, completeness, timeliness, consistency and clarity scores. A critical inaccuracy should remain visible even when the weighted average is high. The indicator supports audits of websites, notifications, displays and contact-centre scripts.

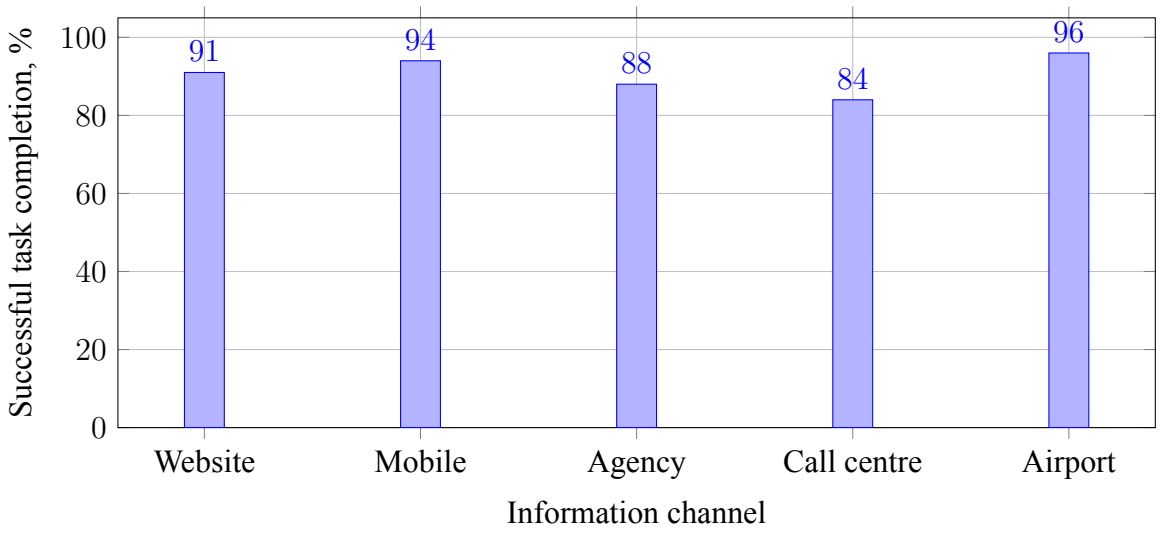

Figure 25: Illustrative completion rate for passenger information and servicing channels

Description of the graph. Airport service points have the highest completion rate because personnel can resolve complex exceptions directly. Mobile and website channels perform strongly for routine transactions. The travel-agency result reflects dependence on information exchange between separate systems. The call centre has the lowest rate, which may indicate waiting, incomplete authority or repeated transfers. Channel management should examine both completion and the cost and complexity of requests handled.

Personalization can improve relevance but requires transparent use of passenger data. Recommendation systems should not conceal mandatory charges or make service conditions difficult to compare. Text analysis of reviews can identify recurring information and service problems, while human validation is necessary before operational rules are changed [96, 102].

Table 16: Control points in reservation, ticketing and information services

Stage	Required result	Principal risk
Availability display	Feasible itinerary and complete price	Stale inventory or hidden conditions
Passenger data	Accurate identity and contact fields	Input error and privacy breach
Payment	Authorized and traceable transaction	Fraud, decline or duplicate charge
Ticket issuance	Document consistent with booking	Status mismatch or missing service record
Notification	Timely and channel-consistent information	Passenger acts on obsolete instructions

The service process should preserve continuity when the passenger changes channel. A traveller who begins on a mobile application and contacts an agent should

not repeat information already available in the booking. Common records, clear ownership and controlled access reduce handling time. Performance should combine sales, accuracy, first-contact resolution and passenger perception because service quality affects repurchase intention [98, 104].

4.2. Check-in, control, boarding and airport services

Airport departure processing confirms that the passenger, documents and baggage are suitable for the planned journey and transfers the passenger from a public area to the aircraft. Check-in creates the operational passenger record and assigns or confirms a seat. Security and border controls determine access to restricted zones, while gate processing verifies final flight eligibility. The process must remain accessible to passengers who cannot use self-service equipment [92, 99].

The arrival rate at check-in interval t is given by formula (134):

$$\lambda_t = \frac{N(t, t + \Delta t)}{\Delta t}. \tag{134}$$

The profile normally rises before the airline's acceptance deadline and differs by route, baggage behaviour and passenger type. Average hourly demand can conceal a short surge. Resource planning should therefore use intervals consistent with the time required to open additional positions.

For a stable single-stage queue, utilization is given by formula (135):

$$\rho = \frac{\lambda}{c\mu}, \tag{135}$$

where c is the number of parallel servers and μ is the service rate of one server. Operation near $\rho = 1$ produces rapidly increasing waiting and little recovery margin. Different passenger categories may require separate service-time distributions and routing.

The required number of open positions can be approximated by formula (136):

$$c = \left\lceil \frac{\lambda t_s}{\rho^*} \right\rceil, \tag{136}$$

where t_s is mean service time and ρ^* is target utilization. The result is a planning value that must be checked by queue simulation when arrivals are peaked. Cross-trained staff and common-use systems allow capacity to be adjusted between airlines and processes.

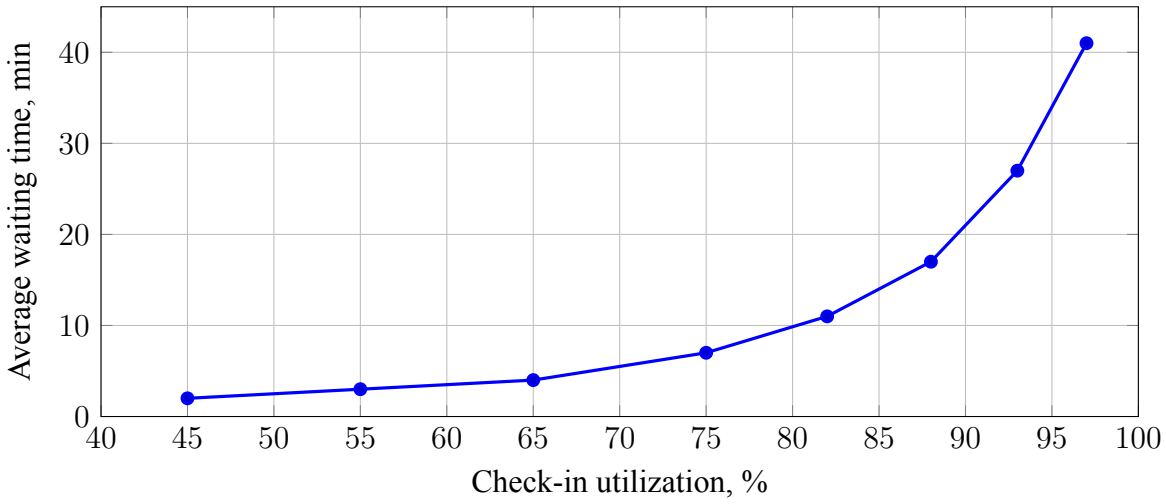

Figure 26: Illustrative relationship between check-in utilization and passenger waiting

Description of the graph. Waiting time remains modest while utilization is below approximately seventy percent. It begins to increase more rapidly as utilization approaches eighty-five percent. At very high loading, small changes in arrivals or service time produce severe queues. The curve demonstrates why nominal processing capacity should not be treated as sustainable capacity. A target utilization preserves service quality and recovery capability.

Self-service check-in and bag drop reduce routine counter work but create supervision, document-verification and exception demand. Passenger acceptance of biometric processes depends on perceived usefulness, security, benefits and emotional response [92, 99]. Enrollment and consent must be understandable, and a non-biometric alternative should remain available where required.

Biometric match performance is described by formula (137):

$$FAR = \frac{N_{false\ accept}}{N_{impostor}}, \qquad FRR = \frac{N_{false\ reject}}{N_{genuine}}. \tag{137}$$

The decision threshold trades false acceptance against false rejection. Operational design must include lighting, document quality, passenger assistance and manual resolution. A technically accurate system can still create delay when exception routing is poorly organized.

Security and border processes require separation of passenger streams and controlled reconciliation of identity, document and flight status. Queue information should be shared with airline and airport control so that emerging congestion is reflected in gate and staffing decisions. Priority channels require clear eligibility to prevent conflict and ineffective queue jumping.

The probability of completing all departure controls is given by formula (138):

$$P_{complete} = \prod_{j=1}^{m} (1 - p_j), \tag{138}$$

where p_j is the probability that stage j produces an unresolved exception. Even small failure probabilities accumulate over multiple stages. The model motivates first-time-right document preparation and rapid resolution points before the gate.

Boarding converts a gate queue into seated passengers while maintaining document control, cabin safety and baggage rules. Time depends on aircraft layout, passenger sequence, groups, mobility, carry-on baggage and seat or aisle interference. Stochastic and agent-based boarding models are useful because average service times do not represent interactions inside the cabin [93, 100, 103, 105].

Total boarding time can be represented as formula (139):

$$T_b = T_{scan} + \max_{g \in \mathcal{G}} \left(T_g^{walk} + T_g^{stow} + T_g^{seat} + I_g \right), \tag{139}$$

where I_g represents interference affecting passenger group g. Parallel gate scanning does not eliminate cabin bottlenecks. Boarding strategies should therefore coordinate release rate with aisle and storage capacity.

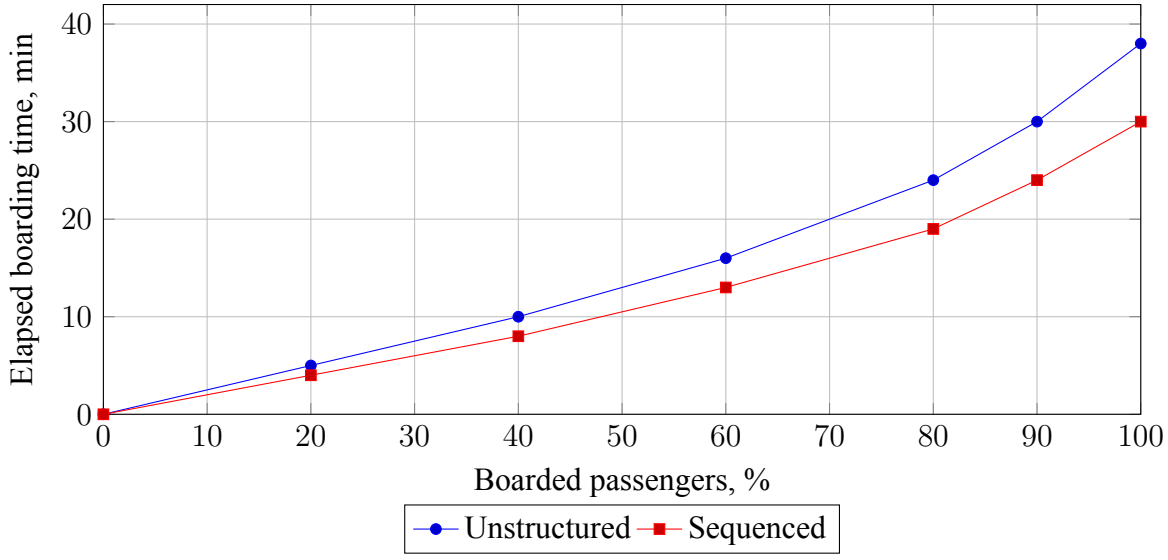

Figure 27: Illustrative boarding progress under two passenger-release strategies

Description of the graph. Sequenced boarding reaches every completion level earlier than unstructured boarding. The difference becomes larger during the final twenty percent of passengers, when aisle and seat interference normally increase. Early progress alone is therefore an incomplete measure of boarding performance. The release

strategy must also accommodate families, passengers requiring assistance and priority groups. Real operations should compare time savings with staff effort and passenger comprehension.

Two-door boarding and apron-bus strategies can reduce aisle concentration, although their benefit depends on stand layout, aircraft type and passenger distribution [101]. Health-related spacing restrictions can reverse the ranking of classical boarding methods [103]. Procedures must therefore be selected for current operating conditions rather than adopted as universal rules.

The boarding completion forecast is given by formula (140):

$$\widehat{T}_{complete} = t + \frac{N - N_b(t)}{\widehat{r}_b(t)}, \tag{140}$$

where $N_b(t)$ is boarded passengers and $\widehat{r}_b(t)$ is the estimated current boarding rate. Updating the forecast allows the gate, cabin crew and operations centre to act before the target becomes unattainable. Rate estimates should be smoothed because temporary pauses can otherwise create unstable predictions.

Table 17: Departure-process stages and principal controls

Stage	Operational result	Main exception
Check-in	Passenger and flight record confirmed	Document, seat or itinerary problem
Bag drop	Accepted baggage linked to passenger	Weight, item or tag exception
Security	Passenger admitted to restricted area	Alarm or prohibited item
Border control	Travel authorization confirmed	Identity or entry-condition issue
Boarding	Passenger reconciled and seated	Late passenger or cabin interference

Airport service quality is shaped by wayfinding, staff behaviour, accessibility, seating and the fairness of waiting. Full-service and low-cost passengers can assign different importance to service attributes, but both require reliable basic processes [104]. The operational design should therefore distinguish optional product differentiation from minimum standards of safety, information and dignity.

4.3. Acceptance, tagging, sorting, loading and delivery of baggage

Baggage transportation is a controlled chain linking passenger acceptance with delivery at the destination. The chain includes allowance verification, security questions where applicable, physical acceptance, weighing, tagging, screening, conveyance, sorting, make-up, reconciliation, loading, transfer, unloading and reclaim. Each handover must preserve identification and status because a local error can separate a bag from its passenger across several airports [95].

The accepted baggage mass for passenger n is given by formula (141):

$$M_n^{acc} = \sum_{b=1}^{B_n} m_{nb}, \qquad E_n = \max\left(0, M_n^{acc} - M_n^{allow}\right), \tag{141}$$

where E_n is excess mass above the applicable allowance. The acceptance system must also evaluate item dimensions, restricted articles and special handling. A numerical allowance does not by itself determine acceptance when an individual item exceeds equipment or occupational-safety limits.

The first-time acceptance rate is given by formula (142):

$$FTA = \frac{N_{bags}^{accepted\ without\ correction}}{N_{bags}^{presented}} \times 100\%. \tag{142}$$

Corrections include repacking, payment, tag replacement and routing changes. A low rate increases counter time and passenger stress. Pre-travel information and automated validation can move predictable exceptions away from the airport peak.

A baggage tag contains a unique identifier and routing information that must correspond to the passenger and flight record. Printed barcodes remain common, while RFID and Internet-of-Things concepts can improve read rates and location visibility [95]. Technology does not remove the need for exception procedures because labels can be damaged, attached incorrectly or linked to an outdated itinerary.

The probability of obtaining at least one successful read across k independent points is given by formula (143):

$$P_{read} = 1 - \prod_{j=1}^{k}(1 - r_j), \tag{143}$$

where r_j is the successful-read probability at point j. Additional readers improve trace-

ability, but independence is only an approximation when the same damaged tag affects every point. Manual encoding should record the reason and maintain the original bag identity.

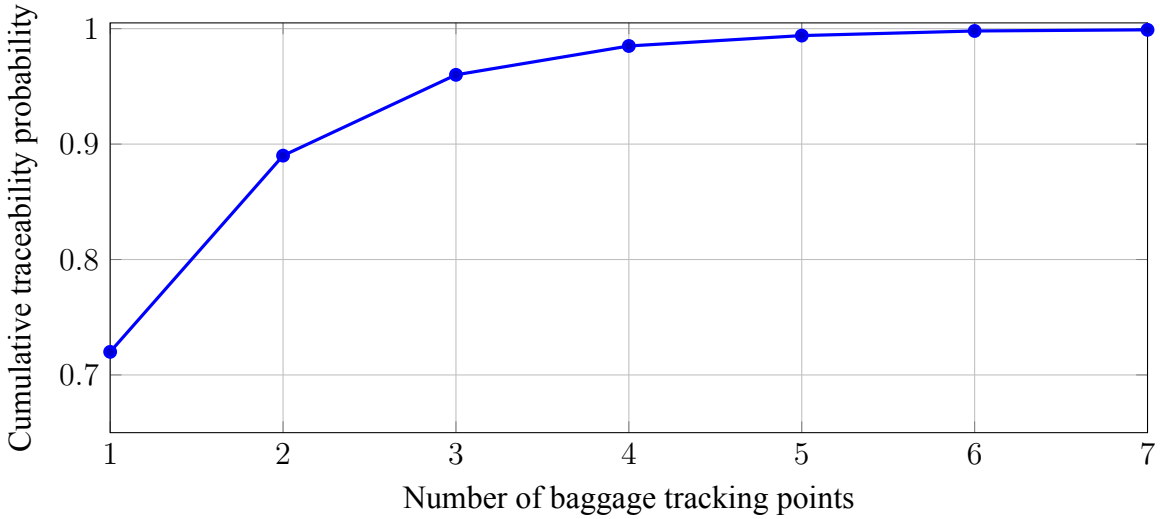

Figure 28: Illustrative effect of successive tracking points on baggage traceability

Description of the graph. Traceability improves sharply when the second and third tracking points are introduced. Later points provide smaller incremental benefits but remain useful for locating the stage where an exception occurred. The curve assumes reasonably high read performance at each point. A damaged or incorrect tag can create correlated failures and reduce the actual result. System design should combine automated reads with controlled manual exception recording.

Sorting assigns accepted bags to a flight, container, cart or make-up position. Capacity depends on belt speed, induction spacing, destination distribution, screening alarms and the availability of chutes. Early bags require storage, while late bags require expedited routing. Transfer bags add time constraints determined by the inbound and outbound aircraft positions.

The nominal sorter throughput is given by formula (144):

$$Q_s = \frac{3600v}{d_b}, \tag{144}$$

where v is conveyor speed and d_b is average required spacing between bags. Sustainable throughput is lower after merging, scanning, security resolution and failures are included. Simulation is required when several induction streams compete for common equipment.

The baggage-system utilization coefficient is given by formula (145):

$$U_{bag} = \frac{Q_{peak}}{Q_s^{sust}}. \tag{145}$$

Values close to one indicate little reserve for flight banks or equipment downtime. Peak analysis should use short intervals because a daily average does not represent make-up demand before simultaneous departures. Reserve chutes and alternative routes improve resilience.

Baggage reconciliation confirms whether an accepted bag may be loaded according to passenger and security status. When a passenger does not board, the bag may require identification and removal. The process must exchange final passenger status rapidly with the ramp and load-control teams. Boarding and baggage policies interact because large carry-on volumes can move items from cabin to hold late in the process [100].

The number of bags authorized for loading is given by formula (146):

$$N_{load} = N_{screened} - N_{hold} - N_{remove} + N_{gate}, \tag{146}$$

where N_{hold} represents bags awaiting resolution, N_{remove} represents bags withdrawn from the flight and N_{gate} represents accepted gate-checked items. Every change must update the load plan and final baggage count.

Loading must respect aircraft mass, balance, compartment limits, transfer priorities and unloading sequence. Containers and carts should be prepared so that short-connection and priority bags remain accessible. Heavy or irregular items require approved positions and handling equipment. The final load instruction must correspond to the physical loading state.

The baggage mass assigned to compartment c is given by formula (147):

$$M_c = \sum_{b \in \mathcal{B}_c} m_b, \qquad M_c \le M_c^{max}. \tag{147}$$

Additional constraints control volume and aircraft balance. A feasible mathematical assignment is not operationally useful if it causes excessive rehandling or delays destination unloading. Load planning should therefore incorporate sequence and equipment availability.

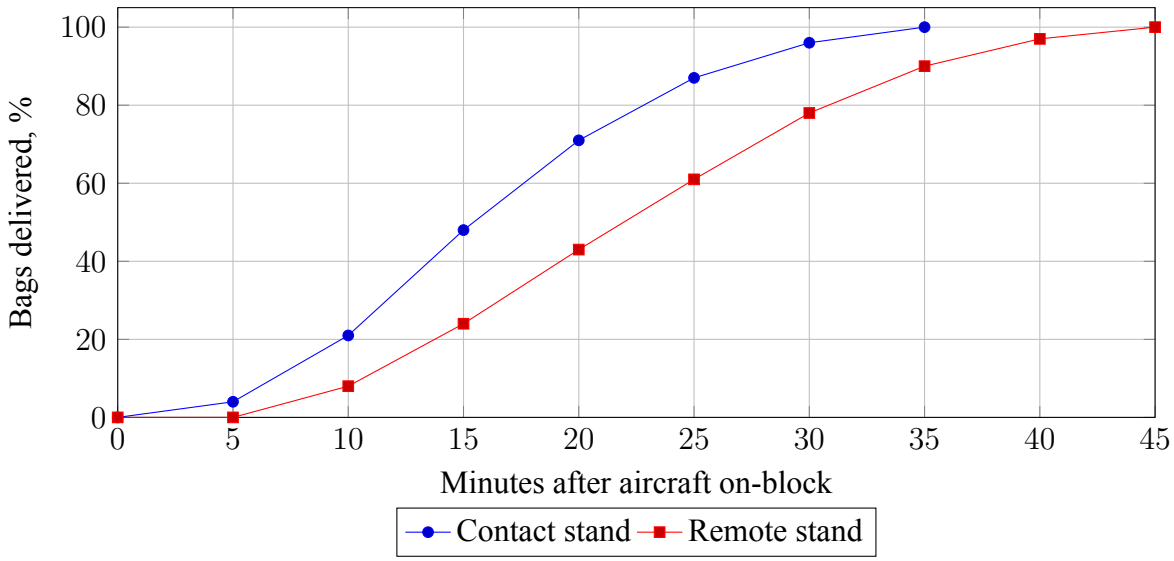

Figure 29: Illustrative baggage-delivery progress for two stand conditions

Description of the graph. Delivery from the contact stand begins earlier and reaches completion in approximately thirty-five minutes. The remote-stand curve is delayed by additional transport distance and handling. The difference is greatest during the middle of the reclaim process. First-bag and last-bag indicators should therefore be interpreted together. Airport planning can use the curves to evaluate tug availability, routes and reclaim-belt assignment.

Delivery performance is measured by formula (148):

$$T_{FB} = t_{first} - t_{onblock}, \qquad T_{LB} = t_{last} - t_{onblock}. \tag{148}$$

The first-bag time represents responsiveness, while the last-bag time reflects complete service. Percentile targets are more informative than averages because a small number of very late flights can affect many passengers. Results should be segmented by stand, aircraft size and arrival bank.

The mishandling rate is given by formula (149):

$$MBR = \frac{N_{mishandled}}{N_{carried}} \times 1000. \tag{149}$$

Mishandling includes delayed, misrouted, damaged and lost baggage according to the reporting definition. Root-cause analysis should distinguish acceptance, transfer, loading, unloading and delivery failures. Tracking technology supports investigation, but process redesign is required to reduce recurrence [95].

Table 18: Baggage-process stages, information and controls

Stage	Required information	Principal control
Acceptance	Passenger, route, allowance and item status	Identity and acceptance eligibility
Sorting	Flight, destination and connection priority	Correct chute, cart or container
Reconciliation	Screening and passenger boarding status	Authorization before loading
Loading	Mass, compartment and sequence	Physical match with load instruction
Delivery	Arrival flight, reclaim belt and item status	Complete and timely return to passenger

When baggage is delayed, the passenger needs a clear report, reference number, delivery plan and communication channel. Service recovery should avoid repeated requests for information already recorded. Performance includes not only physical return time but also information accuracy and reimbursement handling. The passenger's evaluation of the journey can be strongly affected by how an irregularity is managed.

4.4. Passenger services during flight and after arrival

Passenger service continues after boarding. Cabin crew deliver safety instructions, assist seating and stowage, monitor the cabin and provide the service elements included in the carrier's product. Comfort, cleanliness, communication, food and beverage, staff behaviour and perceived value influence satisfaction. The importance assigned to each element varies by flight duration, class, traveller purpose and expectations [94, 97, 104].

A weighted in-flight service-quality index is given by formula (150):

$$SQ_f = \frac{\sum_{k=1}^{K} w_k s_k}{\sum_{k=1}^{K} w_k}, \tag{150}$$

where s_k is the passenger rating of attribute k. The aggregate enables comparison across flights, while attribute-level results identify improvement priorities. Segmentation is necessary because a feature valued on a long-haul full-service flight may be irrelevant on a short low-cost journey [104].

The service gap for attribute k is given by formula (151):

$$G_k = P_k - E_k, \tag{151}$$

where P_k is perceived performance and E_k is expectation. A negative gap indicates service below expectation. Expectations are influenced by price, brand, prior experience and communications, so overpromising can reduce satisfaction even when operational performance is unchanged.

Cabin service must remain subordinate to safety. Turbulence, medical events or operational instructions can interrupt planned service. Passenger communication should explain the reason without creating false certainty. Accessibility needs, dietary requirements and unaccompanied passengers require accurate information transferred from reservation and ground systems.

The completion rate for planned cabin services is given by formula (152):

$$SCR = \frac{N_{services}^{completed}}{N_{services}^{planned}} \times 100\%. \tag{152}$$

The denominator should exclude services cancelled for documented safety reasons when the objective is commercial performance, but safety interruptions should still be reported separately. Completion does not measure quality and must be combined with passenger feedback.

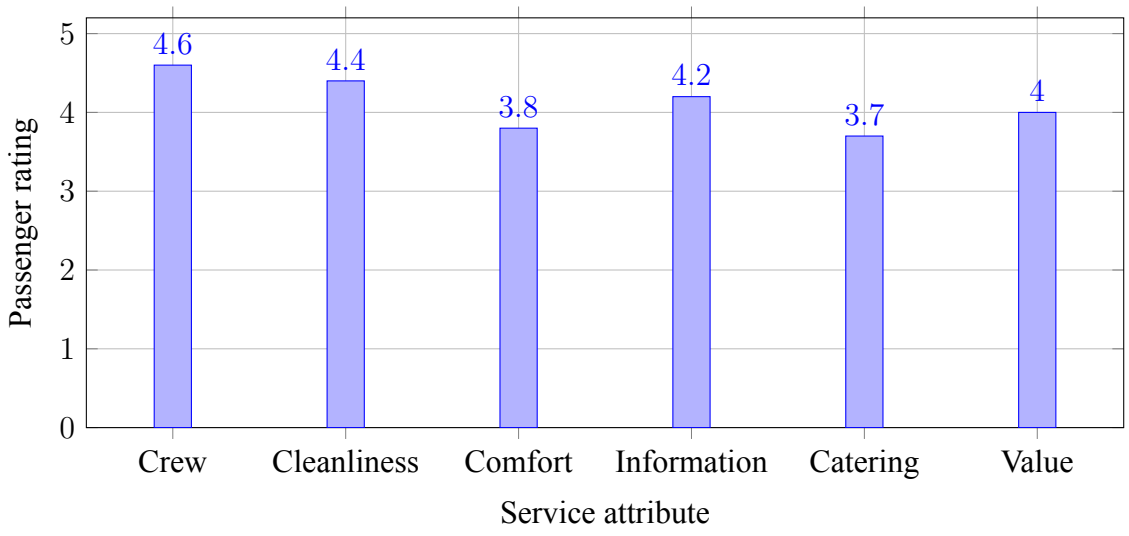

Figure 30: Illustrative passenger ratings of in-flight service attributes

Description of the graph. Crew service receives the highest passenger rating, followed by cleanliness. Comfort and catering have the lowest scores and therefore represent potential improvement priorities. Information performance remains strong but below the interpersonal crew rating. The aggregate experience depends on the relative importance assigned to each attribute. Results should be segmented by cabin class, aircraft type and flight duration before investment decisions are made.

Passenger service is also constrained by the physical characteristics of the assigned aircraft. Seat geometry, aisle width, lighting, noise, ventilation, lavatory availability and storage space influence comfort and the crew's ability to deliver service [106]. Fleet planning and airline operations determine which cabin product is available on a route, while aircraft substitution can change seating, baggage capacity and service procedures shortly before departure [107, 108]. Route-selection and stochastic scheduling models should therefore include passenger-product compatibility in addition to demand and direct operating cost [109, 113].

A comfort-adjusted service score can be written as formula (153):

$$SQ_f^{adj} = SQ_f \left(1 - \omega_c C_f^{def}\right), \tag{153}$$

where C_f^{def} is a normalized cabin-comfort deficiency and ω_c is its importance weight. The expression shows that attentive crew service cannot fully compensate for persistent physical discomfort. Calibration should distinguish aircraft type, cabin class, flight duration and passenger characteristics [106].

Future propulsion technologies can affect passenger and baggage carriage through payload, range, cabin layout, refuelling or charging time and airport equipment.

Sustainable aviation fuels can often use existing aircraft with operational adaptations, whereas hybrid-electric, battery-electric and hydrogen concepts may require different energy storage, mass distribution and turnaround processes [110, 111, 114–117]. Electric taxiing can reduce local emissions and auxiliary-engine use but adds equipment, energy and maintenance interfaces to ground operations [118]. These changes should be evaluated as a complete passenger-service system rather than only as propulsion efficiency.

The payload margin available for passengers and baggage is given by formula (154):

$$M_{pay}^{avail} = M_{TOW}^{lim} - M_{OEW} - M_{energy} - M_{reserve}, \tag{154}$$

where M_{TOW}^{lim} is the applicable take-off mass limit, M_{OEW} is operating empty mass, M_{energy} represents fuel or alternative energy storage, and $M_{reserve}$ includes required operational reserves. Passenger, baggage and cargo acceptance must remain within this margin. Alternative propulsion can change the relationship between range and payload and therefore influence baggage restrictions or aircraft choice [111, 114–117].

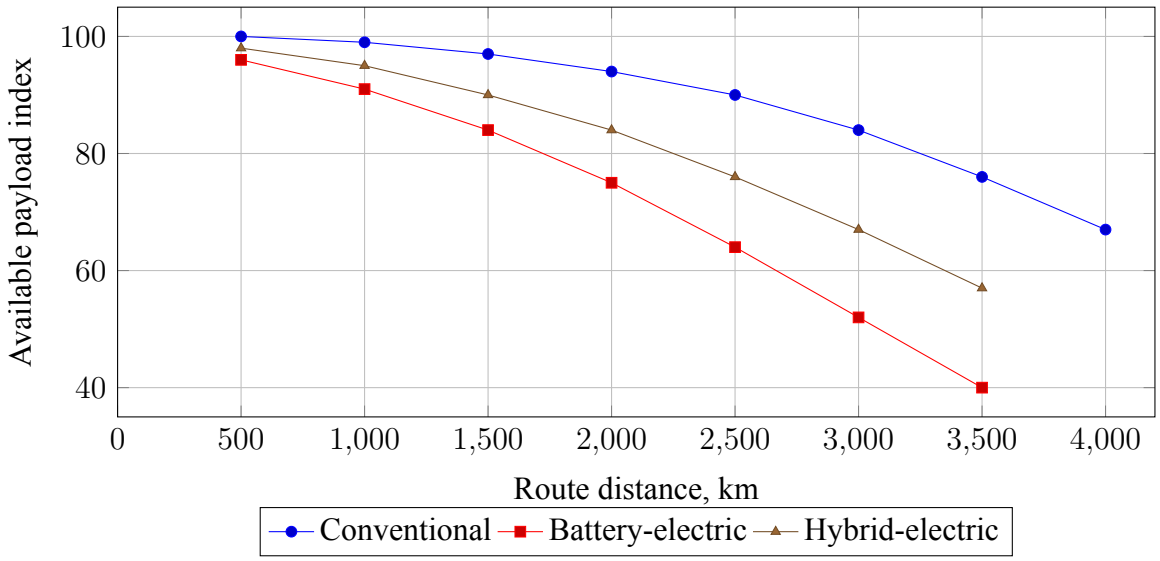

Figure 31: Illustrative influence of route distance and propulsion concept on available payload. Conceptual comparison based on [114–117]

Description of the graph. Available payload decreases as route distance increases for all three illustrative concepts. The conventional aircraft retains the largest payload margin over the full comparison range. The battery-electric curve decreases most rapidly because energy-storage mass becomes increasingly restrictive. The hybrid-electric concept occupies an intermediate position and preserves more flexibility on medium-distance routes. Actual results depend on aircraft design, reserves, weather

and technology maturity and must not be inferred directly from the illustrative indices.

Technical reliability directly affects passenger experience through delays, aircraft changes and cancellations. Condition monitoring and remaining-useful-life prognostics can identify degradation before it produces an operational interruption [112]. Machine-learning and data-driven maintenance methods support earlier decisions, but their outputs require validated data, uncertainty assessment and engineering oversight [119, 120]. Maintenance planning should coordinate with reservations, baggage, crew and passenger recovery so that a technically necessary action does not create avoidable information gaps.

The probability that the assigned aircraft remains serviceable until departure is given by formula (155):

$$P_{svc}(\Delta t) = \exp\left[-\int_0^{\Delta t} h(u \mid \mathbf{x})\, du\right], \tag{155}$$

where $h(u \mid \mathbf{x})$ is the conditional hazard rate based on component condition and operational data. A declining probability can trigger reserve-aircraft evaluation, maintenance preparation or proactive passenger-recovery planning. The threshold should reflect safety rules, forecast uncertainty and the availability of operational alternatives [112, 119, 120].

Arrival services begin with safe disembarkation and continue through transfer routing, border control, baggage reclaim, customs and surface-transport information. Contact stands generally simplify the flow, while remote stands require buses, stairs and coordination with terminal capacity. Passengers with reduced mobility need assistance continuity rather than a new request at every organizational boundary.

The total arrival-process time is given by formula (156):

$$T_{arr} = T_{dis} + T_{walk} + T_{border} + T_{bag} + T_{customs}, \tag{156}$$

where stages not applicable to a passenger are set to zero. The maximum of passenger and baggage readiness can be more useful than their sum because some walking and control occur while baggage is being unloaded. Timestamp analysis identifies the actual critical path for each arrival category.

For transfer passenger n, remaining connection margin is given by formula (157):

$$M_n = t_n^{next\ dep} - t^{current} - \widehat{T}_n^{transfer}. \tag{157}$$

A negative value indicates that the connection is no longer feasible under current conditions. Real-time margin supports prioritization, passenger messaging and rebooking. Assistance decisions should consider walking ability, border requirements and the location of the onward gate.

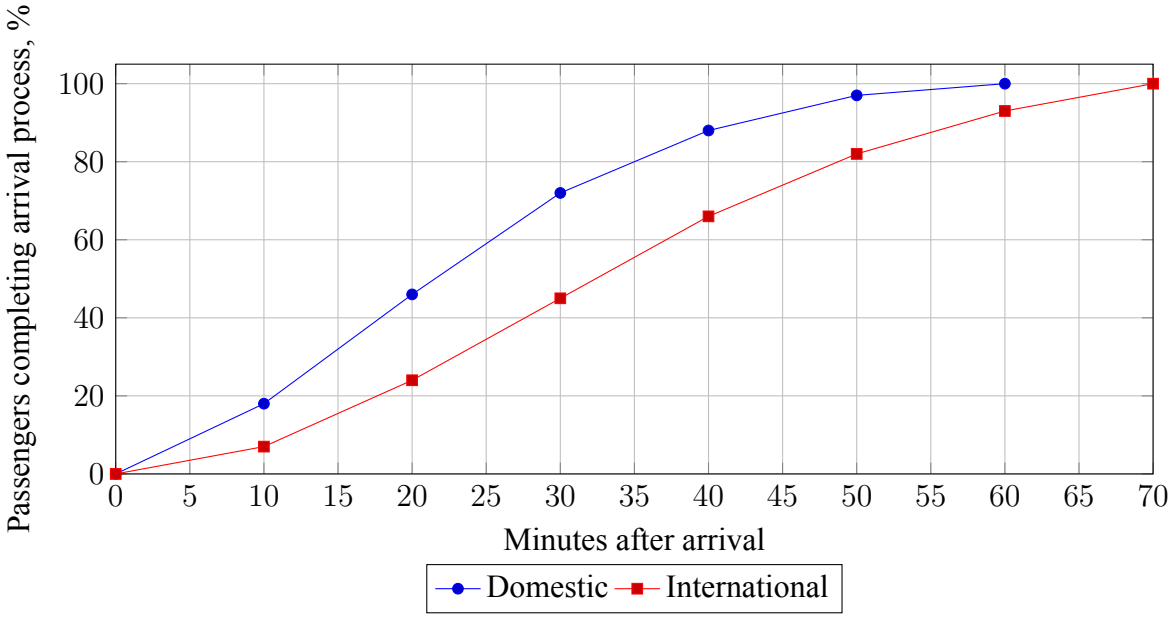

Figure 32: Illustrative completion of domestic and international arrival processes

Description of the graph. Domestic passengers complete the arrival process more rapidly because they normally avoid border control. The international curve rises more slowly throughout the first fifty minutes. The difference narrows only after most domestic passengers have already exited. Border staffing, walking distance and baggage delivery jointly shape the international result. Capacity planning should use the complete distribution rather than only average arrival time.

Passenger satisfaction is influenced by both performance and recovery. Online-review research can identify recurring service themes and the factors associated with positive or negative recommendations [91, 94, 96, 102]. Such data are valuable but self-selected and should be combined with structured surveys and operational measures.

The net promoter score is given by formula (158):

$$NPS = \%Promoters - \%Detractors. \tag{158}$$

The measure summarizes recommendation intention but does not identify the cause of dissatisfaction. Attribute ratings, comments and journey records should be linked at an appropriate anonymized level. A high score should not replace monitoring of safety, accessibility or complaint obligations.

The complaint-resolution time for case i is given by formula (159):

$$T_i^{res} = t_i^{close} - t_i^{open}, \qquad P_{SLA} = \frac{N(T_i^{res} \le T^{target})}{N_{cases}} \times 100\%. \tag{159}$$

Resolution quality matters alongside speed. Closing a case before the passenger receives a complete answer improves the metric but damages trust. Cases should be classified by cause, severity and required external coordination.

Repurchase intention can be represented as formula (160):

$$RI = \alpha_0 + \alpha_1 SQ + \alpha_2 PV + \alpha_3 TR - \alpha_4 IR, \tag{160}$$

where SQ is service quality, PV is perceived value, TR is trust and IR is the effect of unresolved irregularities. Empirical research shows that quality and value influence future passenger behaviour through direct and mediated relationships [98]. The expression supports survey modelling but should not be interpreted as a universal causal equation without calibration.

Table 19: Passenger-service indicators during flight and after arrival

Dimension	Representative indicator	Management use
Cabin service	Attribute quality and completion rate	Product and crew-process improvement
Arrival	Disembarkation and total exit time	Terminal and staffing coordination
Transfers	Remaining connection margin	Assistance and rebooking priority
Baggage	First bag, last bag and mishandling	Handler and infrastructure control
Recovery	Resolution time and satisfaction	Corrective action and loyalty protection

End-to-end service management assigns ownership without hiding organizational boundaries from internal control. Airlines, airports, handlers and authorities need common event data, escalation contacts and service standards. Passengers should receive one coherent explanation even when several organizations contribute to the result. Continuous improvement combines operational timestamps with surveys and review analysis so that recurrent failures are redesigned rather than repeatedly compensated [96–98, 102].

CHAPTER 5

VEHICLES

Vehicles form the physical basis of passenger air transportation. Passenger aircraft provide line-haul movement, while buses, stairs, loaders, tractors, service vehicles and fixed ground equipment connect the aircraft with the terminal and supporting infrastructure. Their capacities, dimensions, energy systems and technical condition determine whether the planned passenger and baggage process can be completed safely and punctually.

Aircraft selection is a system decision rather than a comparison of seat counts. Range, payload, runway requirements, cabin arrangement, baggage volume, fuel or energy demand, maintenance programme and airport compatibility must correspond to route conditions. Emerging electrical and hybrid propulsion concepts expand the design space but introduce demanding mass, thermal-management and infrastructure constraints [121, 122].

Passenger experience is directly influenced by vehicle characteristics. Cabin width affects seating and aisle movement, door arrangement affects boarding, and hold geometry affects baggage loading. Noise, vibration, air quality and lighting shape perceived comfort. A technically efficient aircraft can therefore be unsuitable for a market when its configuration conflicts with passenger expectations or airport processes.

Ground vehicles have a similar interaction with service quality. Insufficient buses delay boarding, unavailable lifts disrupt assistance, and unreliable baggage tractors separate bags from passengers. Equipment fleets must be sized for simultaneous peaks rather than daily averages. Pooling can increase utilization, but only when dispatch information and travel routes are reliable.

Environmental requirements are changing vehicle design and operation. Sustainable fuels, electrification, hydrogen and improved aircraft efficiency can reduce emissions, yet each pathway has different implications for energy supply, payload, turnaround and investment [121, 122]. Airport environmental performance also depends on ground vehicles, auxiliary power, charging infrastructure and the source of electricity [144].

Digitalization creates a continuous information layer around vehicles. Sensors, operational records and maintenance systems describe configuration, location, utilization and component condition. Digital-twin concepts connect these observations with

models so that behaviour can be simulated and anomalies detected before they interrupt service [131, 134, 140].

Vehicle reliability is inseparable from schedule reliability. A technical event can cause aircraft substitution, delay, cancellation, baggage rehandling and passenger reaccommodation. Predictive models can support earlier intervention, but maintenance decisions remain safety-critical and require validated data and accountable engineering judgement [123–125].

Machine-learning applications also support delay prediction, fleet assignment and schedule assessment. Their operational value depends on accuracy at the relevant horizon and on the ability of decision makers to understand the factors driving a prediction [127, 128, 133].

Interpretable methods are particularly important where model output influences high-consequence operational or maintenance action [136, 145].

The vehicle system must be resilient to uncertainty. Weather changes runway and performance limits, traffic restrictions alter flight time, and passenger demand changes the required capacity. Planning should preserve alternatives such as compatible aircraft types, reserve equipment, charging margin and maintenance access. Maximum utilization without reserve can reduce both punctuality and safety margins.

Economic evaluation combines acquisition, leasing, energy, crew, maintenance, airport, emissions and residual-value effects. The least expensive vehicle per unit is not necessarily the most economical network solution. A larger aircraft may reduce unit cost but create low-frequency service, while a smaller aircraft can improve schedule quality at a higher cost per seat.

This chapter examines aircraft classification, cabin and baggage configuration, aircraft selection, airport ground vehicles, operational and environmental characteristics, and maintenance support. Formulas provide a transparent basis for comparing capacity, performance, cost, emissions and reliability. Graphs illustrate the principal trade-offs, while tables connect technical characteristics with passenger-transport decisions.

5.1. Classification and principal characteristics of passenger aircraft

Passenger aircraft can be classified by propulsion, range, capacity, aerodynamic configuration and operational role. Conventional turboprops and turbofans dominate current services, while battery-electric, hybrid-electric and hydrogen concepts are being developed for future markets [121, 122]. Classification should support a decision rather than merely describe technology.

Aircraft seating density is given by formula (161):

$$D_s = \frac{S}{A_c}, \tag{161}$$

where S is installed seats and A_c is usable cabin floor area. Higher density can improve unit economics but reduce comfort, storage and boarding flexibility. Comparison requires the same cabin-class and monument assumptions.

The payload fraction is given by formula (162):

$$f_{pay} = \frac{M_{pay}}{M_{TOW}}, \tag{162}$$

where M_{pay} includes passengers, baggage and cargo. Energy-storage mass can reduce payload fraction in electric concepts, especially as range increases [121]. The applicable take-off limit may also be constrained by runway, temperature or obstacle conditions.

The still-air range approximation is presented in formula (163):

$$R = V \frac{L}{D} \frac{\eta_E E}{W}, \tag{163}$$

where V is speed, L/D is aerodynamic efficiency, E is usable energy, η_E is conversion efficiency and W is weight. The expression provides conceptual comparison rather than certified performance. Reserve, wind, routing and degradation must be added in operational planning.

The seat-range productivity indicator is given by formula (164):

$$P_{SR} = S\, R\, U_a, \tag{164}$$

where U_a is the daily utilization factor. It combines capacity, mission capability and productive use. A high theoretical range has limited value when turnaround or mainte-

nance constraints reduce utilization.

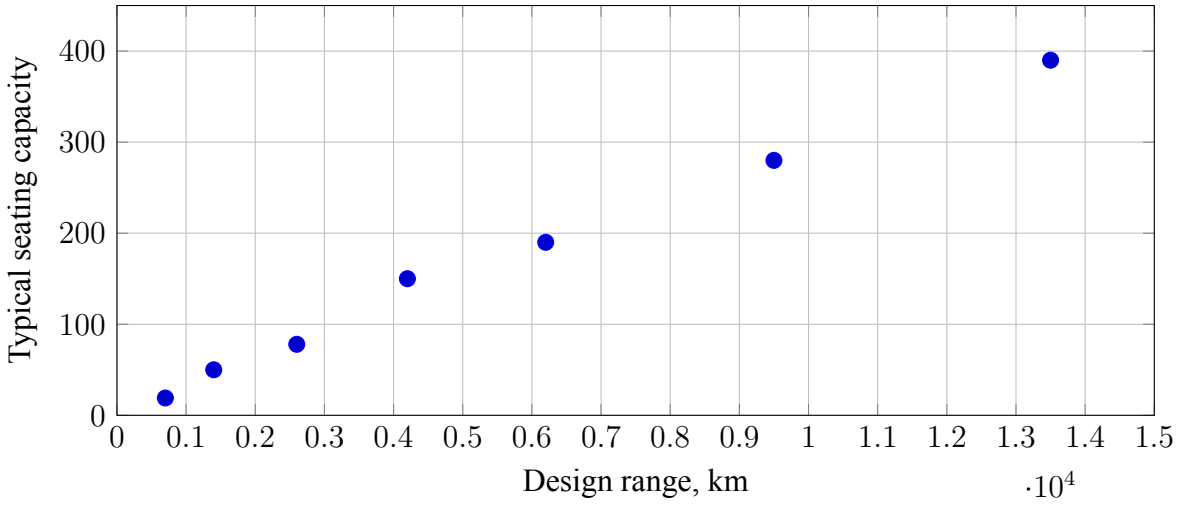

Figure 33: Illustrative relationship between passenger-aircraft range and seating capacity

Description of the graph. Short-range aircraft occupy the lower-left part of the graph and normally serve thin regional markets. Seating capacity tends to increase as design range grows because long missions require stronger economies of scale. The relationship is not deterministic because airlines can select different cabin densities. Very large capacity is concentrated in long-haul aircraft, while medium-capacity types cover the widest range of missions. Fleet planning should therefore examine route-specific payload and frequency rather than selecting aircraft from the trend alone.

Table 20: Classification of passenger aircraft by operational role

Class	Principal characteristics	Typical transport role
Regional turboprop	Low speed, short runway and moderate capacity	Thin short-distance services
Regional jet	Higher speed with limited seating	Business and feeder routes
Single-aisle jet	Flexible capacity and medium range	Domestic and continental networks
Wide-body jet	High payload and long range	Intercontinental and dense routes
Electric or hybrid concept	High efficiency with energy constraints	Emerging short- and medium-range roles

Classification must remain connected to infrastructure. Wingspan determines stand compatibility, door sill height affects ground equipment, and turning geometry affects taxi routes. New propulsion systems can require charging, hydrogen or thermal-management facilities. These interfaces influence whether a technically capable aircraft can be introduced at a particular airport [121, 129].

Wing loading is given by formula (165):

$$W_S = \frac{W}{S_w}, \tag{165}$$

where W is aircraft weight and S_w is wing area. Higher wing loading can support cruise efficiency but normally increases take-off and landing speed. Airport compatibility must therefore consider runway length and surface condition.

The installed power-to-weight ratio is given by formula (166):

$$P_W = \frac{P_{installed}}{W}. \tag{166}$$

The indicator supports conceptual comparison of climb and acceleration capability. Electric propulsion can distribute power differently, but battery and thermal limits remain important [121].

The runway suitability margin is given by formula (167):

$$M_{RWY} = L_{available} - L_{required}. \tag{167}$$

A positive margin is necessary but must be recalculated for mass, wind, temperature, contamination and obstacle conditions. Scheduled operations require a robust margin rather than feasibility under one reference condition.

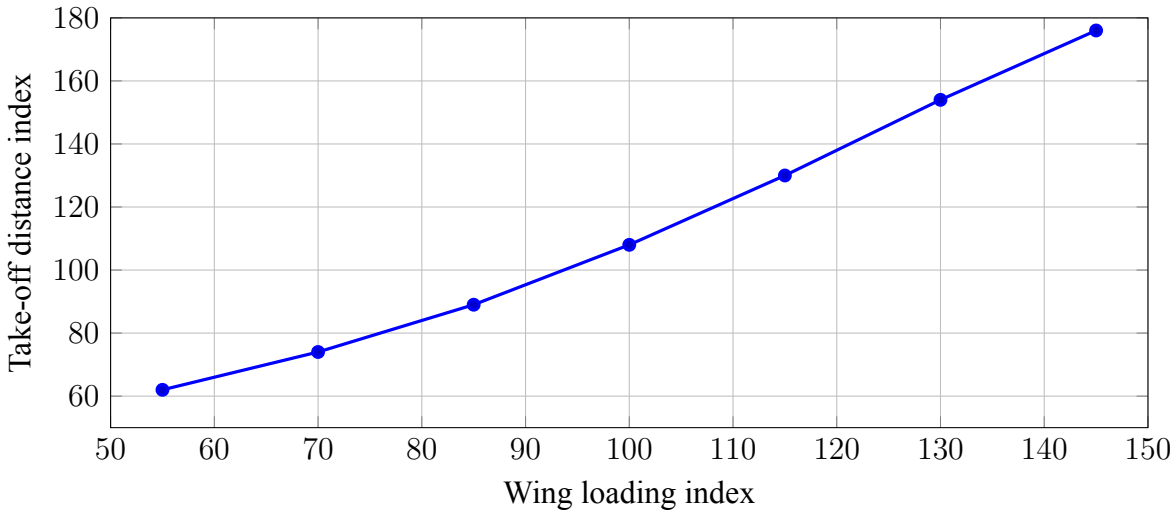

Figure 34: Illustrative relationship between wing loading and take-off distance

Description of the graph. The take-off distance index rises as wing loading increases. The relationship becomes steeper in the upper part of the illustrated range. Aircraft with lower wing loading can be more suitable for constrained regional airports.

Higher installed power and aerodynamic devices can modify the relationship. Operational selection must use certified performance data for the actual conditions.

5.2. Cabin configurations, seating capacity and baggage compartments

Cabin configuration allocates limited fuselage volume among seats, aisles, doors, lavatories, galleys, accessible spaces and storage. It determines sellable capacity and also affects boarding, evacuation, comfort and crew workload. Configuration changes require coordinated updates to reservations, seat maps, catering, baggage planning and safety documentation.

The usable seat capacity is given by formula (168):

$$S_u = \sum_{k=1}^{K} r_k n_k, \tag{168}$$

where r_k is seats per row and n_k is installed rows in cabin zone k. Monument and exit restrictions reduce the rows available. Revenue evaluation should use seats actually offered after operational blocks.

Average passenger-space allocation is given by formula (169):

$$a_p = \frac{A_c - A_m}{S_u}, \tag{169}$$

where A_m is floor area occupied by non-seat monuments. The indicator supports comparison but does not capture seat width, pitch or perceived privacy. Digital cabin models can test alternative layouts before physical modification [131, 132].

Available baggage volume per passenger is given by formula (170):

$$v_b = \frac{V_{hold} + \eta_o V_{overhead}}{S_u}, \tag{170}$$

where η_o is the usable fraction of overhead volume. Cabin baggage policy changes demand between overhead bins and holds. Insufficient volume can create gate checking and departure delay.

The cabin boarding resistance index is given by formula (171):

$$BR = \alpha \frac{S_u}{N_d} + \beta \frac{S_u}{W_a} + \gamma I_s, \tag{171}$$

where N_d is usable boarding doors, W_a is aisle-width index and I_s is expected seat interference. Lower values indicate a configuration more suitable for rapid boarding. Coefficients must be calibrated from observed operations.

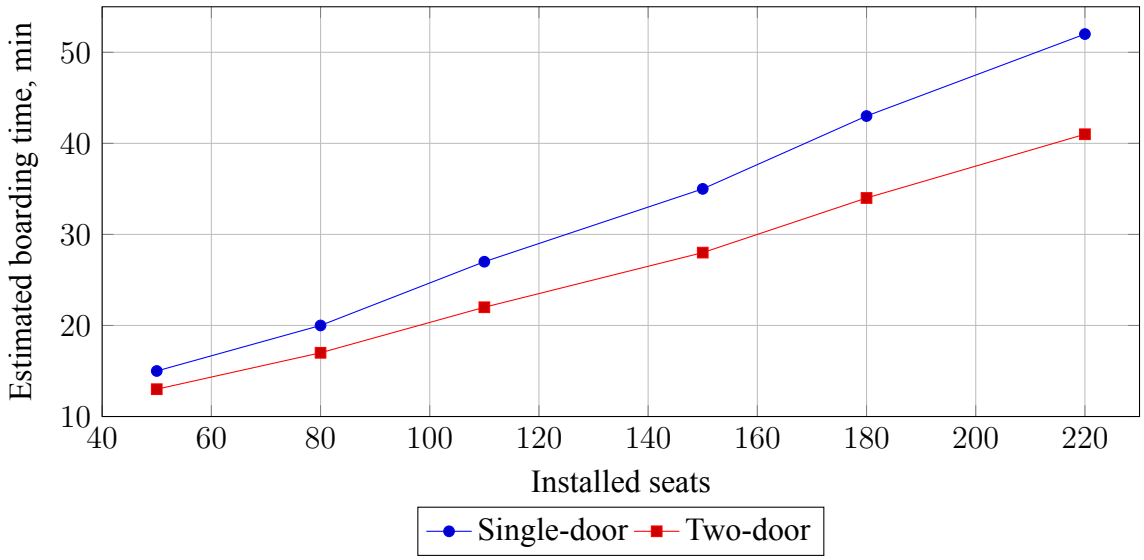

Figure 35: Illustrative influence of seating capacity and door use on boarding time

Description of the graph. Boarding time increases with installed seating capacity under both operating strategies. Two-door use produces a lower time because passenger flow is divided between cabin sections. The advantage becomes larger as capacity rises. Actual performance also depends on stairs, buses, carry-on baggage and passenger sequence. Cabin configuration should therefore be evaluated together with stand and terminal operations.

Table 21: Cabin and baggage-compartment design criteria

Element	Capacity effect	Operational effect
Seat pitch and width	Determines density and product	Influences comfort and movement
Aisles and doors	Reduce seat area	Determine boarding and evacuation flow
Overhead bins	Support cabin-baggage capacity	Affect stowage and aisle interference
Cargo holds	Support checked baggage and cargo	Require loaders, containers and balance control
Galleys and lavatories	Reduce seating space	Enable service and accessibility

Digital twins can connect cabin geometry with passenger-flow simulation, equipment condition and operational observations [134, 140]. Model validity requires controlled configuration data because an outdated seat map can invalidate boarding or load calculations. The same digital representation can support crew training and modification planning.

The longitudinal seat-density coefficient is given by formula (172):

$$K_{pitch} = \frac{L_{seat\ zone}}{n_r\, p_s}, \tag{172}$$

where n_r is the number of seat rows and p_s is nominal pitch. A value near one indicates full use of the planned seat zone. Additional clearance around exits and partitions reduces usable density.

Hold-volume utilization is given by formula (173):

$$U_V = \frac{\sum_b v_b}{V_{hold}^{usable}} \times 100\%. \tag{173}$$

Volume and mass limits must be checked together. Irregular baggage can leave unusable gaps even when total measured volume is below capacity.

Cabin revenue per unit floor area is given by formula (174):

$$R_A = \frac{\sum_k S_k y_k}{A_c}. \tag{174}$$

The indicator compares alternative class layouts but should be evaluated with demand, service cost and passenger acceptance. Digital configuration models help test these trade-offs before modification [132, 134].

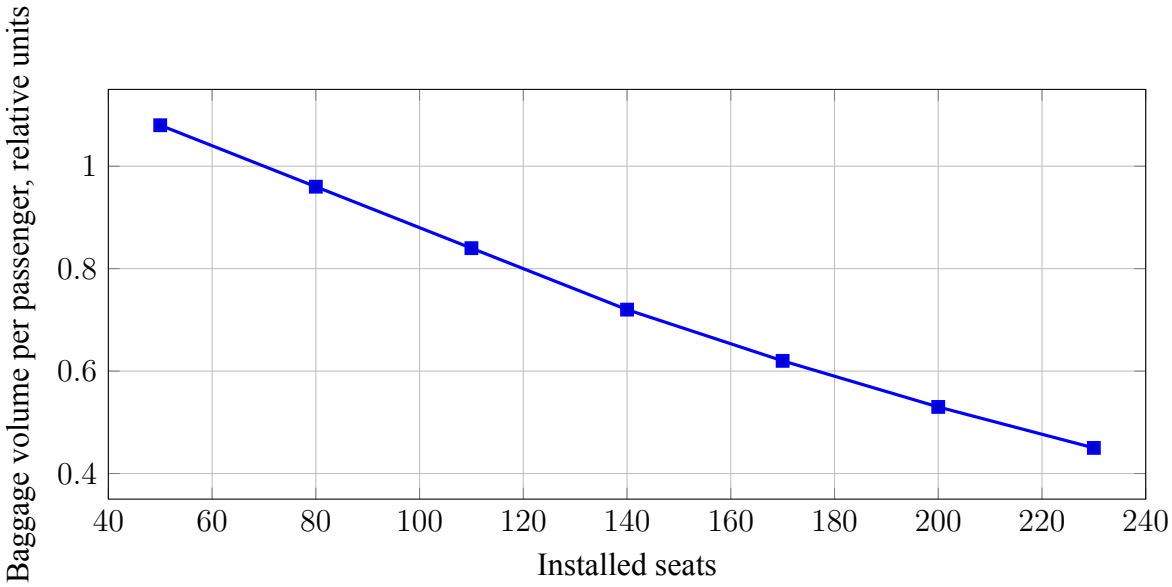

Figure 36: Illustrative effect of seating density on baggage volume per passenger

Description of the graph. Available baggage volume per passenger declines as more seats are installed in the same aircraft. The reduction can increase gate checking and hold-loading pressure. Markets with high checked-baggage demand may therefore

require a lower-density configuration. The relationship also depends on overhead-bin design and cargo commitments. Configuration decisions should balance ticket revenue against baggage and boarding performance.

5.3. Selection of aircraft type according to route and passenger flows

Aircraft selection matches forecast passenger flow with frequency, route distance, airport limits and economic objectives. Demand uncertainty makes one deterministic load estimate inadequate. The selected type should remain feasible during low periods while providing capacity during peaks or allowing supplementary frequency.

Required directional frequency is given by formula (175):

$$f = \left\lceil \frac{D}{S\, LF_t} \right\rceil, \tag{175}$$

where D is period demand and LF_t is target load factor. Frequency influences schedule attractiveness and connection opportunities. A larger aircraft can reduce frequency below the level expected by passengers.

The route contribution is given by formula (176):

$$CM = R_p + R_c + R_a - C_{var}, \tag{176}$$

where revenues arise from passengers, cargo and ancillary services. Variable cost includes energy, crew, maintenance reserves and route-dependent charges. Fixed fleet costs must be considered in the portfolio decision.

The aircraft compatibility score is given by formula (177):

$$AC = \sum_{j=1}^{J} w_j c_j, \qquad \sum_{j=1}^{J} w_j = 1, \tag{177}$$

where criteria include runway, stand, range, payload, cabin and maintenance compatibility. Hard safety or infrastructure limits cannot be compensated by other criteria. Multi-criteria selection is useful after infeasible types are removed.

The delay-adjusted operating value is given by formula (178):

$$V_a = CM_a - \mathbb{E}[C_a^{delay} + C_a^{cancel}], \tag{178}$$

where expected disruption cost depends on aircraft reliability, schedule buffer and recovery alternatives. Data-mining and deep-learning methods can estimate delay risk for candidate schedules [127, 128, 133].

Strategic assessment should use interpretable variables and stress scenar-

ios [136, 145].

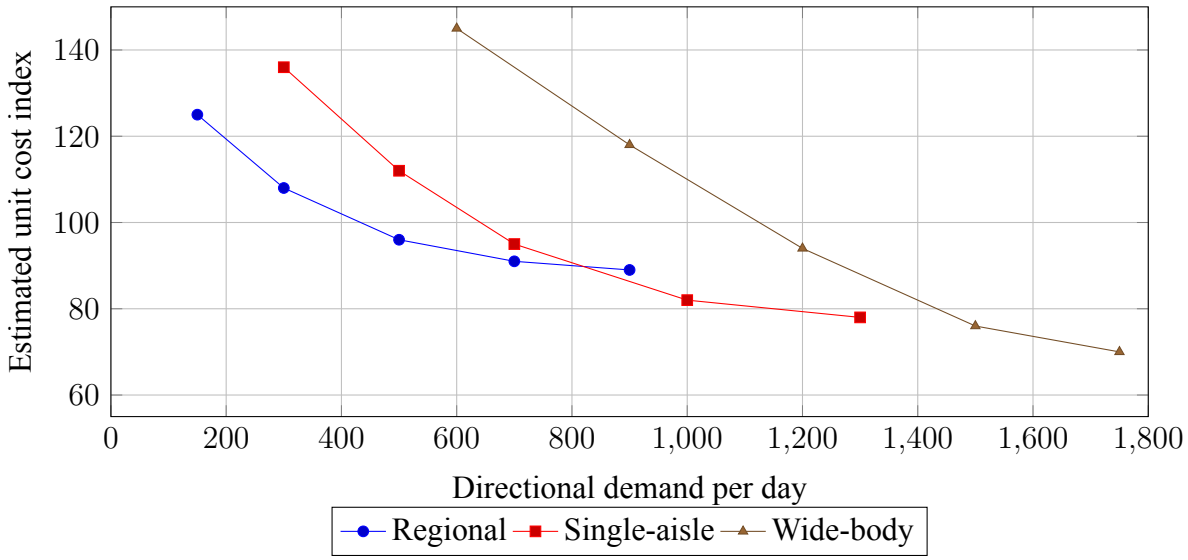

Figure 37: Illustrative relationship between passenger demand and aircraft unit cost

Description of the graph. Each aircraft class becomes more efficient as demand approaches its suitable operating range. Regional aircraft are competitive at low volumes but lose their advantage as traffic grows. Single-aisle aircraft provide the broadest middle-demand range. Wide-body aircraft require high traffic before their unit-cost advantage appears. Selection must additionally consider frequency, direction imbalance and seasonal variation.

Table 22: Aircraft-selection criteria for passenger routes

Criterion	Required analysis	Decision implication
Demand	Directional, seasonal and connection flow	Capacity and frequency
Mission	Distance, reserve, payload and weather	Performance feasibility
Airport	Runway, stand, noise and ground equipment	Infrastructure compatibility
Economics	Revenue, cost, utilization and ownership	Route and fleet contribution
Resilience	Reliability, substitution and recovery	Disruption exposure

Air traffic management conditions can change actual block time and fuel or energy consumption. Flow restrictions, route availability and airport congestion should therefore be included in aircraft comparison [129]. Machine-learning schedule assessment can test whether planned utilization remains realistic under observed delay patterns [137, 138].

The demand-coverage ratio is given by formula (179):

$$DC_a = \frac{\min(D, f_a S_a)}{D}. \tag{179}$$

The indicator shows the share of demand accommodated by the proposed aircraft-frequency combination. A value of one does not guarantee profitability or schedule attractiveness.

The fleet-hour feasibility condition is given by formula (180):

$$\sum_r x_{ar}(BH_r + T_r^{turn}) \le N_a H_a^{available}. \tag{180}$$

The constraint includes flight and turnaround time. Maintenance, reserve and recovery requirements reduce the available hours. Delay predictions can test the robustness of the planned rotation [127, 137].

Scenario regret for aircraft a is given by formula (181):

$$RG_a^{(s)} = V_{best}^{(s)} - V_a^{(s)}. \tag{181}$$

Minimizing maximum regret avoids a type that performs well only under one demand scenario. Interpretability is important when several technical and financial criteria drive the result [136, 145].

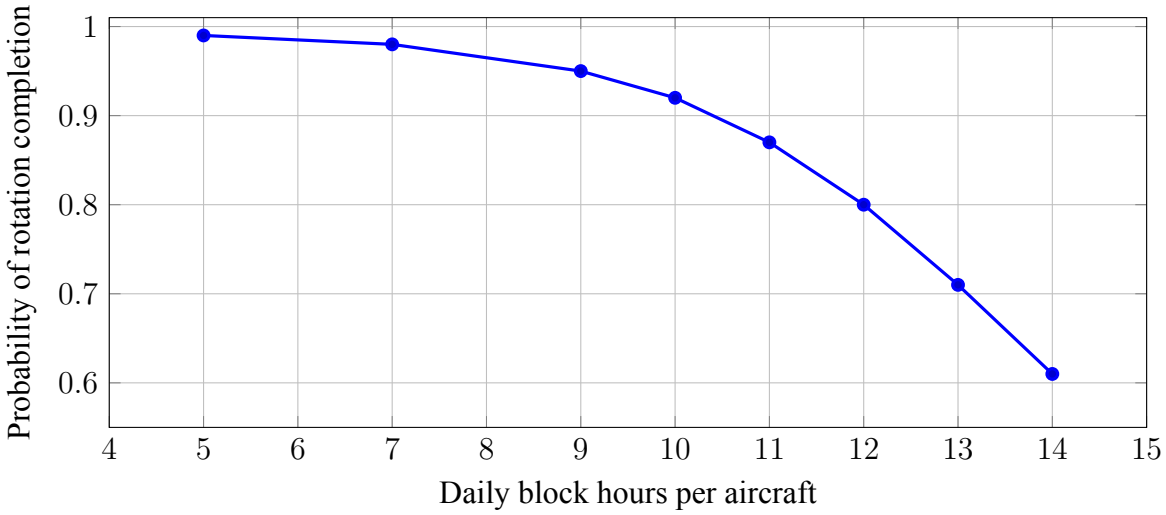

Figure 38: Illustrative relationship between planned aircraft utilization and rotation completion

Description of the graph. Rotation-completion probability declines as planned daily block hours rise. Moderate utilization preserves time for small delays and technical actions. Beyond approximately eleven hours, the illustrated reliability decreases

rapidly. A high-utilization plan can remain economical only when recovery resources are available. Fleet selection should therefore compare productive hours with disruption exposure.

5.4. Ground vehicles and airport servicing equipment

Ground support equipment includes passenger buses, boarding stairs, ambulifts, baggage tractors, belt loaders, container loaders, pushback tugs, catering trucks, water and lavatory vehicles, ground-power units and charging systems. Compatibility depends on aircraft geometry, stand layout and service sequence. A sufficient total fleet can still be infeasible when the required equipment is unavailable at the correct stand and time.

The fleet requirement for equipment type e is given by formula (182):

$$N_e = \left\lceil \frac{\lambda_e t_e}{\rho_e^*} \right\rceil, \tag{182}$$

where λ_e is peak task demand and t_e is equipment occupation time. The target utilization preserves reserve for travel, charging and disruption. Qualification and aircraft compatibility must be checked separately.

Equipment utilization is given by formula (183):

$$U_e = \frac{H_e^{task}}{H_e^{available}} \times 100\%. \tag{183}$$

Travel and queueing time should be reported separately because they reveal dispatch or layout losses. Very high utilization can increase departure risk even when unit productivity appears strong.

The energy requirement of an electric ground fleet is given by formula (184):

$$E_{day} = \sum_{e=1}^{N} d_e e_e + E_{aux}, \tag{184}$$

where d_e is daily travel or task distance and e_e is specific energy use. Charging demand must be distributed across locations and time intervals. Electricity source and battery replacement affect environmental performance [121, 144].

The dispatch cost of assigning vehicle e to task j is given by formula (185):

$$C_{ej} = \alpha d_{ej} + \beta \max(0, t_{ej} - t_j^{req}) + \gamma I_{ej}^{inc}, \tag{185}$$

where the terms represent travel, lateness and incompatibility. Optimization minimizes total assignment cost subject to non-overlap and charging constraints. Real-time location data improve the feasibility of central pooling.

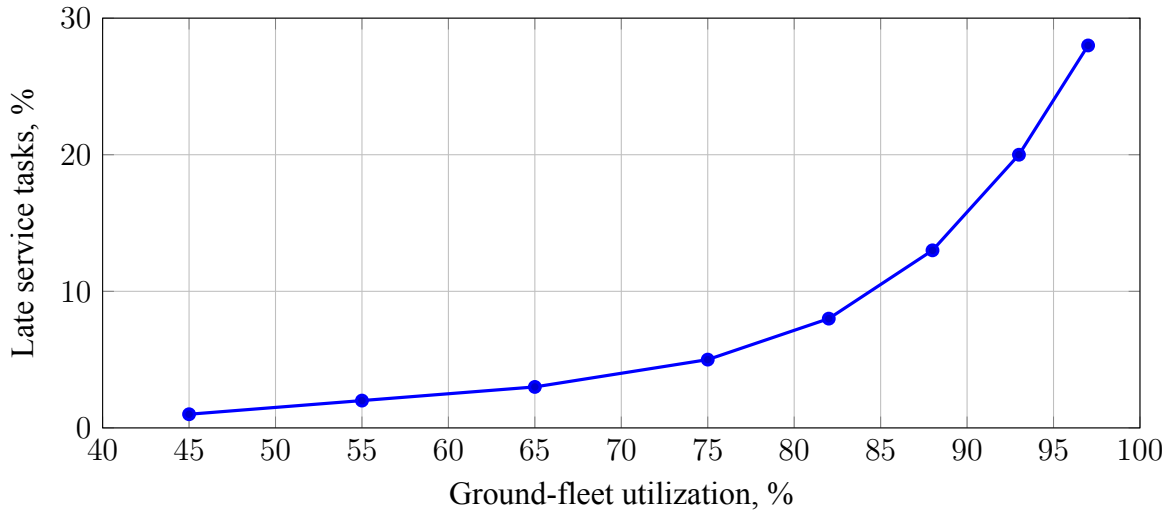

Figure 39: Illustrative relationship between ground-equipment utilization and late tasks

Description of the graph. Late tasks remain uncommon while equipment utilization is moderate. The share begins to rise quickly after utilization exceeds approximately eighty percent. High loading leaves little time for travel, charging or recovery from a preceding delay. Maximum fleet productivity is therefore not identical to minimum turnaround cost. Dispatch planning should preserve reserve for critical equipment categories.

Table 23: Ground vehicles and their passenger-transport functions

Equipment	Principal function	Critical requirement
Passenger bus	Remote-stand transfer	Capacity, accessibility and synchronization
Stairs and bridge	Aircraft access	Door and sill-height compatibility
Ambulift	Reduced-mobility assistance	Availability and trained operators
Baggage tractor and loader	Hold transport and loading	Traceability and safe positioning
Ground-power and charging unit	Aircraft and vehicle energy	Connector, power and location compatibility

Blockchain and shared information platforms can improve traceability of equipment service and energy transactions when responsibilities are distributed among organizations [139]. Digital-twin monitoring can connect location, battery state and maintenance condition with turnaround demand [142]. Technology creates value only when dispatchers can act on its information.

Ground-equipment availability is given by formula (186):

$$A_e = \frac{T_e^{ready}}{T_e^{scheduled}}. \tag{186}$$

Availability should be calculated during operational demand periods rather than over the full calendar day. Equipment undergoing charging or waiting for an operator may be technically serviceable but operationally unavailable.

The minimum number of charging points is given by formula (187):

$$N_c = \left\lceil \frac{E_{peak}}{P_c T_c \eta_c} \right\rceil. \tag{187}$$

The expression converts peak energy demand into charging capacity. Location and connector compatibility can require more points than the aggregate result [121, 144].

The probability of completing a service chain is given by formula (188):

$$P_{chain} = \prod_{j=1}^{m} A_{e_j} P_j^{on\ time}. \tag{188}$$

The product emphasizes that several individually reliable equipment tasks can still create material chain risk. Shared monitoring can identify the weakest link before departure [139, 142].

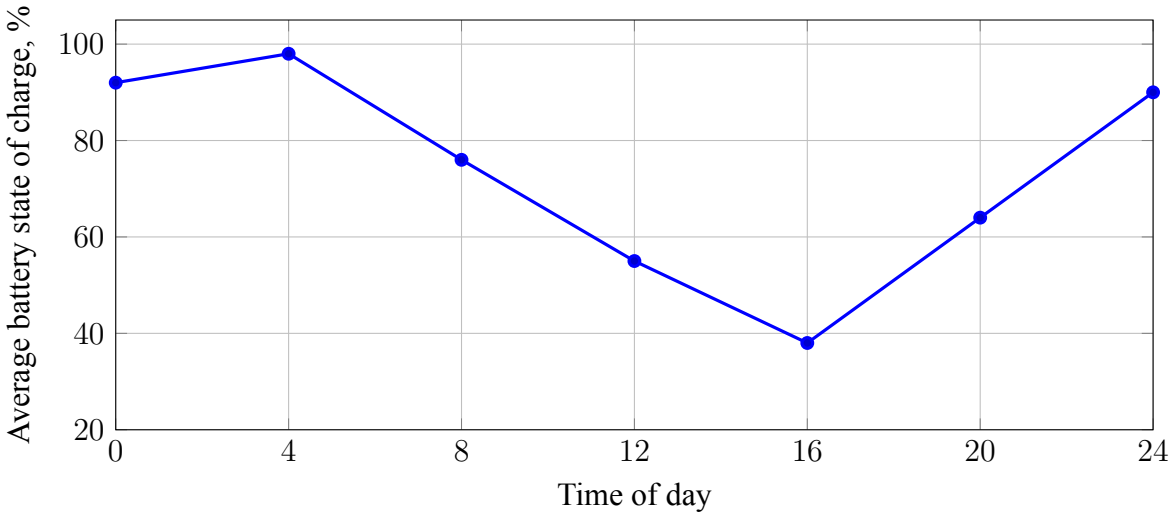

Figure 40: Illustrative daily state-of-charge profile for electric ground equipment

Description of the graph. Battery state is highest before the morning operating peak. It declines during successive aircraft turns and reaches its minimum in the late afternoon. Opportunity charging restores part of the energy before evening demand.

The final charging period returns the fleet close to its initial state. Dispatch rules should protect a reserve for disruption and unplanned travel.

5.5. Operational, economic and environmental characteristics of vehicles

Vehicle performance must be assessed across operational, economic and environmental dimensions. Speed, range and capacity describe mission capability, but schedule value also depends on reliability, turnaround and airport access. Economic comparison includes ownership, energy, crew, maintenance and infrastructure. Environmental analysis should use a defined life-cycle boundary [122, 144].

Direct operating cost per flight is given by formula (189):

$$DOC = C_{energy} + C_{crew} + C_{maint} + C_{airport} + C_{capital}. \tag{189}$$

The allocation of capital and maintenance cost must be consistent across types. Route comparison should include directional payload and utilization. Low acquisition cost can be offset by energy or downtime.

Unit cost is given by formula (190):

$$C_{ASK} = \frac{DOC}{S\,d}, \tag{190}$$

where d is route distance. The indicator falls when fixed flight cost is spread across more seats and distance. It does not show whether seats can be sold or whether the offered frequency is attractive.

Carbon intensity is given by formula (191):

$$I_{CO_2} = \frac{E_{LC}}{P\,d}, \tag{191}$$

where E_{LC} represents life-cycle emissions within the selected boundary. Sustainable fuels and electricity require source-specific factors [121, 122]. Airport ground activity should be added when a door-to-door operational boundary is used [144].

The environmental-economic score is given by formula (192):

$$V = \omega_1 \frac{C_{ASK}^{min}}{C_{ASK}} + \omega_2 \frac{I_{CO_2}^{min}}{I_{CO_2}} + \omega_3 R_{op}, \tag{192}$$

where R_{op} is normalized operational reliability. Weights make the trade-off explicit but cannot override safety or airport constraints. Sensitivity analysis should accompany the ranking.

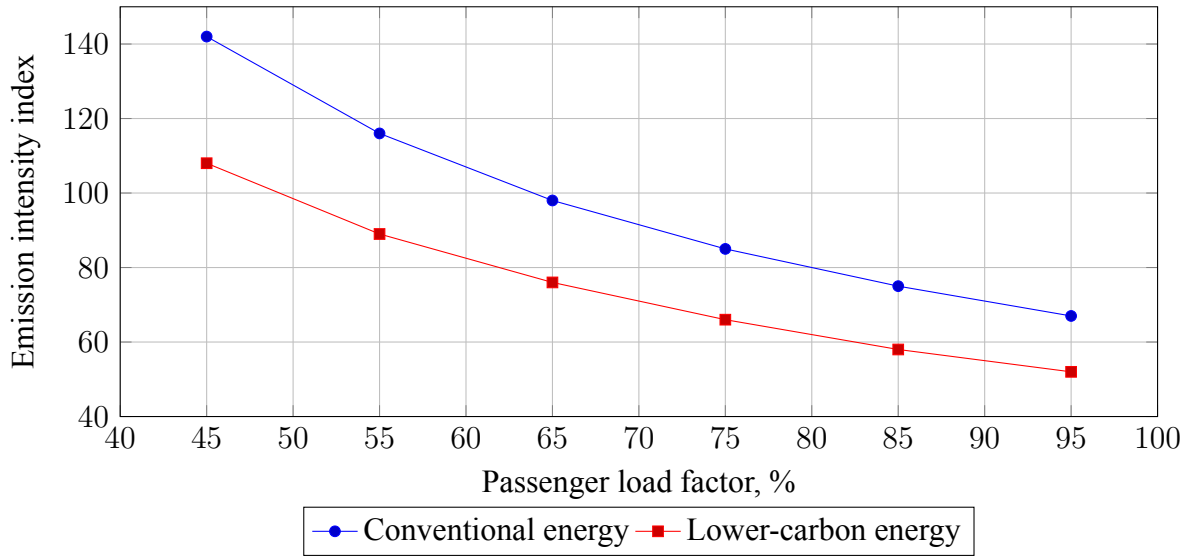

Figure 41: Illustrative influence of load factor and energy pathway on emission intensity

Description of the graph. Emission intensity declines as more passengers share the flight's energy use. The lower-carbon pathway remains below the conventional pathway at every load factor. Poor load factor can nevertheless weaken the benefit of an efficient vehicle. Network planning and vehicle technology therefore influence environmental performance together. Life-cycle factors should be used before comparing fuels or electricity sources.

Table 24: Balanced characteristics for vehicle comparison

Dimension	Representative indicators	Planning question
Operational	Range, payload, turnaround and reliability	Can the mission be completed consistently?
Economic	Cost per flight, seat and life cycle	Is the service financially sustainable?
Passenger	Frequency, comfort and baggage capacity	Does the vehicle support the promised product?
Environmental	Energy, emissions and noise	What impacts occur within the selected boundary?
Resilience	Substitution, reserve and recovery time	Can service continue after disruption?

Delay prediction improves economic comparison because disruption cost differs among schedules and vehicle types [133, 137]. Strategic schedule models can evaluate the probability that an intensive utilization plan produces cancellation or congestion [138].

Explainable outputs help managers distinguish vehicle weakness from external traffic conditions [145].

The net present value of a vehicle alternative is given by formula (193):

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+d)^t} + \frac{RV_T}{(1+d)^T}. \tag{193}$$

Cash flow includes revenue effects, operating cost and environmental charges. Residual value is especially uncertain for emerging technologies [121, 122].

The energy productivity of passenger transport is given by formula (194):

$$EP = \frac{P\,d}{E_{total}}. \tag{194}$$

Higher values indicate more passenger-kilometres per energy unit. Empty seats, diversions and ground energy must be included consistently.

The normalized noise-exposure indicator is given by formula (195):

$$NEI = \sum_{f=1}^{F} w_f 10^{L_f/10}. \tag{195}$$

The logarithmic transformation aggregates events with different sound levels. Time and population weights can represent community exposure in airport environmental assessment [144].

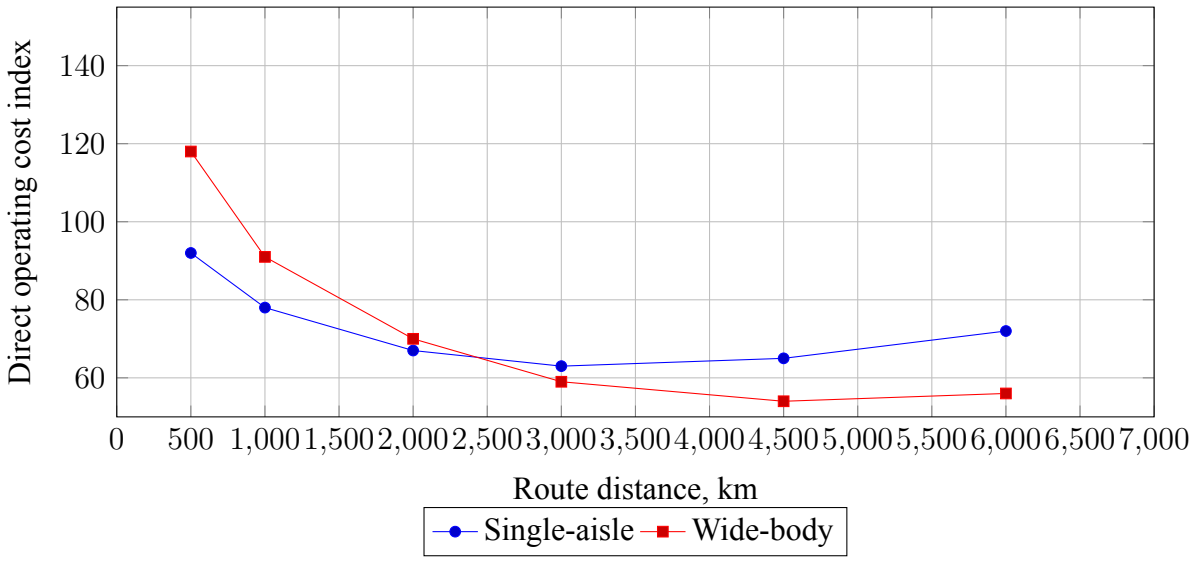

Figure 42: Illustrative route-distance effect on aircraft direct operating cost

Description of the graph. The single-aisle aircraft has the lower cost index on short routes. The wide-body alternative becomes more competitive as distance and demand increase. Both curves show a range where fixed and variable costs are balanced

most effectively. Very long missions increase energy and crew-related cost. The comparison must use compatible load factors and passenger products.

5.6. Maintenance and airworthiness support of aircraft

Airworthiness support ensures that aircraft configuration and condition remain compliant throughout operation. Maintenance includes inspections, scheduled tasks, defect rectification, component replacement, records and release to service. Planning must protect safety while coordinating aircraft availability with the passenger schedule.

Technical availability is given by formula (196):

$$A_t = \frac{T_{scheduled} - T_{technical\ downtime}}{T_{scheduled}}. \tag{196}$$

Availability should be segmented by planned and unplanned downtime. A high fleet average can conceal recurrent defects on one aircraft. Passenger consequences depend on the timing and availability of substitution.

Mean time between unscheduled failures is given by formula (197):

$$MTBF = \frac{H_{operation}}{N_{failure}}. \tag{197}$$

The definition of failure must remain consistent. Reliability growth is demonstrated when MTBF increases without transferring faults into another category. Component age, environment and mission severity should be considered.

Remaining useful life is given by formula (198):

$$RUL = t_{failure} - t_{current}. \tag{198}$$

In practice, it is a probability distribution rather than a known value. Engine and component models can combine sensor history with operating conditions [125]. Predictive maintenance reviews emphasize data quality, integration and decision thresholds [123, 124].

The expected maintenance cost for action a is given by formula (199):

$$EC_a = C_a^{maint} + P_a^{fail} C^{operational} + P_a^{false} C^{unnecessary}. \tag{199}$$

The preferred action minimizes expected cost subject to mandatory safety requirements. Dynamic policies can coordinate several components and future maintenance opportunities [126]. Cost cannot justify operation outside approved airworthiness limits.

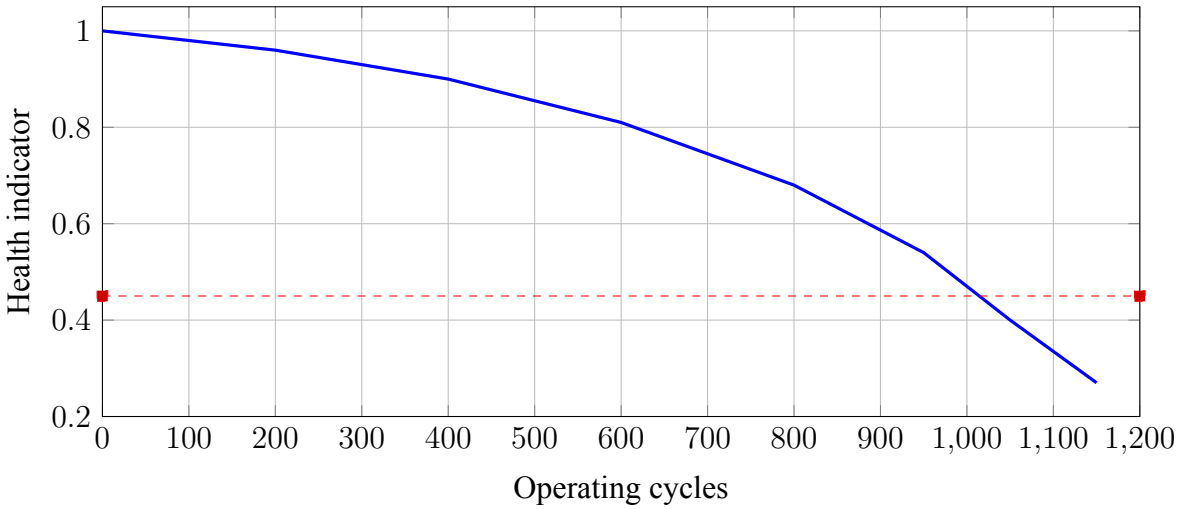

Figure 43: Illustrative degradation trajectory and maintenance threshold

Description of the graph. The component health indicator decreases gradually during early operation and more rapidly near the end of the period. The dashed line represents a maintenance decision threshold. Intervention should be scheduled before the forecast trajectory crosses that threshold. Forecast uncertainty requires a safety margin rather than use of the mean trajectory alone. Updated observations can move the predicted crossing point and change the maintenance plan.

Table 25: Maintenance-data layers supporting airworthiness decisions

Data layer	Example content	Decision use
Configuration	Installed components and modifications	Applicability and compliance
Operation	Cycles, hours, environment and events	Usage severity and planning
Condition	Sensors, inspections and fault messages	Diagnosis and prognostics
Maintenance	Tasks, parts and findings	Reliability and cost analysis
Schedule	Routes, reserves and opportunities	Timing and recovery coordination

IoT-enabled maintenance faces interoperability, cybersecurity, missing data and organizational challenges [123]. Digital twins provide a structured relationship between the physical aircraft, data and models [140, 141].

They can support anomaly detection and maintenance simulation when configuration and uncertainty are controlled [142, 143].

The anomaly score is given by formula (200):

$$A_n = (\mathbf{x}_n - \boldsymbol{\mu})^{\mathsf{T}} \boldsymbol{\Sigma}^{-1} (\mathbf{x}_n - \boldsymbol{\mu}). \tag{200}$$

Large values indicate observations inconsistent with the reference condition. An alert is evidence for investigation rather than proof of failure. Interpretable features and engineering context are necessary in high-stakes decisions [136, 145].

The maintenance-plan compliance rate is given by formula (201):

$$MPC = \frac{N_{tasks}^{on\ time}}{N_{tasks}^{due}} \times 100\%. \tag{201}$$

Compliance should be combined with finding quality, repeat defects and aircraft availability. Deferral within an approved interval is different from an overdue task. Records must preserve authorization and completion evidence.

Digital transformation changes maintenance work but does not remove accountability. Models should be validated for the fleet and operating environment, monitored for drift and designed to support qualified personnel [130, 135]. Transparent governance connects data ownership, model updates and final engineering authority. This approach allows predictive tools to improve availability without weakening airworthiness control.

Weibull component reliability is given by formula (202):

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]. \tag{202}$$

The shape parameter distinguishes early, random and wear-out failure behaviour. Parameters require fleet-specific data and controlled failure definitions [123, 124].

Prognostic accuracy is given by formula (203):

$$PA = 1 - \frac{|\widehat{RUL} - RUL|}{RUL}. \tag{203}$$

The indicator should be evaluated at several prediction horizons. Uncertainty intervals and false-alert consequences are necessary for maintenance decisions [125, 126].

The reorder point for a critical spare is given by formula (204):

$$ROP = \overline{d}L + z\sigma_d\sqrt{L}. \tag{204}$$

The first term covers expected demand during lead time and the second provides safety stock. Prognostic information can update demand, but supply and common-failure uncertainty remain.

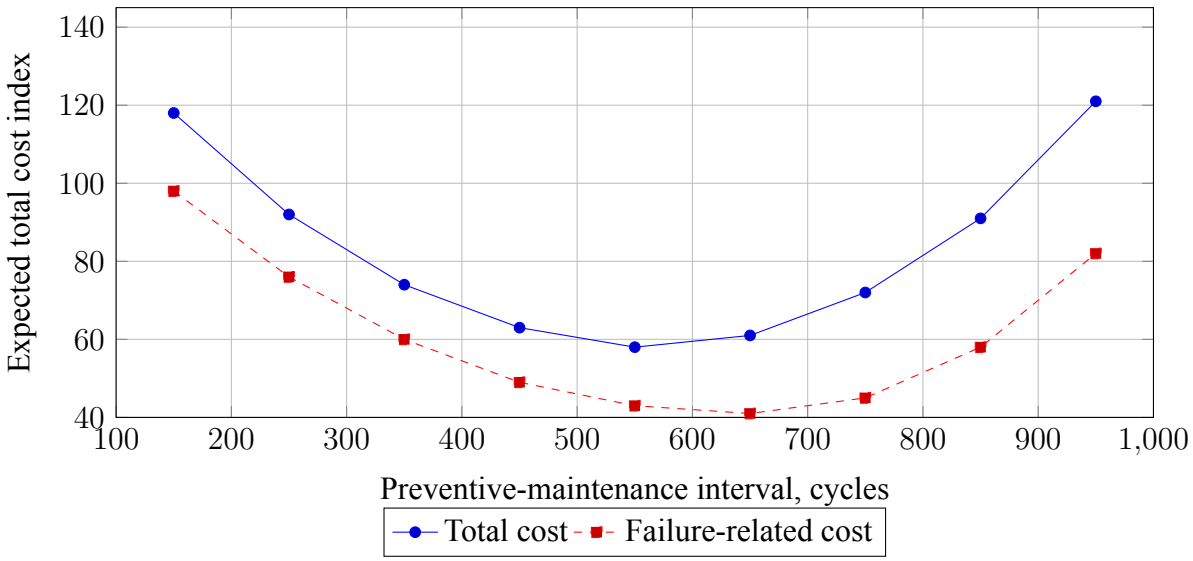

Figure 44: Illustrative relationship between maintenance interval and expected cost

Description of the graph. Very short maintenance intervals create high planned-maintenance cost. Extending the interval initially reduces total cost because fewer interventions are performed. Beyond the minimum region, failure-related cost rises and dominates the saving. The preferred interval lies near the bottom of the total-cost curve but remains subject to approved limits. Predictive condition information can refine timing for individual components.

CHAPTER 6

DIGITALIZATION AND EFFICIENCY ENHANCEMENT OF AIR TRANSPORT

Digitalization changes how airlines, airports and ground handlers represent operations, exchange information and make decisions. Physical events are converted into data that support passenger processing, resource allocation, maintenance, disruption recovery and strategic planning. The objective is not the maximum number of applications but a coherent information environment that improves safety, service quality and productivity.

Digital transformation differs from isolated automation. It changes organizational processes, responsibilities, competencies and relationships with passengers. Successful transformation combines technology with governance, business-model adaptation and measurable operational value [147, 151].

A digital twin links a physical asset or process with a digital representation updated by observations. The representation may describe an aircraft, terminal, baggage system, passenger flow or complete airport. Its value depends on purpose, update frequency, model fidelity and the decisions it supports [140, 146].

Digital twins range from descriptive models to predictive and prescriptive systems. Some receive data without influencing the physical process, while others support closed-loop control. Clear classification prevents a static three-dimensional model from being presented as an operational twin [150, 153].

Artificial intelligence extends digital systems by identifying patterns, forecasting states and ranking alternatives. High accuracy alone is insufficient for aviation decisions. Models need validation, uncertainty estimates, monitoring and explanations suitable for accountable personnel [145, 148].

Integration is a central challenge. Passenger, flight, baggage, aircraft, stand, weather and staff data are created by different organizations and at different time scales. Common identifiers and interface rules are required so that a change in one system becomes available to authorized users without contradictory versions.

Cybersecurity and operational continuity are inseparable from digital efficiency. Communication, surveillance and industrial systems can be affected by spoofing, jamming, unauthorized access and data manipulation. Security controls must protect integrity and availability without preventing timely operational exchange [155, 157].

Digital investment requires economic evaluation. Benefits can arise from shorter processing, lower delay, better utilization, avoided failure and improved passenger loyalty. Costs include software, sensors, integration, data governance, training, cybersecurity and continuing model maintenance.

Environmental improvement also depends on digital coordination. Better prediction and resource assignment can reduce aircraft taxiing, ground-vehicle travel, energy peaks and unused capacity. The effect should be measured against a baseline and should not be claimed solely because a process uses digital technology [144].

The human role remains decisive. Employees need authority to question erroneous outputs, follow fallback procedures and record overrides. Digital maturity therefore includes skills, governance and learning, not only installed systems. This chapter examines self-service, performance optimization, sustainability, system integration, artificial intelligence, economic evaluation and future transformation.

6.1. Digital systems, biometric identification, and self-service technologies

Passenger-facing digital systems include online check-in, mobile boarding passes, kiosks, bag drop, biometric gates, wayfinding and disruption notifications. They reduce routine transactions but require accessible design and staffed exception channels. Data collected at each step should update one authoritative passenger and flight status.

The self-service adoption rate is given by formula (205):

$$AR = \frac{N_{self}}{N_{eligible}} \times 100\%. \tag{205}$$

Eligibility excludes passengers or transactions that require mandatory manual control. Adoption should be segmented by channel and passenger category. A high rate is useful only when completion quality remains acceptable.

The first-time completion rate is given by formula (206):

$$FCR = \frac{N^{(1)}_{complete}}{N^{(1)}_{attempt}} \times 100\%. \tag{206}$$

Repeated attempts and staff intervention reveal interface or data problems. The measure supports comparison of kiosks, mobile applications and automated bag drop.

The biometric decision quality is given by formula (207):

$$Q_b = 1 - \omega_1 FAR - \omega_2 FRR. \tag{207}$$

False acceptance and false rejection have different safety and service consequences. Thresholds must be selected with manual resolution and privacy requirements in mind.

The average passenger time saving is given by formula (208):

$$\Delta T = \frac{1}{N} \sum_{n=1}^{N} (T_n^{manual} - T_n^{digital}). \tag{208}$$

Negative results identify cases where automation adds steps or creates exceptions. Time saving should be measured door to gate rather than at one device.

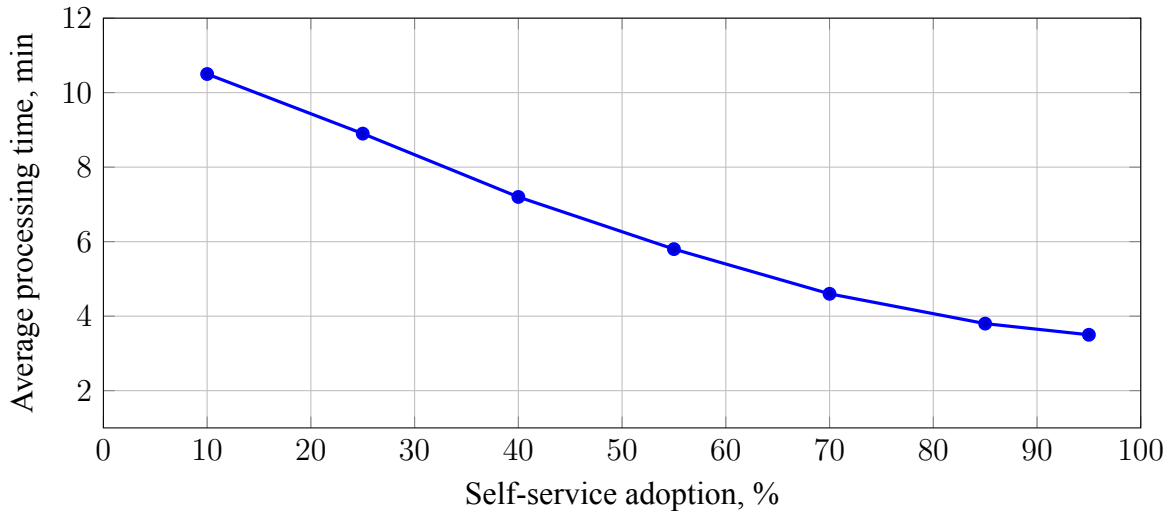

Figure 45: Illustrative relationship between self-service adoption and passenger processing time

Description of the graph. Processing time decreases as self-service adoption rises. The largest gains occur during the transition from low to moderate adoption. Later gains are smaller because complex exceptions remain. Full automation is therefore neither feasible nor necessarily desirable. Staffing should be redirected toward assistance and irregular cases.

Table 26: Digital passenger-processing technologies

Technology	Operational benefit	Required control
Mobile check-in	Early processing and notification	Identity and data accuracy
Kiosk	Common-use airport processing	Accessibility and exception support
Automated bag drop	Lower routine counter workload	Weight, tag and item validation
Biometric gate	Rapid identity-linked passage	Consent, match quality and fallback
Digital wayfinding	Personalized route information	Current location and facility data

The passenger interface should be considered part of a wider digital service architecture. Transformation succeeds when data follow the passenger across channels and organizations [147, 151].

Digital-twin principles can represent process state and predict congestion before passengers reach a control point [140, 149].

Omnichannel servicing must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement

can be attributed to the intervention rather than to unrelated changes in traffic or staffing [147, 151].

Data preparation for this capability includes passenger identity, itinerary status, channel history and unresolved requests. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns when a transaction should remain automated and when it should be transferred to an employee. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in duplicate records, inconsistent instructions and inaccessible interfaces. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Biometric passenger flow must be treated as a controlled operational capability

rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [145, 152].

Data preparation for this capability includes document status, biometric quality, gate events and manual-resolution outcomes. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of match thresholds and allocation of exception positions. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in false decisions, privacy concerns and dependence on one identification channel. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average

from concealing poor performance in the exact situations where digital support is most valuable.

Automated baggage acceptance must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [140, 146].

Data preparation for this capability includes passenger status, tag data, measured mass, item category and equipment state. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns opening positions and redirecting baggage exceptions before queues develop. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in incorrect tags, unreadable identifiers and incomplete reconciliation. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Personalized terminal navigation must be treated as a controlled operational ca-

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

pability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [149, 153].

Data preparation for this capability includes passenger location, accessibility needs, gate changes and route availability. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of a safe and feasible route through the terminal. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in obsolete maps, positioning error and excessive reliance on mobile devices. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

from concealing poor performance in the exact situations where digital support is most valuable.

Self-service operational continuity must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [140, 152].

Data preparation for this capability includes device availability, network status, transaction completion and staff interventions. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns activation of fallback channels during partial digital failure. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in simultaneous device outages, unclear escalation and insufficient staffed reserve. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

6.2. Performance indicators and optimization of technological processes

Operational optimization requires indicators linked to decisions. Real-time measures support lane opening, stand reassignment and dispatch, while historical measures support redesign and investment. Each indicator needs an owner, update frequency, threshold and response.

Process productivity is given by formula (209):

$$P_j = \frac{Q_j}{H_j^{staff}}. \tag{209}$$

Throughput must be compared under equivalent service and safety conditions. Productivity gained through omitted tasks is not an improvement.

The weighted performance index is given by formula (210):

$$KPI = \sum_{k=1}^{K} w_k z_k, \qquad \sum_{k=1}^{K} w_k = 1. \tag{210}$$

Normalized criteria can include waiting, punctuality, baggage, cost and quality. Critical safety limits remain separate constraints.

The optimization objective is given by formula (211):

$$\min J = \alpha T_{wait} + \beta C_{resource} + \gamma D_{delay}. \tag{211}$$

Weights express management priorities and require sensitivity testing. The solution must respect capacity, qualification and compatibility constraints.

The process reserve is given by formula (212):

$$R_j = Q_j^{sust} - \lambda_j^{peak}. \tag{212}$$

A negative reserve signals expected overload. Digital control can redistribute demand but cannot permanently replace insufficient capacity.

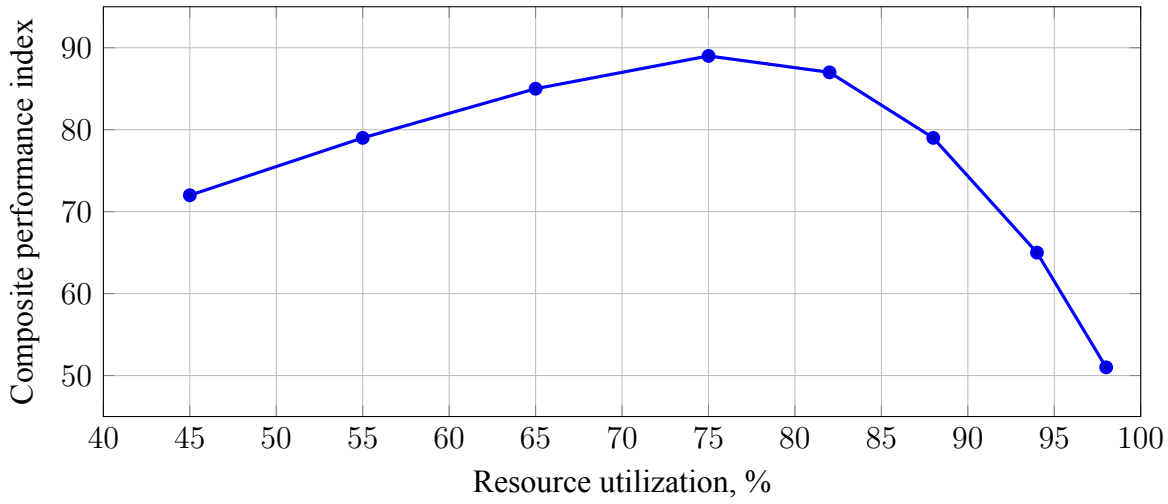

Figure 46: Illustrative relationship between resource utilization and process performance

Description of the graph. Performance improves while low utilization and idle capacity are reduced. The maximum occurs before the resource reaches full loading. Beyond that point, queues and disruption sensitivity reduce the composite result. The graph demonstrates the need for an operating reserve. Optimization should seek balanced performance rather than maximum utilization.

Table 27: Decision levels for digital performance management

Level	Indicators	Typical action
Real time	Queue, milestone and equipment state	Reallocate current resources
Daily	Delay, completion and exceptions	Correct shift and process deviations
Monthly	Productivity, quality and reliability	Revise standards and staffing
Strategic	Capacity, cost and resilience	Invest or redesign infrastructure

Digital twins support optimization when their state remains synchronized with operations [141, 146].

Anomaly detection can identify deviation before a static threshold is exceeded [142, 143]. Model outputs must be explained to the employee responsible for action.

Passenger-queue optimization must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or

staffing [141, 146].

Data preparation for this capability includes arrival profiles, service durations, lane state and passenger category. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns opening, closing and reallocating processing capacity. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in unstable control, local queue transfer and inaccurate arrival forecasts. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Stand and gate optimization must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change

system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [142, 153].

Data preparation for this capability includes aircraft compatibility, passenger connections, towing limits and infrastructure status. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of an allocation that minimizes system-wide passenger and aircraft delay. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in late aircraft changes, conflicting priorities and unavailable alternatives. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most

valuable.

Digital dispatch of ground resources must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [140, 142].

Data preparation for this capability includes vehicle location, qualification, battery state and turnaround milestones. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns assignment of equipment and teams to time-critical tasks. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in excessive utilization, travel conflicts and delayed status reporting. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement,

diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Collaborative milestone control must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [145, 150].

Data preparation for this capability includes planned, predicted and actual times with responsible owners. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns early intervention when departure readiness becomes uncertain. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in artificially stable estimates, missing ownership and repeated resource movement. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

Passenger-process simulation must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [146, 148].

Data preparation for this capability includes arrival distributions, routing rules, resource calendars and failure scenarios. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns comparison of layouts, staffing plans and control strategies before implementation. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in unvalidated assumptions, insufficient scenarios and misuse of average values. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement,

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
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diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

6.3. Sustainable development and prospects for the organization of passenger air transport

Digital systems support sustainability by measuring energy and emissions, coordinating resources and testing alternative operations. The system boundary should include terminal, airside and ground-access activities. Improvement must be demonstrated against a comparable baseline [144].

Energy intensity is given by formula (213):

$$I_E = \frac{E_{airport}}{N_{passenger}}. \tag{213}$$

Weather, terminal use and traffic composition should be normalized. The indicator can be segmented by facility or process.

The avoided-emission estimate is given by formula (214):

$$\Delta E = E_{baseline} - E_{digital}. \tag{214}$$

The digital scenario includes the energy used by sensors, computing and communication. Benefits should not be double counted across projects.

The electric-equipment charging peak is given by formula (215):

$$P_{peak} = \max_{t} \sum_{e=1}^{N} p_e(t). \tag{215}$$

Scheduling can shift flexible charging away from terminal and grid peaks. Minimum state-of-charge constraints protect operational readiness.

The sustainability score is given by formula (216):

$$SUS = \omega_E z_E + \omega_C z_C + \omega_Q z_Q + \omega_R z_R. \tag{216}$$

The components represent energy, carbon, service quality and resilience. A balanced index prevents environmental measures from being evaluated without passenger and continuity effects.

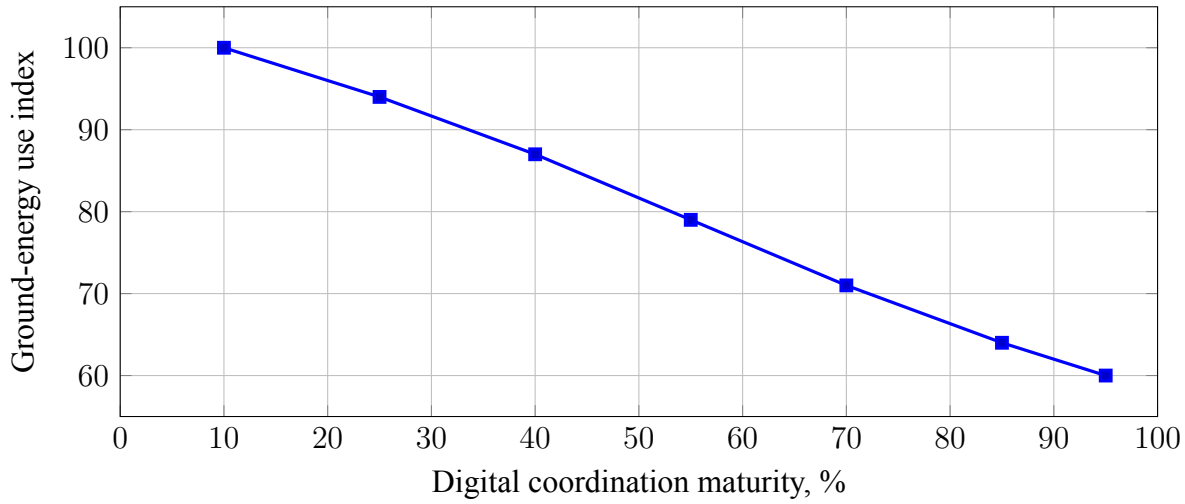

Figure 47: Illustrative relationship between digital coordination and ground-energy use

Description of the graph. Ground-energy use declines as coordination maturity increases. Early gains arise from visibility of idle running and equipment location. Later gains depend on integrated dispatch and charging schedules. The curve does not imply that software alone creates the reduction. Vehicle technology, electricity supply and employee practice remain important.

Table 28: Digital contributions to sustainable airport operation

Application	Sustainability effect	Verification measure
Resource dispatch	Less travel and idle operation	Energy per completed task
Predictive maintenance	Longer asset life and fewer failures	Avoided replacement and downtime
Building control	Reduced heating and cooling demand	Weather-normalized energy
Passenger-flow prediction	Better matching of open capacity	Energy and service per passenger
Charging optimization	Lower peaks and improved renewable use	Load profile and readiness

City and infrastructure twins can connect airport decisions with land use, transport access and environmental conditions [149]. Transformation governance should make sustainability indicators part of routine investment and operating decisions [147].

Digital terminal-energy management must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or

staffing [144, 149].

Data preparation for this capability includes occupancy, weather, equipment load and indoor-condition measurements. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns adjustment of heating, cooling, lighting and ventilation schedules. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in passenger discomfort, sensor bias and peak-load transfer. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Electric ground-fleet coordination must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise

description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [140, 144].

Data preparation for this capability includes task demand, vehicle charge, charger availability and energy price. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns dispatch and charging that preserve operational reserve. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in battery degradation, simultaneous charging and unavailable connectors. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most

valuable.

Digital taxi and stand coordination must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [141, 144].

Data preparation for this capability includes aircraft readiness, route occupancy, pushback sequence and restrictions. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns reduction of waiting with safe separation and feasible stand release. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in optimistic readiness data, route conflicts and disruption propagation. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement,

diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Environmental performance monitoring must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [144, 147].

Data preparation for this capability includes meter data, emission factors, passenger volumes and operational boundaries. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns verification of claimed energy and emission reductions. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in inconsistent baselines, double counting and omitted digital-system energy. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

Sustainable infrastructure scenarios must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [149, 151].

Data preparation for this capability includes traffic forecasts, technology adoption, energy supply and asset life cycles. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of staged investments robust to demand and technology uncertainty. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in premature investment, incompatible systems and stranded infrastructure. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement,

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

6.4. Integration of airline, airport, and ground handling information systems

Integrated operations require consistent flight, passenger, baggage, resource and infrastructure data. Interfaces should define authoritative sources, identifiers, event times and failure behaviour. Integration is an organizational agreement supported by technology rather than a software connection alone.

Interface completeness is given by formula (217):

$$IC = \frac{N_{fields}^{valid}}{N_{fields}^{required}} \times 100\%. \tag{217}$$

Critical fields should be monitored separately. A message can be syntactically valid while containing obsolete operational status.

Information latency is given by formula (218):

$$L_I = t_{available} - t_{generated}. \tag{218}$$

Percentiles reveal rare but operationally serious delays. The acceptable value depends on the decision horizon.

System availability is given by formula (219):

$$A_s = \frac{T - T_{down}}{T}. \tag{219}$$

Availability should include interfaces and dependent services. Fallback operation must be tested when a central platform is unavailable.

Data-integrity risk is given by formula (220):

$$R_D = \sum_i p_i I_i. \tag{220}$$

Manipulated or inconsistent information can create unsafe resource decisions. Secure industrial connectivity and digital-twin exchange require authentication, access control and monitoring [152].

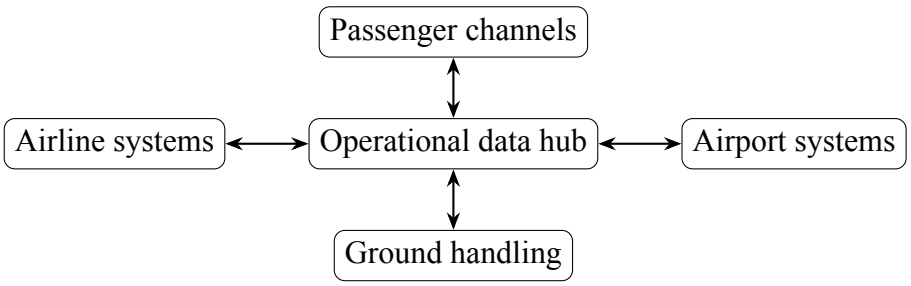

Figure 48: Integrated information exchange among passenger air-transport participants

Description of the graph. The operational data hub connects airline, airport, handler and passenger channels. Bidirectional exchange allows each participant to receive updates and return confirmed events. The hub does not remove ownership of source data. Access rules limit each user to information required for the task. Fallback procedures are necessary when the central exchange is unavailable.

Table 29: Principal fields for operational system integration

Data group	Authoritative content	Main consumer
Flight	Schedule, estimates and status	All operational participants
Passenger	Acceptance, assistance and connection	Airline and passenger services
Baggage	Tag, screening and loading status	Handler and load control
Resource	Stand, gate, vehicle and staff allocation	Airport and handler control
Infrastructure	Capacity, failure and restriction	Operations centres

Digital-twin archetypes help define whether information exchange is descriptive, predictive or control-oriented [150, 153].

Communication security must also address aviation-specific links such as controller–pilot data exchange [155].

Common operational data exchange must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [150, 153].

Data preparation for this capability includes flight identifiers, event definitions, source authority and message quality. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should

produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns acceptance or rejection of conflicting operational updates. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in duplicate truth sources, semantic mismatch and late correction. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Passenger–baggage information linkage must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [152, 155].

Data preparation for this capability includes passenger acceptance, tag identity, screening, loading and transfer status. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns reconciliation and exception routing before aircraft closure. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in orphan records, separate tickets and network interruption. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Integrated disruption information must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [147, 150].

Data preparation for this capability includes aircraft, crew, passenger, baggage and airport alternatives. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection and communication of a feasible recovery plan. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in partial optimization, inconsistent messages and delayed authority. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Secure operational interfaces must be treated as a controlled operational capa-

bility rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [155, 160].

Data preparation for this capability includes authentication events, access roles, message signatures and anomaly alerts. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns blocking or isolating a suspicious exchange without stopping safe operations. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in credential compromise, replay and unauthorized data modification. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic pe-

riod, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Integrated-system degraded mode must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [152, 160].

Data preparation for this capability includes local caches, fallback communications, manual logs and restoration status. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns transition between automated, degraded and restored operation. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in data divergence, uncontrolled synchronization and unclear recovery priority. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

6.5. Application of artificial intelligence for forecasting and decision support

Artificial intelligence can forecast passenger demand, delay, equipment condition and resource conflicts. Decision support should present uncertainty and relevant drivers rather than only one recommended action. Physics-informed learning can combine operational observations with known process constraints [148].

Mean absolute prediction error is given by formula (221):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \widehat{y}_i|. \tag{221}$$

Results should be segmented by horizon and operating regime. Aggregate accuracy can conceal failure during peaks.

Classification precision is given by formula (222):

$$Precision = \frac{TP}{TP + FP}. \tag{222}$$

False-alert cost determines whether precision or recall receives greater emphasis. Security and safety applications normally require both.

Decision confidence is given by formula (223):

$$C_d = 1 - \frac{H(\mathbf{p})}{\log K}. \tag{223}$$

The normalized entropy of class probabilities expresses model certainty. Low confidence should trigger human review rather than automatic action.

Explanation fidelity is given by formula (224):

$$F_X = 1 - \frac{1}{N}\sum_{i}|f(x_i) - g(x_i)|. \tag{224}$$

Here, g is an interpretable approximation of model f after normalization. Explanations must be accurate enough to support accountable decisions [145].

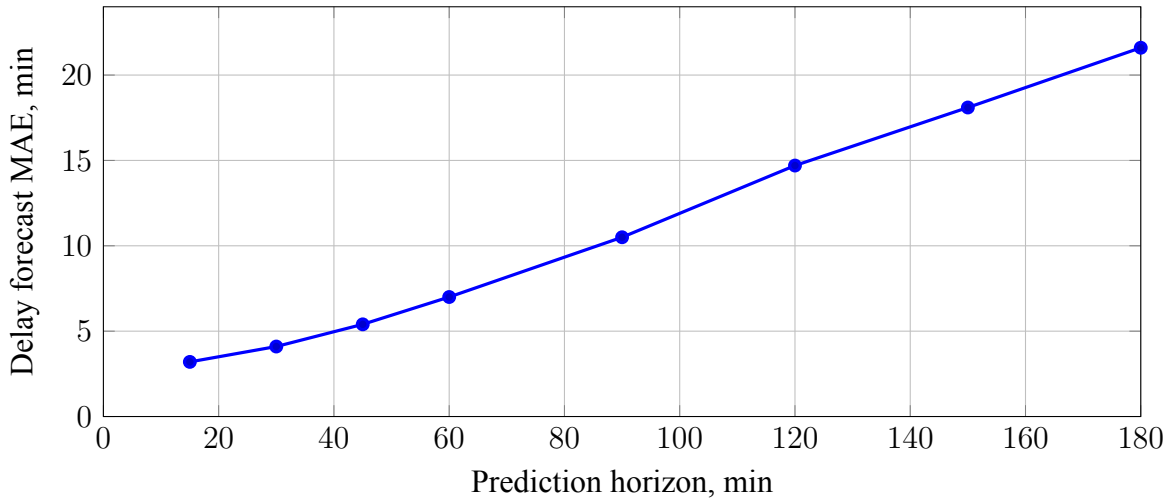

Figure 49: Illustrative relationship between prediction horizon and delay-forecast error

Description of the graph. Forecast error grows as the prediction horizon becomes longer. Near-term estimates benefit from current milestones and resource states. Strategic estimates depend more heavily on uncertain future events. Decision thresholds should therefore vary with the horizon. Prediction intervals are required when consequences are asymmetric.

Table 30: Artificial-intelligence applications in passenger air transport

Application	Model output	Required oversight
Demand forecast	Passenger volume and distribution	Scenario and drift review
Delay prediction	Probability and expected duration	Cause and horizon validation
Maintenance	Anomaly and remaining life	Engineering authorization
Passenger service	Recommendation and assistance need	Fairness and privacy review
Security monitoring	Attack or anomaly alert	False-alert and response control

Deep models can detect spoofing patterns in surveillance data [158].

High-stakes use requires interpretable evidence and protection against manipulated input [145, 159].

Passenger-demand forecasting must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [145, 148].

Data preparation for this capability includes bookings, schedules, fares, events and economic indicators. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of staffing, capacity and schedule response to predicted demand. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in structural breaks, biased samples and unreported forecast uncertainty. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Flight-delay prediction must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system

state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [145, 150].

Data preparation for this capability includes operational milestones, weather, airspace and preceding rotations. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns proactive reassignment and passenger recovery before delay propagation. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in data leakage, horizon-dependent accuracy and false confidence. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most

valuable.

AI-supported condition forecasting must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [142, 148].

Data preparation for this capability includes sensor history, maintenance findings, usage and environmental exposure. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns timing of inspection or component action within airworthiness limits. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in model drift, false alarms and incomplete physical representation. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

AI surveillance anomaly detection must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [158, 159].

Data preparation for this capability includes trajectory consistency, signal features, receiver state and network context. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns escalation of suspected spoofing or jamming for operational verification. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in adversarial input, false positives and unavailable independent evidence. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

from concealing poor performance in the exact situations where digital support is most valuable.

Explainable decision support must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [145, 148].

Data preparation for this capability includes model features, confidence, alternatives and recorded human overrides. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns acceptance, modification or rejection of a model recommendation. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in plausible but inaccurate explanations and automation bias. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

6.6. Economic evaluation of digital technology implementation

Digital projects should be evaluated through measurable process changes. Benefits may include saved labour time, avoided delay, greater capacity, lower energy use and reduced failure. Costs continue after implementation through licensing, integration, cybersecurity, training and model maintenance.

Net present value is given by formula (225):

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{B_t - C_t}{(1+d)^t}. \tag{225}$$

Benefits should be attributed only when the digital project changes the outcome. Sensitivity analysis is required for adoption and integration assumptions.

Payback time is given by formula (226):

$$T_{PB} = \min \left\{ t : \sum_{k=1}^{t} (B_k - C_k) \geq I_0 \right\}. \tag{226}$$

The measure is intuitive but ignores benefits after payback and discounting unless modified.

Benefit–cost ratio is given by formula (227):

$$BCR = \frac{\sum_t B_t/(1+d)^t}{I_0 + \sum_t C_t/(1+d)^t}. \tag{227}$$

A value above one indicates positive discounted net benefit. Projects should use the same boundary when compared.

Expected cyber-loss reduction is given by formula (228):

$$\Delta L = \sum_i (p_i^0 - p_i^1) I_i. \tag{228}$$

Security benefits include avoided operational interruption and data compromise. Surveillance and communication vulnerabilities make these effects economically relevant [157, 160].

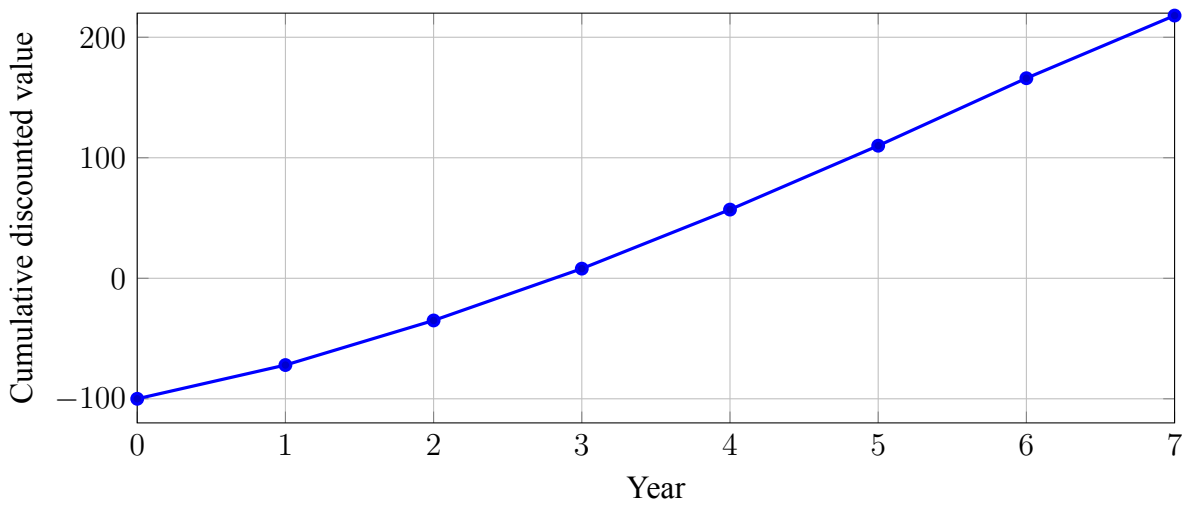

Figure 50: Illustrative cumulative value of a digital technology project

Description of the graph. The project begins with a substantial negative investment value. Annual operating benefits reduce the deficit during the first two years. The cumulative value becomes positive during the third year. Later years produce increasing net benefit. Scenario analysis should test whether slower adoption delays the crossing point.

Table 31: Economic effects of digital technology implementation

Effect	Measurement	Frequent error
Labour	Hours saved or reassigned	Treating reassignment as cash saving
Capacity	Additional sustainable throughput	Ignoring connected bottlenecks
Reliability	Avoided delay and downtime	Using unsupported failure reduction
Passenger value	Time, completion and loyalty	Double counting revenue effects
Security	Avoided expected loss	Omitting continuing control cost

Digital transformation research emphasizes organizational change and capability development [147, 151]. Economic evaluation should therefore include transition and governance, not only software purchase.

Self-service investment appraisal must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [147, 151].

Data preparation for this capability includes transaction demand, processing time, device cost and exception staffing. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of deployment scale and implementation sequence. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in overestimated adoption, omitted support cost and connected bottlenecks. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Digital-twin economic appraisal must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [140, 146].

Data preparation for this capability includes sensor coverage, model fidelity, integration effort and avoided failures. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of assets and decisions that justify twin development. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in unclear use case, continuing model cost and duplicated platforms. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Operational data-platform appraisal must be treated as a controlled operational

capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [150, 153].

Data preparation for this capability includes interface costs, decision latency, data quality and user participation. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns prioritization of integrations with measurable cross-organizational benefit. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in benefit double counting, weak ownership and vendor dependence. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic pe-

riod, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Cybersecurity investment appraisal must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [159, 160].

Data preparation for this capability includes threat likelihood, operational consequence, control effectiveness and recovery cost. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of layered controls and continuity resources. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in rare-event uncertainty, displaced risk and underestimated downtime. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Digital-project portfolio planning must be treated as a controlled operational

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [147, 151].

Data preparation for this capability includes project dependencies, resource limits, readiness and expected benefit. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns sequencing initiatives to create enabling capabilities before advanced analytics. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in parallel overload, incompatible architectures and unrealized benefits. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic pe-

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

riod, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

6.7. Prospects for the digital transformation of passenger air transport

Future passenger air transport will use more connected models, adaptive automation and cross-organizational data exchange. Development should proceed through controlled maturity stages so that operational value, security and employee competence grow together.

Digital maturity is given by formula (229):

$$DM = \sum_{k=1}^{K} w_k m_k. \tag{229}$$

Capabilities include data, integration, analytics, governance, security and skills. A high average should not conceal a critical weakness.

Transformation readiness is given by formula (230):

$$TR = DM\, O_r\, S_r, \tag{230}$$

where organizational and security readiness are expressed as fractions. The multiplicative form penalizes imbalance between technology and governance.

The secure-data trust score is given by formula (231):

$$DT = \alpha A + \beta I + \gamma C, \tag{231}$$

where availability, integrity and confidentiality are normalized. Aviation surveillance and communication require particular protection against spoofing and jamming [156, 157].

The transformation priority is given by formula (232):

$$TP_j = \frac{V_j R_j}{C_j T_j}. \tag{232}$$

Value and readiness increase priority, while cost and implementation time reduce it. Mandatory security or safety actions should not be ranked solely by this ratio.

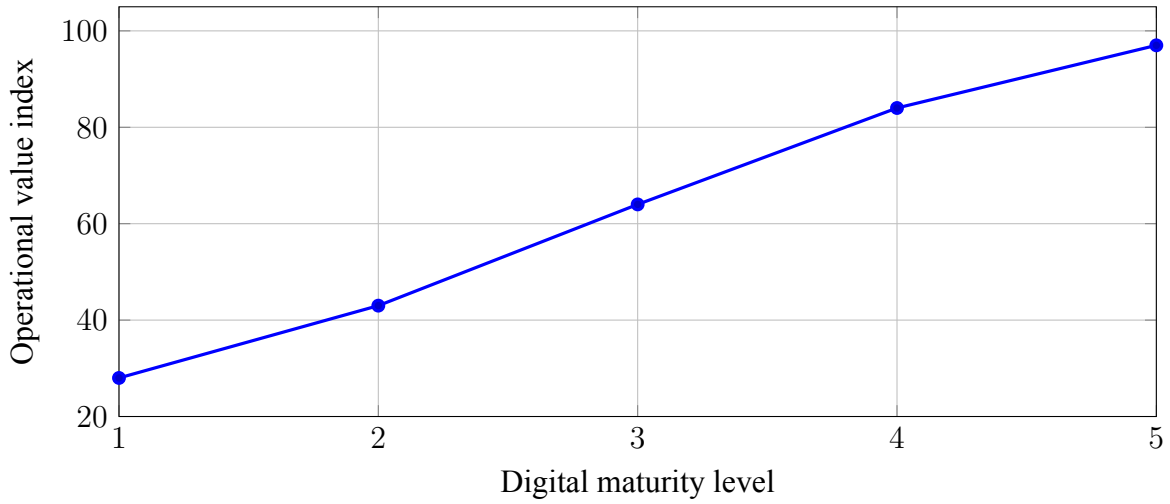

Figure 51: Illustrative operational value across digital maturity levels

Description of the graph. Operational value increases at every maturity level. Early stages provide visibility and standardized data. Larger gains occur when integrated prediction supports coordinated decisions. The highest level requires governance, security and continuous learning. Organizations should not automate unstable processes merely to claim greater maturity.

Table 32: Prospective stages of passenger-air-transport digital transformation

Stage	Dominant capability	Management focus
Digitized	Reliable electronic records	Data definition and quality
Connected	Cross-system event exchange	Interfaces and ownership
Predictive	Forecasts and anomaly detection	Validation and uncertainty
Prescriptive	Ranked operational alternatives	Authority and explanation
Adaptive	Controlled feedback and learning	Safety, security and audit

Digital-twin research identifies interoperability, fidelity and life-cycle governance as continuing challenges [140, 150].

Secure industrial connectivity and intrusion detection must develop with integration [152, 160].

Cryptographic protection alone cannot solve every surveillance threat, so layered monitoring and operational fallback remain necessary [159].

Future autonomous aircraft and drone-related services will add safety, privacy and command-link requirements to the airport digital ecosystem [154].

Airport digital-twin ecosystems must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise

description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [140, 149].

Data preparation for this capability includes asset models, passenger flows, environmental state and operational events. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns coordination of infrastructure and service decisions across time horizons. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in model inconsistency, excessive complexity and uncertain ownership. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average

from concealing poor performance in the exact situations where digital support is most valuable.

Adaptive passenger services must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [145, 147].

Data preparation for this capability includes journey context, accessibility needs, disruption state and channel preference. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns personalization that remains fair, transparent and operationally feasible. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in privacy intrusion, discriminatory outcomes and unstable recommendations. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Autonomous airside operations must be treated as a controlled operational ca-

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

pability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [154, 160].

Data preparation for this capability includes vehicle perception, route authorization, human supervision and conflict state. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns controlled movement and safe transfer to manual operation. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in sensor deception, communication loss and unclear responsibility. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

from concealing poor performance in the exact situations where digital support is most valuable.

Future secure surveillance and communication must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [156, 159].

Data preparation for this capability includes signal authentication, receiver diversity, network alerts and operational cross-checks. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns selection of trustworthy information during suspected attack. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in spoofing, jamming and dependence on a single protection mechanism. Controls should include access management, fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
Human factors	Override, workload and training results	Revise interface, authority or instruction
Governance	Ownership, audit trail and compliance	Escalate unresolved responsibility gaps

The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

Long-term digital-transformation governance must be treated as a controlled operational capability rather than as an isolated software function. Its design begins with a precise description of the physical process, the responsible organizations, the events that change system state and the decisions expected from the digital output.

The analytical boundary must remain stable so that observed improvement can be attributed to the intervention rather than to unrelated changes in traffic or staffing [147, 153].

Data preparation for this capability includes capability maturity, architecture, workforce skills and audited outcomes. Every field requires an authoritative source, update rule, validation threshold and retention policy. Missing or delayed values should produce an explicit quality status instead of being silently replaced. Historical records support calibration, while live records support operational use; the two datasets must use compatible definitions.

The principal management decision concerns revision of the roadmap as technology and operational evidence develop. A dashboard is useful only when a threshold activates a defined response, identifies the person with authority and records the resulting action. Alternative responses should be tested under normal demand, concentrated peaks, equipment failure and degraded communication. The preferred response is the one that improves the complete passenger and aircraft process rather than one local indicator.

Implementation risk is concentrated in technology-led change, fragmented investment and loss of human competence. Controls should include access management,

fallback procedures, staff training, model monitoring and periodic review of assumptions. A pilot stage should compare the proposed process with a documented baseline, and expansion should occur only after safety, quality and productivity results remain stable across representative operating conditions.

Control dimension	Evidence required	Management response
Data quality	Completeness, latency and consistency	Correct source or suspend automated use
Operational value	Time, capacity, cost and quality change	Retain, redesign or scale the capability
Reliability	Availability and recovery performance	Activate redundancy and continuity action
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The capability should be reviewed through a recurring cycle of measurement, diagnosis, corrective action and verification. Results must be segmented by traffic period, passenger category and disruption condition. This prevents a favourable average from concealing poor performance in the exact situations where digital support is most valuable.

CHAPTER 7

CONTEMPORARY CYBER THREATS IN THE AVIATION SECTOR

Civil aviation increasingly depends on connected information, communication and operational-technology systems. Passenger processing, baggage reconciliation, flight planning, surveillance, navigation, maintenance and airport-resource control exchange data across organizational boundaries. This connectivity improves coordination but also allows a defect or hostile action in one component to affect several operational processes.

Cybersecurity in aviation is therefore a safety, continuity and service-quality requirement. Protection cannot be limited to office networks because digital messages influence physical movement, access to restricted areas and operational decisions. Secure industrial connectivity and digital-twin architectures require controlled interfaces, trustworthy state data and explicit responsibility for every connection [152, 153].

The threat environment includes unauthorized access, malware, denial of service, manipulation of operational data, spoofing, jamming, credential theft and misuse of legitimate privileges. The consequence depends on the affected function and on the availability of independent verification. A disrupted administrative service may be inconvenient, whereas corrupted surveillance or command data can require immediate operational restrictions.

Air-traffic communication and surveillance illustrate the problem. Controller–pilot data links require protection of message origin and integrity, while broadcast surveillance can be exposed to false messages and radio-frequency interference [155, 157].

Authentication can reduce some risks, but cryptographic design must also address key management, compatibility, latency and failure recovery [156, 159].

Intrusion detection complements preventive control by identifying unusual sequences, values or communication behaviour. Detection must be linked to a response that an operational team can perform safely. An alert without context, confidence and an assigned decision owner may increase workload without reducing risk [158, 160].

Global navigation signals, wireless links and remotely piloted systems expand the set of external dependencies. Cross-checking independent receivers and observations can support localization of spoofing, while secure cellular and command links re-

quire protection against interception, impersonation and loss of availability [161, 162].

Unmanned aircraft create additional challenges near airports. Threats may originate from a compromised authorized vehicle, an unauthorized vehicle, its control station or the communication channel between them. Security, privacy and safety must be evaluated together because a protective action that disables a vehicle can itself create a physical hazard [154, 163].

Risk management begins with assets and operational consequences rather than with a generic list of vulnerabilities. The same technical weakness has different significance in a public information display, a baggage sortation controller and an air-traffic communication link. Prioritization should include traffic conditions, fallback capacity, time to detect and time to restore.

Resilience means the ability to maintain or recover an acceptable level of operation during a cyber incident. It requires segmentation, trusted backups, alternate communication, manual procedures, trained teams and exercises. Recovery is complete only when data, identities, configurations and physical process state have been reconciled.

Passenger data deserve specific protection because a journey record can combine identity, contact, payment, itinerary, baggage and assistance information. Access should follow operational need, and exchange between airlines, airports and service providers should be traceable. Privacy is not achieved by secrecy alone; collection, retention, reuse and deletion must also be governed.

Personnel remain essential. Employees need to recognize abnormal behaviour, protect credentials, report events and perform fallback procedures. Specialists require deeper competence in investigation, containment and restoration, while managers need authority to balance cyber controls with immediate operational safety.

The chapter examines infrastructure vulnerabilities, threats to airline and airport systems, passenger-data protection, resilience, regulatory controls, risk management, training and the creation of a secure aviation digital ecosystem. The objective is a layered approach in which technology, procedures, organizations and people support one another.

7.1. Digital infrastructure of the aviation sector and potential vulnerabilities

Aviation digital infrastructure combines enterprise applications, operational databases, radio systems, sensors, identity services, industrial controllers, cloud platforms and supplier connections. An asset inventory should describe not only hardware and software but also data flows and physical functions. Digital-twin models can assist by representing dependencies, provided that their scope and synchronization are controlled [152, 153].

The weighted exposure of an asset is given by formula (233):

$$E_i = \sum_{j=1}^{m} w_j x_{ij}, \qquad \sum_{j=1}^{m} w_j = 1. \tag{233}$$

The variables may represent external accessibility, privilege, legacy interfaces and supplier dependence. Critical safety consequence should remain a separate constraint rather than be hidden by averaging.

The dependency concentration index is given by formula (234):

$$DC = \sum_{k=1}^{n} s_k^2, \tag{234}$$

where s_k is the share of critical processes dependent on component k. A high value indicates a common point whose failure can propagate widely.

The attack-surface density is given by formula (235):

$$ASD = \frac{N_{interface} + N_{remote} + N_{priv}}{N_{asset}}. \tag{235}$$

The indicator supports comparison of architectural alternatives. It does not imply that every interface has equal risk.

The trusted-state coverage is given by formula (236):

$$TC = \frac{N_{asset}^{baseline}}{N_{asset}^{critical}} \times 100\%. \tag{236}$$

The baseline includes approved configuration, software version and integrity evidence. Assets without a trusted baseline are difficult to restore confidently.

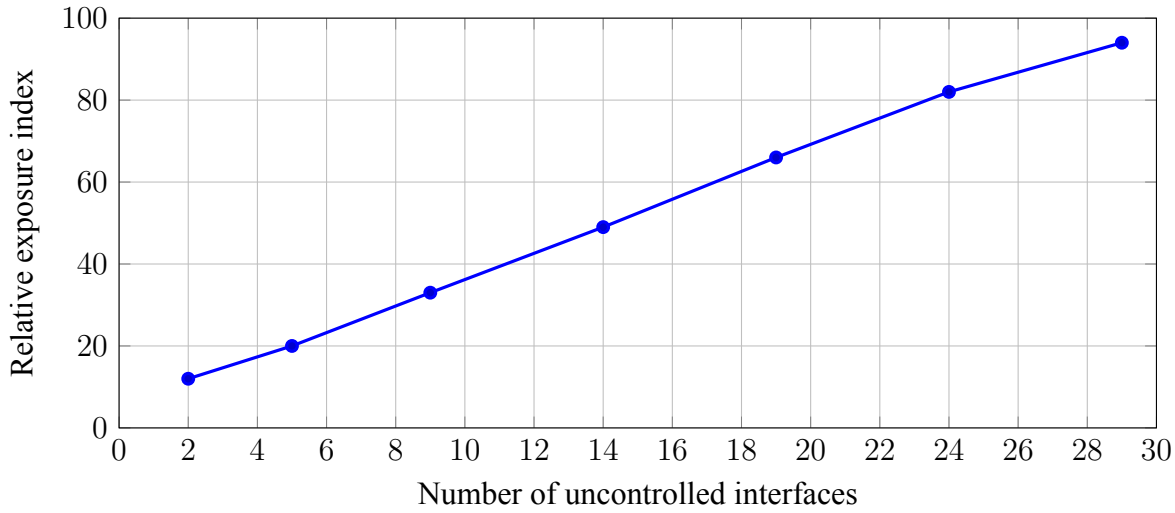

Figure 52: Illustrative effect of uncontrolled interfaces on infrastructure exposure

Description of the graph. Exposure rises as undocumented or weakly governed interfaces accumulate. Initial growth is moderate because some interfaces remain isolated. Growth becomes faster when connections create indirect paths between operational domains. The curve demonstrates why inventory and segmentation must precede advanced analytics. Removing obsolete connections can reduce exposure without changing the core service.

Table 33: Principal aviation digital-infrastructure domains

Domain	Typical dependency	Essential control
Passenger systems	Identity, booking and departure data	Access control and traceability
Baggage systems	Tags, routing and reconciliation	Integrity and physical cross-check
Airport operations	Resource and milestone status	Segmentation and continuity
Air traffic data	Communication and surveillance messages	Authentication and anomaly detection
Industrial systems	Sensors, controllers and actuators	Restricted access and trusted recovery

Broadcast and wireless infrastructure needs independent verification because an apparently well-formed message may be false or replayed [156, 158].

Radio interference additionally requires operational fallback rather than a purely software response [157].

Aviation asset and interface management is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include

normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes network flows, software inventories, supplier links and physical-process mappings. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [152, 153].

The principal operational decision concerns which connections are essential and which should be removed or isolated. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is undocumented dependencies and inherited trust between domains. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine segmentation, authenticated administration, configuration control and periodic discovery. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Air-traffic communication protection is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes message origin, sequence, timing, route and controller confirmation. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [155, 160].

The principal operational decision concerns whether a questionable message may be used, cross-checked or rejected. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is impersonation, replay and disruption of controller–pilot exchange. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine authentication, independent confirmation, monitoring and procedural fallback. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by

traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Surveillance-data integrity is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes receiver observations, aircraft tracks, message consistency and independent sensor data. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [156, 159].

The principal operational decision concerns when a track should be marked uncertain or excluded from automated use. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is fabricated, altered or replayed surveillance messages. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine batch verification, multilateration, anomaly detection and operator confirmation. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Radio-frequency availability is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes signal strength, receiver diversity, interference location and operational impact. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [157, 161].

The principal operational decision concerns activation of alternate surveillance or separation procedures. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is low-cost jamming and localized denial of service. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine spectrum monitoring, receiver diversity, geographic correlation and contingency procedures. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Operational-technology segmentation is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes controller state, maintenance sessions, firmware, alarms and physical outputs. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [152, 160].

The principal operational decision concerns isolation of a device without creating an unsafe process state. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is remote compromise and lateral movement from enterprise networks. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine allow-listed communication, privileged-access control, trusted backups and recovery tests. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures,

trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

7.2. Cyber threats to the information systems of airlines and airports

Airline and airport systems operate as a service chain. A cyber event in reservation, departure control, flight operations, baggage, access control or resource management can produce queues, missed connections and delayed aircraft. Threat analysis must therefore estimate system-wide consequences and not only direct technical damage.

The expected cyber loss is given by formula (237):

$$L_e = \sum_{i=1}^{n} p_i (C_i^{op} + C_i^{rec} + C_i^{rep}). \tag{237}$$

Operational, recovery and reputational consequences should be evaluated separately. Rare events can remain material when their interruption cost is high.

The propagation factor is given by formula (238):

$$PF = \frac{N_{process}^{affected}}{N_{system}^{initial}}. \tag{238}$$

A large value indicates weak segmentation or excessive common dependencies. The denominator refers to the initially compromised systems.

The detection precision is given by formula (239):

$$P_d = \frac{TP}{TP + FP}. \tag{239}$$

False alarms consume operational attention and can conceal real incidents. Precision should be assessed together with recall and detection delay.

The service degradation index is given by formula (240):

$$SDI = \sum_{j=1}^{m} w_j \left(1 - \frac{Q_j^{incident}}{Q_j^{normal}} \right). \tag{240}$$

The index can combine check-in, boarding, baggage and turnaround performance. Negative component values should be reviewed rather than automatically interpreted as improvement.

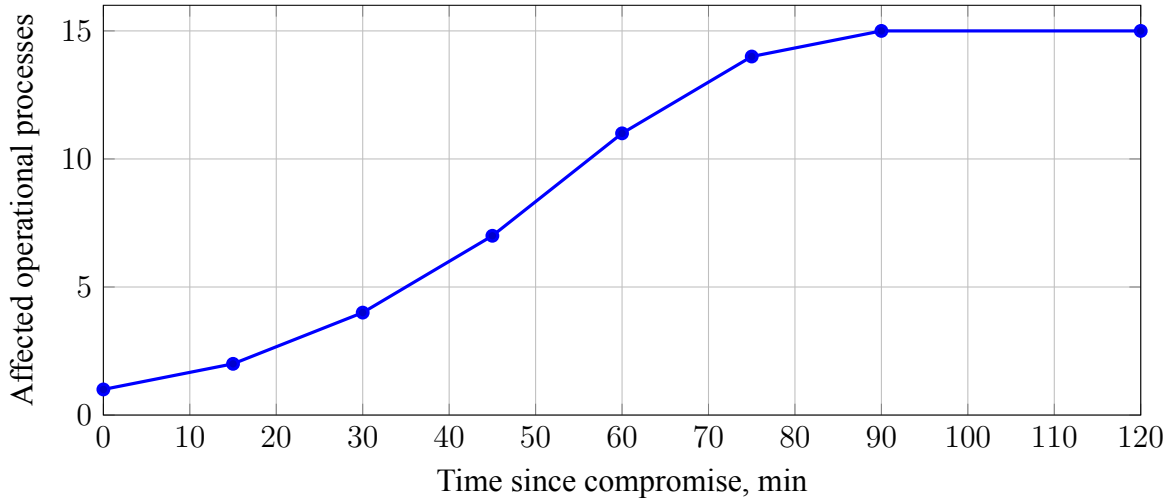

Figure 53: Illustrative propagation of an uncontained cyber incident

Description of the graph. The incident begins in one system and spreads slowly during the first interval. Propagation accelerates as shared identities and interfaces are used. Most operational processes become affected before two hours have elapsed. The pattern shows the value of rapid containment and architectural separation. Delayed action increases both restoration effort and passenger disruption.

Table 34: Threats to airline and airport information systems

Threat	Operational manifestation	Priority response
Credential compromise	Unauthorized transactions or access	Revoke, investigate and revalidate
Malware	Unavailable or altered systems	Isolate and restore trusted services
Denial of service	Passenger and staff channel outage	Activate alternate capacity
Data manipulation	Incorrect flight or baggage decisions	Cross-check and reconcile records
Supplier compromise	Multi-system or multi-airport exposure	Restrict connection and coordinate response

Intrusion detection should use communication context and operational state, because volume-based alarms alone may miss plausible false messages [158, 160].

Drone-related threats add unauthorized devices and compromised command links to the airport perimeter [163, 171].

Airline identity and access management is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes account privilege, login context, device state and high-risk transaction history. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [160, 163].

The principal operational decision concerns whether access should continue, require additional verification or be revoked. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is stolen credentials and misuse of legitimate administrative authority. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine least privilege, multifactor verification, session monitoring and rapid revocation. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Departure-control continuity is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear

boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes passenger, flight, document, seat and boarding status. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [152, 160].

The principal operational decision concerns transition from primary processing to a controlled alternate procedure. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is malware or denial of service during concentrated departure demand. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine segmented replicas, offline instructions, reconciled queues and restoration testing. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one

control.

Airport operational-database protection is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes stand, gate, belt, resource and milestone records. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [153, 158].

The principal operational decision concerns which operational state is trusted when sources disagree. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is manipulation that produces conflicting resource assignments. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine source authentication, plausibility checks, audit trails and human confirmation. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, oper-

ationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Airport protection from unauthorized aircraft is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes radar, radio-frequency, optical, acoustic and authorization records. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [164, 171].

The principal operational decision concerns classification and proportionate response to a detected object. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is unauthorized drones, deceptive signatures and unsafe countermeasures. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine multi-sensor fusion, authorization checks, escalation and safety coordination. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Secure management of autonomous vehicles is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes route, command, software, sensor and supervision records. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [166, 169].

The principal operational decision concerns continuation, restriction or safe termination of an autonomous task. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is command injection, navigation deception and compromised onboard software. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine authenticated command, geofencing, diverse sensing and supervised fallback. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, oper-

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

ationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

7.3. Protection of passengers' personal data and transportation information

Passenger servicing uses identity, contact, payment, itinerary, baggage and assistance data. Protection should follow the data through collection, exchange, use, retention and deletion. A service provider should receive only the fields and access duration necessary for its assigned task.

The data-minimization ratio is given by formula (241):

$$DMR = \frac{N_{field}^{necessary}}{N_{field}^{collected}}. \tag{241}$$

A value close to one indicates limited excess collection. Necessity should be reviewed whenever a process or regulation changes.

The privileged-access rate is given by formula (242):

$$PAR = \frac{N_{user}^{priv}}{N_{user}^{active}} \times 100\%. \tag{242}$$

The rate should be low but sufficient for reliable administration. Dormant and emergency accounts require separate monitoring.

The traceability coverage is given by formula (243):

$$AC = \frac{N_{event}^{logged}}{N_{event}^{required}} \times 100\%. \tag{243}$$

Logging is useful only if records are protected, time-synchronized and reviewed. Excessive collection of log content can create another privacy risk.

The residual privacy risk is given by formula (244):

$$R_p = \sum_{i=1}^{n} p_i I_i (1 - e_i), \tag{244}$$

where e_i is the effectiveness of applicable control. Estimates should be revised after incidents, audits and process changes.

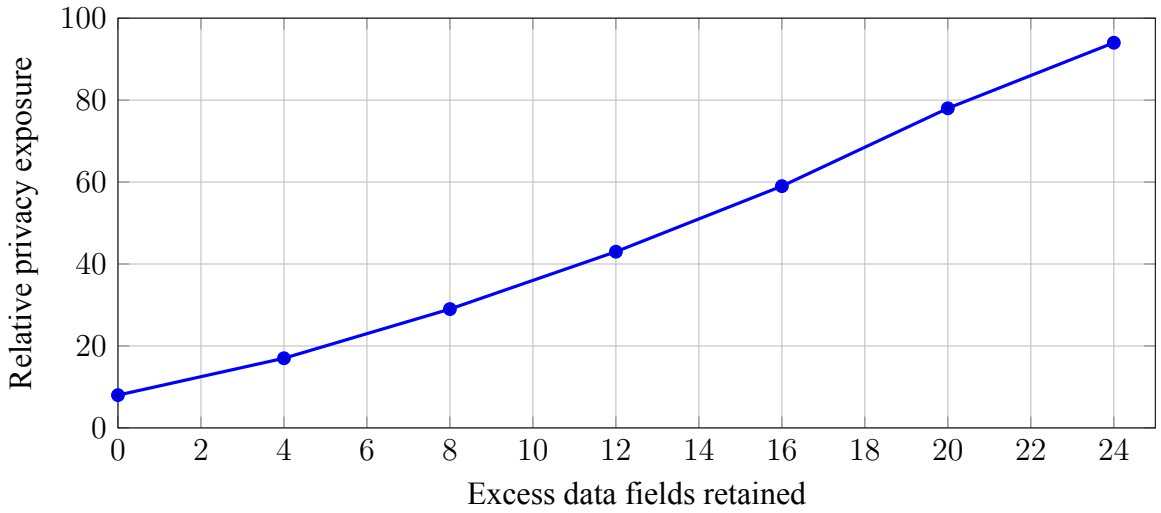

Figure 54: Illustrative relationship between excess data retention and privacy exposure

Description of the graph. Privacy exposure increases with every unnecessary retained field. Growth becomes steeper when datasets can be linked across services. Longer retention also gives attackers more time to obtain historical records. Data minimization reduces both breach consequence and governance burden. Essential operational records should nevertheless remain available for their justified retention period.

Table 35: Controls across the passenger-data life cycle

Stage	Main risk	Control
Collection	Excess or inaccurate data	Necessity and validation rules
Exchange	Disclosure or alteration	Authenticated encrypted transfer
Use	Unauthorized purpose or user	Role and purpose restriction
Retention	Unbounded historical exposure	Scheduled review and deletion
Incident	Delayed containment and notice	Traceable response procedure

Privacy controls must also cover wireless and remotely operated services that may collect location, image or telemetry information [154, 162].

Distributed data processing can reduce central exposure, but model updates and participants still require protection [170, 173].

Passenger identity-data governance is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes collection purpose, consent status,

identity evidence, access history and retention date. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [154, 172].

The principal operational decision concerns whether a field may be collected, shared, corrected or deleted. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is function creep, excessive retention and unauthorized identity correlation. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine data minimization, role restriction, encryption, audit and scheduled deletion. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Secure itinerary and departure records is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a

clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes reservation changes, passenger status, document checks and channel events. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [152, 160].

The principal operational decision concerns acceptance of a transaction when several systems report different states. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is account takeover, fraudulent changes and synchronization failure. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine strong authentication, transaction confirmation, version control and reconciliation. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one

control.

Baggage-information protection is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes tag identity, passenger association, screening status, routing events and custody. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [165, 170].

The principal operational decision concerns release or rerouting of an item after verified reconciliation. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is tag substitution, false routing events and unauthorized record access. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine authenticated events, physical checks, least privilege and immutable audit evidence. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, oper-

ationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Privacy-preserving collaborative analytics is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes local model updates, participant identity, aggregation state and model performance. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [173, 175].

The principal operational decision concerns whether shared learning may continue after a suspicious contribution. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is reconstruction, poisoned updates and disclosure through model parameters. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine secure aggregation, participant validation, update screening and privacy testing. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

control.

Passenger-data incident handling is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes affected records, access path, time window, recipients and containment status. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [163, 172].

The principal operational decision concerns scope of isolation, correction and communication to affected parties. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is incomplete breach scoping and continued use of corrupted records. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine forensic logging, data mapping, coordinated notification and verified remediation. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, oper-

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

ationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

7.4. Ensuring cyber resilience and incident response

Cyber resilience combines preparation, resistance, controlled degradation, recovery and learning. An incident-response plan must connect technical containment with operational authority. The team should know which services may be isolated, which must remain available and which fallback procedures require approval from safety or operations personnel.

The mean time to detect is given by formula (245):

$$MTTD = \frac{1}{N}\sum_{i=1}^{N}(t_i^{detect} - t_i^{start}). \tag{245}$$

The starting time may be uncertain and should be updated after investigation. Median and upper-percentile values supplement the mean.

The mean time to contain is given by formula (246):

$$MTTC = \frac{1}{N}\sum_{i=1}^{N}(t_i^{contain} - t_i^{detect}). \tag{246}$$

Containment must be defined through operational effect, not merely through closure of an alert. Partial isolation should be recorded separately.

The recovery-point compliance is given by formula (247):

$$RPC = \frac{N_{recovery}^{within\ RPO}}{N_{recovery}^{total}} \times 100\%. \tag{247}$$

The recovery-point objective sets the tolerated data loss. Compliance requires usable and reconciled records.

The resilience index is given by formula (248):

$$RI = \frac{1}{T}\int_0^T \frac{Q(t)}{Q_0}\,dt. \tag{248}$$

The index captures the depth and duration of degradation. Critical minimum service should additionally be expressed as a hard limit.

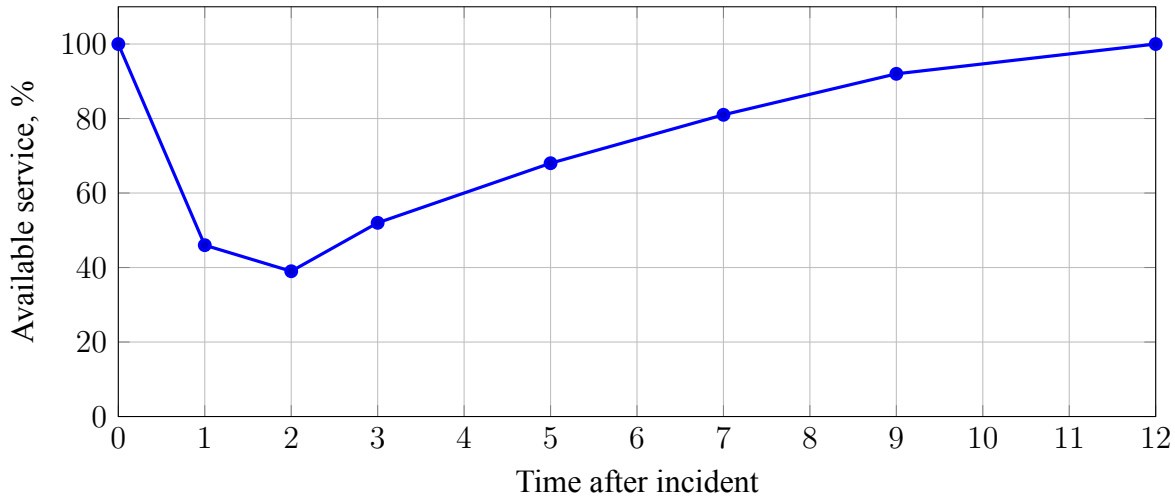

Figure 55: Illustrative service degradation and recovery during a cyber incident

Description of the graph. Service availability falls sharply after the incident. Containment initially prevents further decline but does not restore normal capacity. Alternate procedures then support gradual improvement. Trusted restoration returns the service to its baseline. The area below full performance represents the operational consequence that resilience measures seek to reduce.

Table 36: Incident-response phases in aviation operations

Phase	Key question	Output
Triage	Is the alert credible and operationally relevant?	Severity and owner
Containment	What can be isolated safely?	Controlled affected boundary
Continuity	Which minimum services must continue?	Fallback operating mode
Recovery	Is the restored state trustworthy?	Reconciled service release
Review	Why did controls succeed or fail?	Corrective-action plan

Crowdsourced and diverse observations can improve detection of navigation deception, while communication-network monitoring can reveal coordinated anomalies [160, 161].

Machine-learning detection requires representative data and controlled false-alarm behaviour [176].

Aviation security monitoring is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include

normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes network alerts, identity events, operational milestones and physical observations. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [160, 176].

The principal operational decision concerns whether an anomaly is benign, suspicious or an operational incident. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is late detection and alert fragmentation across organizational teams. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine central correlation, operational context, escalation criteria and round-the-clock ownership. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Navigation-spoofing response is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes receiver disagreement, reported position, observed movement and nearby sensor reports. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [161, 167].

The principal operational decision concerns restriction of navigation use and transition to an alternate source. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is plausible false positioning that passes a single-receiver check. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine receiver diversity, crowd correlation, geographic tests and pilot procedures. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, oper-

ationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Airport counter-drone incident response is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes object track, authorization, payload indicators, flight path and protected-zone status. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [164, 171].

The principal operational decision concerns selection of observation, restriction, interception or emergency action. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is misclassification and a countermeasure that increases physical risk. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine multi-sensor confirmation, proportional authority, airspace coordination and post-event evidence. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

count from concealing slow detection, weak recovery or excessive dependence on one control.

Trusted restoration of operational systems is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes backup integrity, configuration baseline, dependency state and reconciled transactions. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [166, 174].

The principal operational decision concerns release of each service from recovery into normal operation. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is restoring malware, stale data or incompatible dependent systems. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine offline backups, staged restoration, integrity testing and business-owner acceptance. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained

personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Cyber exercises and operational learning is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes scenario injects, decision times, communication paths and unresolved actions. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [167, 176].

The principal operational decision concerns which control, procedure or competence requires correction. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is exercise success being declared without testing difficult degraded modes. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine independent observation, measurable objectives, corrective ownership and retesting. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

7.5. International standards and regulatory framework for cybersecurity in aviation

Aviation cybersecurity governance converts broad obligations into asset-specific controls and evidence. International coordination is important because aircraft, passengers, data and suppliers cross jurisdictions. The organization should maintain a requirements register linking each obligation to an owner, process, technical control, record and review date.

The compliance coverage is given by formula (249):

$$CC = \frac{N_{requirement}^{verified}}{N_{requirement}^{applicable}} \times 100\%. \tag{249}$$

A requirement is verified only when evidence demonstrates effective implementation. Policy publication alone does not establish coverage.

The control-evidence freshness is given by formula (250):

$$EF = \frac{1}{N} \sum_{i=1}^{N} e^{-\lambda a_i}, \tag{250}$$

where a_i is evidence age. The decay rate should reflect change frequency and control criticality.

The supplier-assurance rate is given by formula (251):

$$SAR = \frac{\sum_i w_i v_i}{\sum_i w_i} \times 100\%, \tag{251}$$

where v_i indicates verified assurance for supplier i. Higher weights are assigned to providers with privileged or operational access.

The unresolved-exception exposure is given by formula (252):

$$UE = \sum_{i=1}^{n} s_i d_i, \tag{252}$$

where severity s_i is multiplied by the age d_i of an approved exception. Long-standing exceptions require renewed justification or remediation.

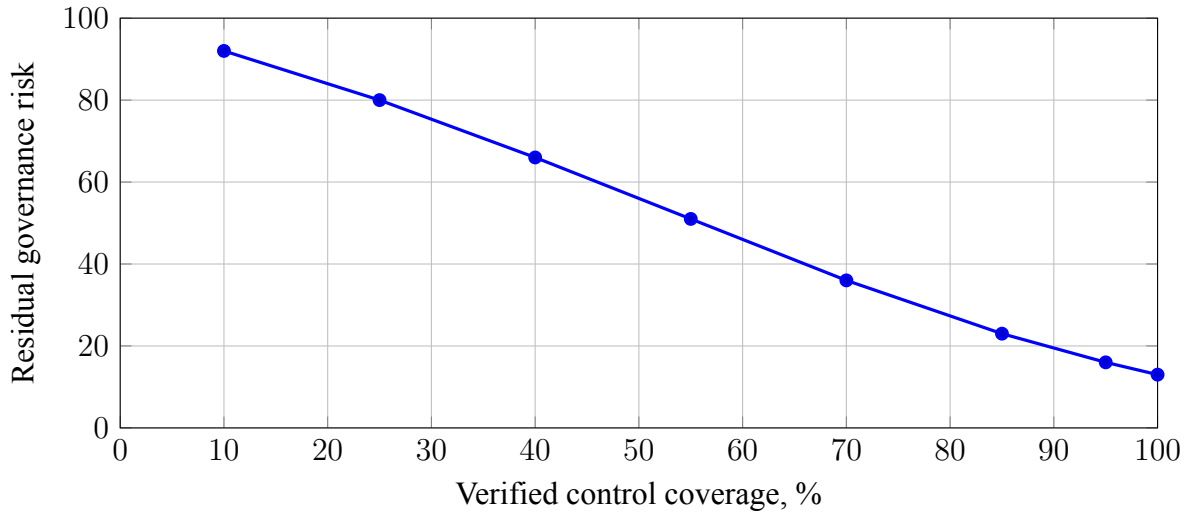

Figure 56: Illustrative relationship between verified control coverage and residual governance risk

Description of the graph. Residual governance risk declines as more applicable controls are verified. The reduction is strongest when major coverage gaps are closed. Risk does not reach zero because implementation can fail between assessments. Continuous monitoring is therefore needed alongside periodic audit. Exceptions and supplier dependencies explain part of the remaining exposure.

Table 37: Structure of an aviation cybersecurity requirements register

Register field	Purpose	Evidence example
Requirement	Define the applicable obligation	Approved interpretation
Asset and process	Establish operational scope	Current dependency map
Owner	Assign decision authority	Named accountable role
Control	Describe implementation	Configuration or procedure
Verification	Demonstrate effectiveness	Test, audit or exercise result

Requirements for communication and surveillance should be technology-aware because authentication, interference and interoperability have different controls [155, 159].

Remotely piloted and autonomous systems also require coordinated security, safety and privacy treatment [169, 175].

Aviation cybersecurity governance is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes applicable obligations, assets, owners, controls and verification results. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [155, 159].

The principal operational decision concerns acceptance, remediation or escalation of a compliance gap. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is fragmented requirements and evidence that does not demonstrate effectiveness. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine a unified register, independent tests, management review and traceable exceptions. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Cross-organizational incident coordination is a component of operational safety

and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes contact points, reporting thresholds, affected services and shared indicators. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [160, 168].

The principal operational decision concerns what information must be exchanged and under which authority. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is delayed reporting and inconsistent classification between partners. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine predefined channels, common severity criteria, exercises and protected evidence exchange. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident

count from concealing slow detection, weak recovery or excessive dependence on one control.

Supplier and cloud assurance is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes service dependencies, privileged access, subcontractors, recovery commitments and test evidence. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [152, 165].

The principal operational decision concerns continuation, restriction or replacement of a supplier connection. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is hidden fourth-party exposure and weak contractual recovery obligations. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine security clauses, access boundaries, audit rights and joint continuity testing. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Governance of unmanned-aircraft services is a component of operational safety

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes vehicle authorization, operator identity, airspace limits and command-link assurance. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [162, 169].

The principal operational decision concerns approval of an operation and conditions for suspension. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is unclear accountability across manufacturer, operator and communication provider. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine certified configurations, authenticated control, operational limits and incident reporting. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, oper-

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

ationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Continuous compliance monitoring is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes control telemetry, change records, exceptions, vulnerabilities and audit findings. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [165, 175].

The principal operational decision concerns when a control must be retested or a risk acceptance withdrawn. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is formal compliance persisting after the operational environment changes. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine automated evidence, risk-based review, expiry dates

and independent assurance. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

7.6. Cyber risk management and personnel training

Cyber risk management connects threats and vulnerabilities to operational consequences. The process should include assets, dependencies, existing controls, uncertainty and the time needed for detection and recovery. Personnel training is a control only when employees can perform the required action under realistic conditions.

The residual risk score is given by formula (253):

$$RR_i = P_i I_i (1 - E_i). \tag{253}$$

Control effectiveness E_i should be supported by evidence. Scores should not replace explicit treatment of intolerable safety consequences.

The risk-treatment efficiency is given by formula (254):

$$RTE_j = \frac{RR_{before,j} - RR_{after,j}}{C_j}. \tag{254}$$

Mandatory controls are implemented regardless of the ratio. The measure helps compare additional discretionary treatments.

The training-completion quality is given by formula (255):

$$TQ = \frac{N_{pass}^{scenario}}{N_{assigned}} \times \frac{S_{retention}}{100}. \tag{255}$$

Attendance alone is insufficient. Scenario performance and retained competence are required.

The human-response reliability is given by formula (256):

$$HR = 1 - \frac{N_{error}^{critical}}{N_{decision}^{tested}}. \tag{256}$$

Tests should include time pressure, incomplete information and degraded communication. Results guide procedure and interface redesign as well as training.

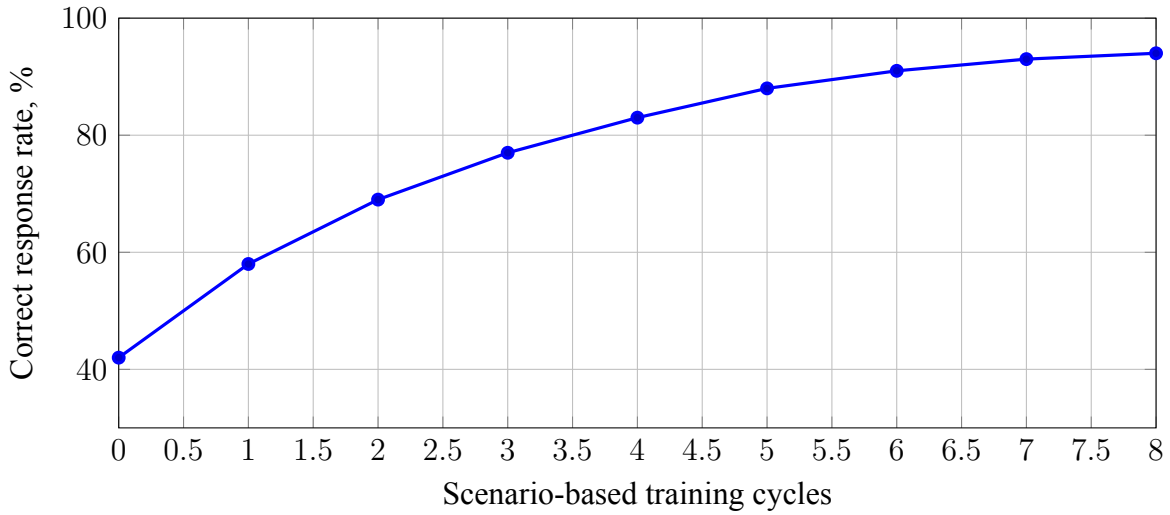

Figure 57: Illustrative improvement in response quality through repeated exercises

Description of the graph. Correct response improves rapidly during the first training cycles. Later improvement is smaller as basic procedures become familiar. Repeated exercises remain necessary to preserve competence and test new threats. A plateau may indicate that the procedure or interface, rather than knowledge, limits performance. Training results should therefore trigger system redesign when errors persist.

Table 38: Cybersecurity competence by aviation role

Role	Required competence	Verification
All personnel	Credential, phishing and reporting practice	Short practical scenario
Operational staff	Safe fallback and data validation	Process exercise
Technical staff	Detection, isolation and restoration	Laboratory and live drill
Managers	Risk acceptance and crisis authority	Tabletop decision exercise
Suppliers	Contracted controls and coordination	Joint assurance test

Risk assessment for remotely operated systems must address both cyber compromise and the physical consequence of a lost or manipulated vehicle [172, 174].

Detection technology should be evaluated through realistic data, false alarms and operator workload [171, 176].

Operational cyber-risk assessment is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes assets, threat paths, vulnerabilities, controls and passenger or flight consequences. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [163, 174].

The principal operational decision concerns acceptance, reduction, transfer or avoidance of a defined risk. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is numerical scoring that conceals an intolerable operational consequence. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine scenario analysis, explicit safety limits, accountable acceptance and scheduled review. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Role-based cybersecurity training is a component of operational safety and con-

tinuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes job tasks, system privileges, fallback duties and previous exercise results. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [166, 167].

The principal operational decision concerns which competence must be trained and how it will be tested. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is generic awareness material that does not prepare staff for operational decisions. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine role-specific scenarios, observation, feedback and recurrent qualification. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident

count from concealing slow detection, weak recovery or excessive dependence on one control.

Security-operations team readiness is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes alert volume, investigation quality, tool availability and escalation performance. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [160, 176].

The principal operational decision concerns staffing, specialization and shift coverage for expected incident demand. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is analyst overload, fragmented tools and delayed operational consultation. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine triage rules, automation, cross-training and joint exercises with operations. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Counter-drone team competence is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes sensor limitations, authorization rules, protected zones and response options. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [164, 171].

The principal operational decision concerns classification and safe escalation of an observed unmanned aircraft. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is false identification and unauthorized or unsafe intervention. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine multi-sensor training, legal authority, simulation and coordinated field exercises. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

control.

Learning from incidents and exercises is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes timeline, decisions, evidence gaps, recovery performance and repeated weaknesses. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [167, 172].

The principal operational decision concerns assignment and verification of corrective actions. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is blame-oriented review and closure without retesting. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine protected reporting, causal analysis, accountable deadlines and independent validation. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

7.7. Creating a secure digital ecosystem for air transport

A secure aviation digital ecosystem provides trusted exchange among airlines, airports, ground handlers, public authorities, navigation services, suppliers and passengers. It requires common identifiers, controlled interfaces, shared incident procedures and governance that follows data across organizational boundaries.

The ecosystem trust index is given by formula (257):

$$ETI = \alpha A + \beta I + \gamma C + \delta R, \tag{257}$$

where availability, integrity, confidentiality and recoverability are normalized. Weights reflect the operational function and should not remove mandatory minimums.

The verified-exchange rate is given by formula (258):

$$VER = \frac{N_{message}^{auth+valid}}{N_{message}^{critical}} \times 100\%. \tag{258}$$

Verification includes origin and semantic plausibility. A signed but operationally impossible message must still be challenged.

The ecosystem concentration risk is given by formula (259):

$$CR = \max_{k} \frac{N_{process,k}^{dependent}}{N_{process}^{critical}}. \tag{259}$$

The measure identifies the provider or platform with the largest critical dependency. Continuity options should reduce unacceptable concentration.

The secure-maturity score is given by formula (260):

$$SM = \left(\prod_{j=1}^{m} m_j^{w_j} \right), \qquad \sum_{j} w_j = 1. \tag{260}$$

The geometric form penalizes a weak dimension. Data, technology, people, governance and recovery should advance together.

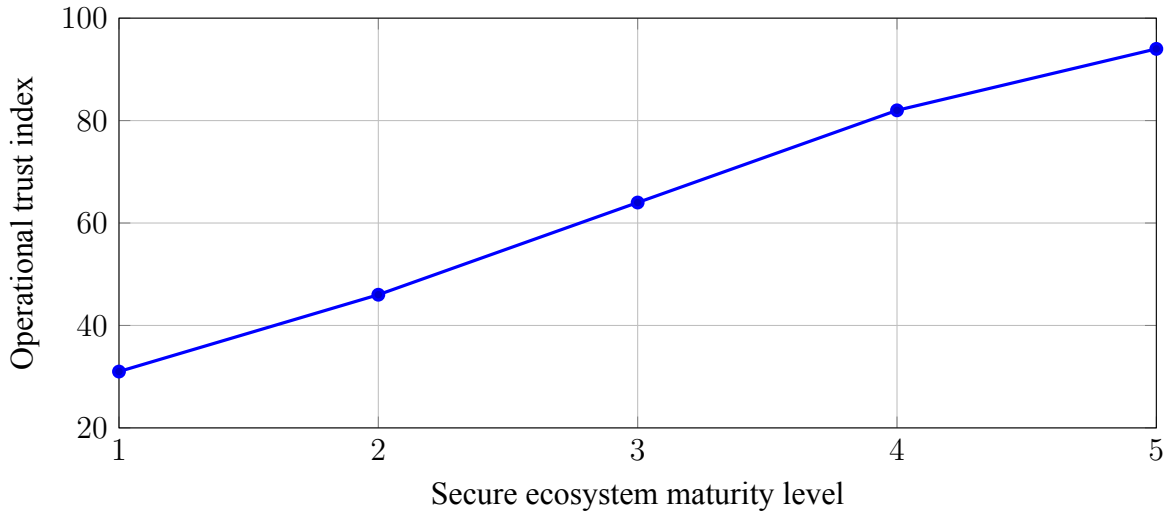

Figure 58: Illustrative increase in operational trust with ecosystem maturity

Description of the graph. Operational trust rises as ecosystem controls mature. Early levels establish inventories and basic protection. Integrated monitoring and coordinated response produce larger gains. The highest level requires continuous verification and learning across partners. Trust remains evidence-based and does not mean that all participants or messages are accepted automatically.

Table 39: Maturity stages of a secure aviation digital ecosystem

Stage	Dominant capability	Management priority
Defined	Assets and responsibilities known	Complete the common baseline
Protected	Interfaces and identities controlled	Remove high-risk exposure
Monitored	Events correlated across domains	Improve detection quality
Resilient	Partners exercise continuity together	Verify safe recovery
Adaptive	Evidence continuously updates controls	Govern change and learning

Distributed ledgers and federated methods may support controlled exchange, but their identity, consensus and update mechanisms remain part of the threat model [170, 173].

Autonomous aviation requires protection throughout sensing, communication, decision and recovery [169, 175].

Trusted aviation data exchange is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes message identity, provenance, time, validation result and receiving-process state. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [156, 159].

The principal operational decision concerns acceptance, quarantine or rejection of shared operational information. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is valid-looking false data and incompatible interpretations between partners. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine authenticated exchange, common semantics, plausibility checks and end-to-end audit. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Secure aviation digital twins is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear

boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes physical observations, model state, synchronization quality and decision history. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [152, 153].

The principal operational decision concerns whether the representation is trustworthy enough for a proposed operational use. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is model poisoning, stale state and unauthorized influence on the physical process. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine source validation, state confidence, access separation and controlled feedback. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one

control.

Distributed trust for drone data is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes vehicle identity, command authorization, delivery evidence and participating-node status. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [170, 172].

The principal operational decision concerns acceptance of data or a transaction without one unrestricted central intermediary. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is compromised participants, consensus delay and irreversible false records. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine permissioned membership, revocation, independent sensing and bounded ledger use. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

Privacy-preserving collaborative defence is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes local detections, model updates, participant reputation and aggregate performance. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [173, 176].

The principal operational decision concerns sharing of defensive knowledge without unnecessary raw-data disclosure. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is poisoned updates, inference leakage and unequal participant quality. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine secure aggregation, robust learning, validation and privacy measurement. No single mechanism is sufficient against every failure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

count from concealing slow detection, weak recovery or excessive dependence on one control.

Long-term ecosystem governance is a component of operational safety and continuity, not merely an information-technology task. Its protection begins with a clear boundary that identifies assets, interfaces, users, suppliers and physical processes affected by a loss of confidentiality, integrity or availability. The boundary must include normal operation, degraded modes, maintenance access and recovery.

The evidence required for control includes maturity, dependency concentration, incident trends, supplier changes and recovery evidence. Each record needs an authoritative source, time stamp, validation rule, retention period and accountable owner. Correlation across independent sources is important because a technically valid message may still conflict with the physical state of an aircraft, passenger process or airport facility [169, 175].

The principal operational decision concerns revision of shared architecture, investment and assurance priorities. Decision thresholds should distinguish warning, confirmed incident and emergency conditions. Each threshold must activate a named role, a communication route and a time limit. Automated blocking is appropriate only when its safety consequence has been assessed; otherwise the system should isolate the suspect component while preserving a controlled fallback.

The principal threat is rapid connectivity growth without corresponding responsibility and fallback capacity. Assessment should consider attacker capability, exposure time, propagation through connected systems and the duration of operational consequences. A low-frequency event can remain a priority when it affects surveillance, flight communication, passenger identity, baggage reconciliation or access to a critical area.

Controls should combine joint governance, interoperable controls, recurrent exercises and transparent evidence. No single mechanism is sufficient against every fail-

ure or attack. Technical protection must therefore be supported by procedures, trained personnel, supplier obligations, exercises and independent verification.

Control stage	Evidence	Required response
Preparation	Asset, dependency and threat records	Assign ownership and protection baseline
Detection	Alerts, anomalies and physical cross-checks	Validate and classify the event
Containment	Affected accounts, links and processes	Isolate while maintaining safe service
Recovery	Restoration tests and data reconciliation	Resume from a trusted state
Learning	Timeline, causes and control performance	Correct design, procedure and training

Performance review should separate attempted attacks, detected events, operationally significant incidents and false alarms. Results should also be segmented by traffic intensity and degraded conditions. This approach prevents a low annual incident count from concealing slow detection, weak recovery or excessive dependence on one control.

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