International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 • Website: www.ijfmr.com • Email: editor@ijfmr.com

From Legacy to Leading Edge: A Reverse Engineering Framework for Digital Innovation in Commercial Aviation

Humayoon Muhammad

Paris American International University, Paris, France

Abstract
Commercial aviation is experiencing a profound transformation driven by digitalization, artificial intelligence, automation, and sustainability imperatives. While these advancements promise enhanced customer experience and operational efficiency, many airlines continue to depend on legacy systems. This paper critically applies a reverse engineering framework to identify both visible and hidden barriers to innovation through the 4Ts model i.e. Transformation, Technology, Tools, and Talent. It assesses organisational readiness, technological integration, and digital maturity. Drawing on 17 expert interviews and 393 survey responses, the study highlights inconsistencies in airlines' adoption of digital platforms and change management. Despite substantial investments, real value creation is often hindered by fragmented systems, vendor dependency, and limited reskilling. Reverse engineering emerges as a strategic approach to map dependencies, evaluate system compatibility, and steer implementation. Its purpose is to align stakeholders with enterprise objectives, enhance agility, and provide strategic recommendations for continued research on aviation's digital evolution.

Keywords: Airline Digital Maturity, Airline Innovation, Commercial Aviation, Customer Experience, Digital Fluency, Digital Transformation, Innovation Framework, Legacy Systems, Operational Efficiency, Organisational Readiness, Reverse Engineering, System Modernization, Technology Adoption, 4Ts: Transformation, Technology, Tools and Talent

1. INTRODUCTION

The aviation industry is under increasing pressure to modernize due to rising fuel costs, environmental scrutiny, and evolving passenger expectations (Lee, Fahey & Forster, 2021; SpringerLink, 2022). Digital platforms offer transformative potential in customer engagement and operational efficiency (Shiwakoti et al., 2022; International Air Transport Association, 2024), yet many carriers remain burdened by legacy systems that hinder innovation. These outdated infrastructures constrain airlines' ability to deliver responsive, personalized, and data-driven services, putting them at a competitive disadvantage (McKinsey & Company, 2018).

Historically, aviation has trailed sectors like retail and banking in digital adoption. This pattern is explained by factors such as high system complexity, significant investment costs, and the critical nature of airline operations, which slow the uptake of new technologies in the industry (Exploring Digital Aviation, 2025). However, the COVID-19 pandemic served as an inflection point when physical interactions were restricted, pushing airlines to accelerate technologies such as biometric boarding, AI-driven customer interfaces, blockchain in logistics, and digital health certification (International Air Transport Association, 2018; DigitalDefynd, 2025). Despite these advances, implementation remains uneven: regional differences and operational constraints continue to shape technology uptake, particularly in markets with limited resources or heavy regulation (Sun, Wandelt & Zhang, 2022).

Digital transformation in aviation now hinges not just on adopting new technologies but on matching rising passenger expectations for omnichannel touchpoints, seamless booking, hyper-personalization, and integrated post-travel services (Pantano, Priporas and Dennis, 2018; Engine Service Design, 2021). These expectations, shaped by leaders in e-commerce and banking, increasingly influence airline standards, manifested in AI-powered interfaces, personalized offers, and seamless app interactions (Ieva and Ziliani, 2018). Many airlines still struggle with fragmented legacy infrastructures, siloed departments, and incomplete digital integration, which result in inconsistent user experiences (Kabashkin, 2024).

Competitive pressure from low-cost carriers and digital-native entrants further complicates transformation. Legacy airlines must improve operational efficiency and elevate customer experience simultaneously without undermining profit margins (Asif, 2013). This dual imperative often prompts disconnected digital efforts, where investments are made in isolated functions such as mobile apps or chatbots that lack an overarching strategic framework (Lavskaya, Barykin et al., 2024).

Amid this complexity, reverse engineering emerges as a powerful diagnostic and planning tool. Traditionally used in mechanical and hardware contexts, reverse engineering refers to the deconstruction of systems to understand their components and interactions (DLA Aviation, 2020; Airframe Designs, 2018). In aviation, it enables granular examination of workflows, technology dependencies, and resource allocation providing a clear picture of what needs reconfiguration (Airframe Designs, 2018; Rozesara, 2023). This insight serves as the foundation for a reverse engineering-based framework grounded in the 4Ts model: Transformation, Technology, Tools, and Talent, a holistic structure for navigating digitalization with inclusivity and equity at its core.

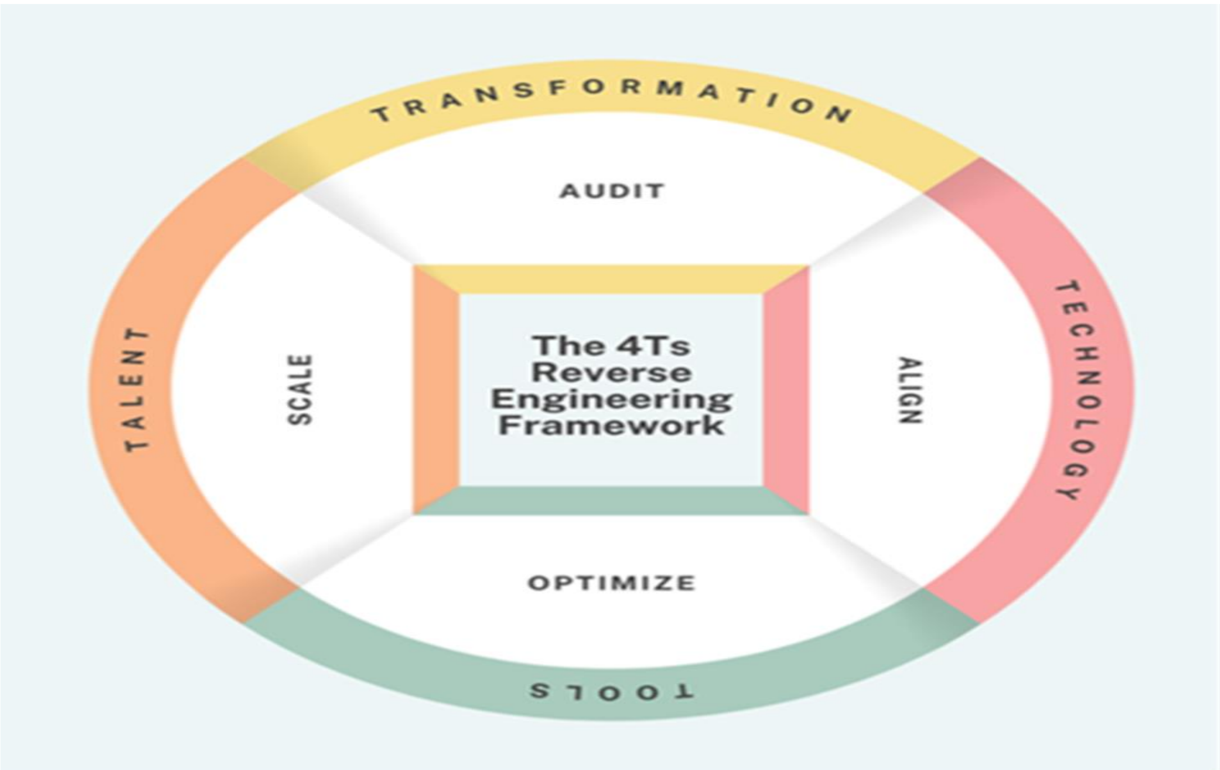

Figure 1. The 4Ts Reverse Engineering Framework

This 4Ts model offers a comprehensive lens through which airline readiness, digital maturity, and organisational bottlenecks can be assessed. The study's mixed-methods approach, featuring expert interviews and a global airline self-assessment, delivers both breadth and depth of insight. Key findings emphasize the importance of viewing digital initiatives holistically. Even when airlines invest in customer-facing innovations, these yield minimal returns if internal systems remain siloed or staff lack the digital fluency to utilise tools effectively (Pilon, 2023). Similarly, digitizing back-office operations without improving customer interfaces creates a disconnect that erodes brand value and customer satisfaction (McKinsey & Company, 2018).

Moreover, many organisations, including airlines, do not lack innovative initiatives but rather suffer from the absence of structured frameworks that systematically assess, prioritize, and implement digital transformation projects (Vuksic, Ivancic and Vugec, 2018; Zamora Iribarren et al., 2024; Alnoor, Atiyah and Abbas, 2024). Without such guiding models, digital efforts often become disjointed, reactive, and misaligned with broader enterprise objectives (Kovynyov & Mikut, 2018). The 4Ts model addresses this challenge by offering a structured toolkit to evaluate digital readiness, coordinate transformation efforts, and promote cross-functional alignment.

Technology adoption in aviation must be understood as an iterative, systemic journey rather than a series of isolated upgrades. Reverse engineering enables this mindset by providing visibility into interdependencies, surfacing hidden inefficiencies, and aligning transformation with strategic objectives. It enables airlines to pivot from reactive digital upgrades toward proactive, scalable transformation strategies (Alnoor, Atiyah & Abbas, 2024; van de Wetering, Mikalef & Pateli, 2021). By leveraging this framework, aviation stakeholders can chart a more coherent and sustainable path forward in the digital age.

Reverse engineering-driven assessment reveals where internal systems falter whether due to outdated reservation systems, rigid middleware, disconnected CRM platforms, or loyalty engines based on batch processing. These diagnostics guide strategic remediation. The transformation dimension ensures that digital investments integrate into an ambitious enterprise roadmap, preventing isolated tools from delivering limited value. Technology modernization through API enablement, microservices, or modular architecture, makes digital capabilities scalable and sustainable. Tools such as sandbox environments, A/B-testing platforms, analytics dashboards, and process orchestration frameworks empower agile experimentation and real-time personalization. Talent readiness ensures staff possess digital fluency, agile mindsets, and clarity of ownership extending beyond training to cultural and structural rebalancing that supports cross-functional collaboration (Kıyıklık et al., 2022).

These four elements are interdependent: transformation strategy needs enabling technology, tools are useless without skilled talent, and talent cannot act effectively without an enterprise strategy. For instance, an AI-powered rebooking chatbot may fail if the reservation system cannot support real-time inventory checks, middleware is brittle, or customer service staff distrust its recommendations. Reverse engineering surfaces these fail-points and triggers coordinated investment i.e. upgrading middleware (Technology), deploying orchestration tools (Tools), training staff (Talent), and integrating the chatbot within strategic digital initiatives (Transformation).

Supporting evidence reinforces this integrated approach. International Air Transport Association (2024) emphasizes the need for integrated systems across booking, operations, and loyalty, as many airlines still operate fragmented platforms. Shiwakoti et al. (2022) demonstrate that airlines aligning technology, process, and strategy outperform peers on customer satisfaction and cost metrics. Sun, Wandelt & Zhang

(2022) find that airlines in constrained environments benefit more from modular tools and talent development than full-scale system overhauls. Zamora Iribarren et al. (2024) caution that transformation projects lack durability without structured frameworks like the 4Ts. Alnoor, Atiyah & Abbas (2024) empirically correlate digital maturity in regional airlines with talent development, executive sponsorship, and agile tooling. Van de Wetering, Mikalef & Pateli (2021) advocate an iterative, pilot-based approach over risky, monolithic modernization. Lavskaya, Barykin et al. (2024) warn that standalone mobile apps unsupported by backend integration lead to inconsistent experiences and erosion of trust. Rozesara (2023) reinforces that reverse engineering creates architectural clarity and feasible incremental transformations. The broader literature on digitalization, including in airports (Tan & Masood, 2021), and adaptive engineering models in aerospace (Brelje & Martins, 2019), support modular, data-driven approaches to complex system modernization.

The reverse engineering–enabled 4Ts model offers airlines a structured and insightful roadmap toward digital maturity. Reverse engineering acts as both a compass and a ruler, revealing inefficiencies and interdependencies within systems. It also guides balanced investments across each "T." Through this framework, digital change evolves into a coordinated and scalable journey rather than a series of disconnected upgrades. As a result, airlines are empowered to deliver seamless, personalized, and resilient experiences that align with customer expectations and operational realities.

2. Thematic Organisation and Analysis

2.1 Transformation: The Strategic Imperative

Transformation in aviation is no longer optional but a strategic imperative. Airlines are increasingly expected to evolve into digital retailers, curating personalized bundles, delivering predictive services, and cultivating omnichannel customer engagement. Still, transformation is often misunderstood as merely a software upgrade rather than an enterprise-wide evolution of workflows, strategies, and mindsets (Aroles et al., 2021; Ndhlovu, Makuyana & Dube, 2024). True transformation requires unified efforts throughout the organisation, not just separate IT updates or department initiatives. Leading carriers embed transformation into their governance structures, encourage cross-functional alignment, and cultivate leadership commitment at all levels to ensure that digital strategies permeate every facet of the business i.e. from customer-facing services to core operational processes, thereby enabling sustainable modernization instead of fragmented improvements (Matt & Benlian, 2015; Ciampi et al., 2022; Schallmo, 2024; van de Wetering, Mikalef & Pateli, 2021).

Lufthansa and Emirates offer instructive examples. Lufthansa has deepened its adoption of AI-driven dynamic pricing specifically through PROS Request-Specific Pricing and Dynamic Ancillary Pricing, allowing it to personalize offers in real time and maximize ancillary revenue, even across a network of multiple carriers (PROS, 2024; Business Wire, 2025). Emirates, alongside Lufthansa, has been publicly acknowledged for championing modular, open AI-powered technologies to fuel next-generation offer and order management, paving a roadmap toward commercial autonomy (PROS, 2024). These initiatives demonstrate how embedding digital transformation as a strategic priority delivers tangible business and customer outcomes.

Yet transformation remains elusive for many others. Organisational inertia, leadership misalignment, and internal resistance often undermine digital goals. Here, reverse engineering provides a powerful diagnostic lens. It helps carriers dissect entrenched processes and systems to pinpoint dependency bottlenecks and inefficiencies, thereby guiding precisely where strategic intervention can yield the greatest value (Alnoor, Atiyah & Abbas, 2024; Zaoui & Souissi, 2020). This approach elevates transformation from aspirational rhetoric to actionable, measurable enterprise progression.

Digitalizing airline workflows and strategies demands not only upgraded technology but transformed mindsets. Enterprise-wide leadership commitment, cross-functional collaboration, and strategic frameworks are essential enablers. Reverse engineering uncovers hidden misalignments and enables targeted, scalable modernization. When transformation is treated as foundational, anchored in governance, illuminated by diagnostic clarity, and powered by modular innovation, it becomes a durable strategic shift rather than a fragile patchwork of IT projects.

2.2 Technology: Enabler or Constraint

Technology in aviation embodies both immense opportunity and persistent risk. Advanced solutions such as AI-driven customer interfaces, predictive maintenance, digital twins, mobile platforms, and analytics dashboards all promise to transform both operations and passenger experience. However, their real impact is determined not by novelty alone, but by how well they align with organisational readiness, cultural adaptation, and legacy system integration (Ma, Flanigan & Bergés, 2024). Airlines often adopt high-profile digital solutions under competitive pressure, yet many overlook the deeper interoperability and governance challenges that define whether a technology can scale successfully. As highlighted in recent research on digital transformation strategy, effective approaches must integrate managerial foresight with technological design to ensure scalability and sustained impact (Ismail, Khater & Zaki, 2017; Annaç Göv, 2023). This misalignment results in costly deployments that underdeliver. Reverse engineering functions here as a critical pre-adoption diagnostic tool mapping dependencies, surfacing inefficiencies, and ensuring adoption represents meaningful integration within the enterprise rather than a superficial layer (Kabashkin, 2024).

Predictive maintenance and digital twins provide a clear illustration of these dynamics. Predictive systems reduce downtime and improve aircraft availability when deployed effectively (Stanton et al., 2022; Lee, Lapira, Bagheri & Kao, 2013). Yet their success depends heavily on live sensor data, robust integration of multiple data streams, and high-quality analytics environments. Legacy architectures and siloed IT landscapes frequently block these prerequisites, leaving predictive models underutilised (Fedorov & Perekrestov, 2025). For example, Lufthansa Technik continues to report strong and expanding interest in predictive maintenance among airlines. While many carriers remain in the pilot or proof-of-concept phase, steadily growing numbers are progressing toward full integration, particularly for non-engine components through platforms such as AVIATAR, which combine condition monitoring, predictive health analytics, and total component support. Nevertheless, industry adoption at scale remains constrained by persistent data quality challenges, hesitance to share operational data across stakeholders, and the inherent complexity of integrating heterogeneous legacy systems (Aviation Week Network, 2020). In the Middle East, carriers such as Emirates and Saudia have signed agreements with Boeing and Collins Aerospace, respectively, to enhance prognostic and predictive maintenance capabilities. Qatar Airways is partnering with Google Cloud to build data and AI foundations that include predictive maintenance among other operational improvements. Although these initiatives highlight commitment to digital advancement, integration across diverse data formats, vendor-specific systems, and legacy operational processes continues to pose hurdles (Aviation Business Middle East, 2024). Digital twins extend predictive capacity by offering simulation-driven insights, but at scale, frameworks remain immature, often failing to meet functional and information requirements needed for real-time optimisation (Ma, Flanigan & Bergés, 2024).

The limitations extend beyond operational platforms. Customer-facing technologies including mobile applications, AI chatbots, and personalization engines are often deployed as headline innovations but fail to deliver coherent experiences without integration into back-end systems such as passenger service systems (PSS), customer relationship management (CRM) databases, and analytics platforms (Pilon, 2023). For example, a chatbot promising real-time rebooking may collapse when PSS infrastructure lacks the ability to update inventory instantaneously. Airlines treating these technologies as stand-alone add-ons risk fragmented customer journeys that undermine satisfaction. Reverse engineering provides a structured way to expose technical debt, identify brittle middleware, and design blueprints for scalable omnichannel delivery. Without such preparation even advanced digital tools erode rather than enhance customer trust and brand value (Kabashkin, 2024).

Modernizing the underlying tools and infrastructure compounds the challenge. Many airlines continue to rely on monolithic PSS platforms that resist modular upgrades, escalate integration costs, and slow innovation cycles (Sabre, 2024). Transitioning to modular architectures and microservices-based designs, however, has been shown in empirical studies to deliver measurable improvements in availability, scalability, and resource efficiency, enabling systems to handle higher volumes of concurrent users with greater fault isolation and resiliency (Tapia et al., 2020). Airlines that have embraced industry standards such as International Air Transport Association's New Distribution Capability (NDC) and One Order are already benefiting from simplified booking processes, improved ancillary product delivery, and greater pricing flexibility that enhances commercial agility and customer experience (International Air Transport Association, 2023b; Yıldız & Mazıoğlu, 2025). For instance, American Airlines has shifted a substantial share of domestic fares to New Distribution Capability (NDC)-enabled channels, while Air France–KLM and Finnair have announced timelines to move the most of indirect sales through New Distribution Capability (NDC) distribution. These changes illustrate how standardisation, when paired with infrastructure readiness, improves both commercial agility and passenger experience.

At the same time, adopting these technologies requires cultural and organisational alignment. Predictive systems, AI-driven decision support, and advanced analytics necessitate a shift from reactive, compliance-focused processes to proactive, data-driven mindsets. However, many airlines still face skill gaps, hierarchical resistance, and legacy mental models that slow transformation (Ndhlovu, Makuyana & Dube, 2024). For example, engineering teams may resist predictive tools if they lack training in data interpretation, while frontline staff may distrust AI-based recommendations without cultural reinforcement. Reverse engineering does more than reveal technical bottlenecks. It highlights organisational misalignments, clarifying where investment in workforce upskilling, governance structures, and cultural adaptation is necessary (Alnoor, Atiyah & Abbas, 2024). In this way, reverse engineering links technological deployment with readiness in talent and leadership, reducing the risk of underutilisation.

Equally, reverse engineering helps avoid technology being perceived merely as cost centres rather than strategic enablers. By systematically uncovering dependencies, airlines can make balanced decisions that harmonise new systems with broader transformation strategies. This is particularly critical in contexts where rapid deployment is tempting, such as during competitive pressure from low-cost carriers or digital-native entrants. Reverse engineering ensures that adoption decisions are not reactive responses to market hype but coordinated steps within a sustainable enterprise roadmap.

Ultimately, technology is both an enabler and a constraint. It enables progress when aligned with tools, talent, and transformation strategy, but becomes a constraint when implemented in isolation. Reverse engineering equips airlines with diagnostic clarity to move beyond fragmented, piecemeal adoption. When predictive maintenance, digital twins, modular PSSs, APIs, analytics dashboards, and AI-driven customer services are designed to converge into a coherent ecosystem, airlines can establish digital infrastructures that are not only scalable but resilient. In this integrated environment, aviation stakeholders can transform technology from a limiting factor into a durable enabler of operational excellence, customer-centric innovation, and long-term competitiveness.

2.3 Tools: Infrastructure and Architecture

Tools refer to the vital technical ecosystem including APIs, data warehouses, Passenger Service Systems (PSS), and service architectures that underpin modern aviation capabilities. Many airlines still operate with monolithic systems, particularly outdated PSS platforms, which significantly hinder the agile deployment of newer, modular tools. These legacy systems impose high integration costs, slow innovation cycles, and yield inconsistent customer experiences (Sabre, 2024).

Reverse engineering offers a structured approach to uncover how digital tools and systems interact within these complex environments. It helps surface technical friction points such as delays in inventory updates, reliance on manual process overrides, and inefficient data flow. These inefficiencies typically originate from fragmented architectures and legacy platforms that restrict real-time integration. Moreover, dependence on third-party technology providers can further impede progress. Proprietary systems may limit adaptability and introduce vendor lock-in, complicating efforts to innovate or pivot swiftly (Sabre, 2024; Alnoor, Atiyah & Abbas, 2024).

Mapping these dependencies via reverse engineering empowers airlines to design more flexible, modular architectures. Adopting microservices and modular design principles allows airlines to isolate functionality and reduce integration complexity. Empirical studies demonstrate that implementing microservices architectures enhances system resiliency and scalability, facilitating improved fault tolerance, load balancing, and service discovery. Migration assessments further show that transitioning from monolithic to microservices-based systems significantly improve availability and scalability in mission-critical environments (Auer et al., 2021).

A growing number of airlines are responding by embracing industry standards that promote simplification and interoperability. Those adopting International Air Transport Association's One Order and New Distribution Capability (NDC) standards benefit from greater flexibility in deploying ancillary services and dynamic pricing models (Sabre, 2024). By consolidating disparate records such as the Passenger Name Record (PNR), electronic tickets, and Electronic Multi-purpose documents (EMDs) into a unified order record, One Order enables streamlined billing, order management, and smoother fulfilment workflows (International Air Transport Association, 2023a; Kıyıklık, Kuşakcı & Mbowe, 2022). This consolidation not only reduces operational complexity but also supports real-time synchronization of travel content across sales and operations channels, significantly enhancing customer experience and efficiency.

Industry examples illustrate the impact: American Airlines removed 40% of its domestic fares from EDIFACT systems, favouring New Distribution Capability (NDC)-enabled channels. Finnair plans to shift entirely to New Distribution Capability (NDC) distribution by the end of 2025, and Air France–KLM targets 90% of its indirect sales via New Distribution Capability (NDC) by 2027. New Distribution Capability (NDC) also supports dynamic pricing, delivering improvements of 1% to 4% in revenue, all while promoting richer content presentation and personalization (International Air Transport Association, 2023b).

Successful adoption of these standards, however, does not happen overnight. Interview-based insights highlight that success depends on long-term planning and phased implementation strategies. Without such planning or without addressing infrastructure readiness and integrating change management, advanced tools can still underperform, failing to align with operational realities or secure internal buy-in (Sabre, 2024; Alnoor, Atiyah & Abbas, 2024).

By pairing reverse engineering with these standards and modular technologies, airlines can transform their tool ecosystems from rigid, expensive monoliths into agile, scalable platforms that support ongoing innovation, operational efficiency, and superior customer experience.

2.4 Talent: Digital Fluency and Culture

Digital transformation in aviation is ultimately people-driven, with technology acting as an enabler rather than the sole catalyst. Despite the availability of advanced tools, transformation efforts frequently falter due to human capital gaps and cultural inertia (Montero Guerra, 2023; Wiblen & Marler, 2021; Thums et al., 2023). In many airlines, digital adoption is uneven, with pockets of innovation undermined by segments of the workforce that lack digital literacy or resist process changes. These issues are often compounded by rigid hierarchies, legacy organisational structures, and training models that have not evolved to meet the demands of a data-driven, customer-centric industry (Bansal et al., 2023; Schallmo, 2024; Sebastian et al., 2017; Vial, 2019).

A major barrier lies in the absence of systematic upskilling and reskilling frameworks. While some airlines introduce ad-hoc training initiatives, they rarely integrate digital competencies into formal workforce planning, succession strategies, or leadership development pipelines (Langer, 2023; Hess et al., 2016). This misalignment is further reflected in performance management systems that fail to incorporate digital KPIs, thereby weakening accountability for transformation outcomes. Without these linkages, transformation risks becoming technology-centric rather than business-centric, resulting in isolated upgrades rather than enterprise-wide change (Ndhlovu, Makuyana, & Dube, 2024).

Cultural readiness is equally critical. Research in organisational change highlights that digital transformation success is strongly correlated with a culture of continuous learning, openness to experimentation, and empowerment of employees to challenge outdated processes (Westerman, Bonnet, & McAfee, 2014). In aviation, where operational safety and procedural adherence are paramount, fostering such a culture requires balancing innovation with risk management.

Reverse engineering provides a diagnostic lens to evaluate workforce readiness and cultural barriers before large-scale rollouts. By mapping dependencies between processes, tools, and skill sets, it helps identify where human capability gaps will create bottlenecks. For instance, if predictive analytics tools are introduced without parallel training in data interpretation for frontline staff, the value of the technology diminishes. Similarly, if decision-making remains centralized, opportunities for innovation at operational levels are lost (Zaoui & Souissi, 2020).

Forward-looking airlines are addressing this by embedding digital literacy into onboarding, incentivizing cross-functional collaboration, and creating “digital ambassador” programs to accelerate adoption (International Air Transport Association, 2023a). Aligning talent strategies with transformation objectives ensures that human capital evolves in tandem with technological capabilities, fostering an adaptable workforce equipped to sustain competitive advantage.

3. Integrated Insights

The interplay between the four pillars of the 4Ts framework i.e. Transformation, Technology, Tools, and

Talent are not merely sequential but deeply interconnected, forming the structural backbone of effective digital transformation in aviation. Each pillar reinforces, and is in turn reinforced by, the others. A weakness in one domain inevitably undermines progress in the others. Technology, no matter how advanced, loses its impact without tools that enable scalability and integration, and without a workforce equipped to exploit its full potential. Transformation efforts, however ambitious, falter when there is no unifying vision or stakeholder alignment across organisational levels.

Reverse engineering is effective here because it highlights interdependencies. By deconstructing existing processes, infrastructures, and skill structures, it uncovers the subtle but significant dependencies between strategic ambition and operational reality. This diagnostic lens exposes inefficiencies such as redundant systems, data silos, and outdated workflows that are often masked in top-down reporting. It also clarifies systemic barriers like vendor lock-in, which not only constrain technology choices but also limit the adaptability of organisational tools and training strategies (Kabashkin, 2024; Sabre, 2024).

Findings from this research confirm that siloed strategies, vendor dependencies, and talent shortfalls are rarely isolated issues. Instead, they tend to compound, creating a reinforcing cycle of inefficiency. For example, when an airline locks itself into a proprietary technology ecosystem, it may restrict its ability to integrate emerging tools or adopt industry standards such as International Air Transport Association's New Distribution Capability (NDC). This, in turn, limits operational flexibility and puts pressure on talent, as staff must work around system constraints rather than optimising processes (Sabre, 2024; Zaoui & Souissi, 2020). Similarly, gaps in digital literacy can prevent employees from fully exploiting the capabilities of newly deployed technologies, leading to underperformance that undermines stakeholder confidence in transformation initiatives (Wiblen & Marler, 2021).

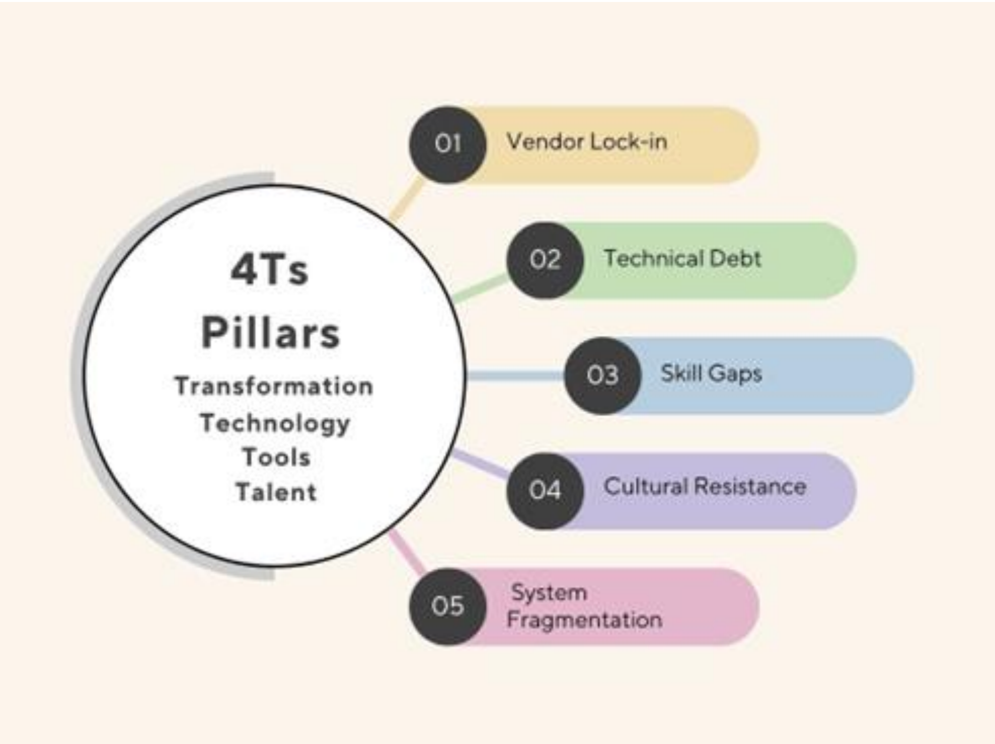

Figure 2. Digital Transformation Barriers in Aviation

Below table 1 clearly illustrates the strategic functions of each pillar i.e. Transformation, Technology, Tools and Talent and how failure points can cascade across the system. Transformation's success is highly dependent on coherent governance and change management structures (Porfírio et al., 2021). Without clear leadership alignment, technology deployments risk being reactive rather than strategic (van de Wetering, Mikalef, & Pateli, 2021). Likewise, if tools particularly Passenger Service Systems (PSS) and integration architectures are outdated, even carefully chosen technologies may fail to achieve their intended operational or customer experience improvements (Sabre, 2024). Talent, meanwhile, operates as the glue binding all other pillars; without a digitally fluent workforce, infrastructure and systems will remain underutilised (Salesforce, 2022).

Table 1. Strategic Functions of the 4Ts Reverse Engineering Framework

4Ts Pillar	Strategic Function	Reverse Engineering Role	Common Failure Points	Citations
Transformation	Align vision, roadmap, and governance for change	Identifies process disconnects, change resistance	Fragmented change efforts; lack of stakeholder alignment	Porfírio et al., 2021
Technology	Ensure technology deployments align with leadership vision and enterprise strategy	Diagnoses misalignment between leadership intent and technology adoption pathways	Reactive deployments; lack of strategic alignment	van de Wetering, Mikalef, & Pateli, 2021
Tools	Optimise infrastructure and architecture for scalability	Audits tool performance and integration capabilities	Outdated PSSs, slow data exchange, legacy lock-in	Sabre, 2024
Talent	Cultivate digital fluency and adaptive workforce	Identifies skill gaps and readiness for digital adoption	Underutilised systems; lack of digital fluency	Salesforce, 2022

Similarly, the interdependencies outlined in Table 2 below demonstrate that transformation is inherently a systems problem. Transformation ↔ Technology alignment ensures that strategic objectives are supported by fit-for-purpose solutions (van de Wetering, Mikalef, & Pateli, 2021). Technology ↔ Tools integration guarantees that the technical ecosystem can scale and adapt to evolving demands (Sabre, 2024). Tools ↔ Talent interaction ensures that deployed infrastructure is effectively leveraged (Salesforce, 2022). Talent ↔ Transformation alignment sustains change momentum by embedding adaptive skills and cultural readiness into the organisation's DNA (Zaoui & Souissi, 2020; Sabre, 2024).

Table 2. Interdependencies Among 4Ts in Digital Transformation

4Ts Interaction	Nature of Dependency	Evidence from Study	Citations

Transformation ↔ Technology	Strategy requires fit-for-purpose technology to be impactful	Technology investments underperform without interoperability	van de Wetering, Mikalef, & Pateli, 2021
Technology ↔ Tools	Tools must support scalable deployment of selected technologies	Outdated PSSs hinder integration of AI and mobile systems	Sabre, 2024
Tools ↔ Talent	Infrastructure is underutilised without a digitally fluent workforce	Only 28% actively upskilling, 73% feel unprepared for digital tools	Salesforce (2022)
Talent ↔ Transformation	Sustaining change momentum requires embedding adaptive skills and cultural readiness	Resistance arises due to untrained staff and poor cultural alignment	Zaoui & Souissi, 2020; Sabre 2024

By viewing these as a network of dependencies rather than discrete stages, reverse engineering enables aviation stakeholders to plot coordinated digital journeys. This means moving beyond departmental project planning towards enterprise-wide digital roadmaps that explicitly account for how each pillar's readiness level influences the others. For instance, before investing in predictive maintenance powered by AI, a reverse engineering assessment would not only evaluate data architecture compatibility but also examine whether engineering staff are trained to interpret AI outputs and whether maintenance workflows can accommodate predictive triggers (Lee et al., 2013; Ma, Flanigan, & Bergés, 2024).

The compounded nature of failure points further underlines the value of a reverse engineering mindset. A talent gap is not simply a training issue; it may also stem from tool complexity, lack of interoperability, or insufficient integration between technology vendors and in-house systems. Likewise, vendor lock-in can be both a technology and a transformation governance issue, reflecting decisions made without fully mapping long-term architectural flexibility (Kabashkin, 2024). These feedback loops suggest that successful transformation is achieved when dependencies are designed in rather than reactively managed.

Another benefit of this integrated perspective is the ability to identify leverage points—areas where targeted improvements in one pillar generate amplified, system-wide benefits across the organisation. For instance, upgrading core tools such as the PSS to support modular APIs can instantly expand the range of compatible technologies, reduce vendor dependency, and make it easier to upskill staff on interoperable systems (Sabre, 2024). Similarly, embedding digital skills metrics into performance management can accelerate transformation by ensuring that talent development directly supports strategic objectives (Wiblen & Marler, 2021).

Critically, reverse engineering also supports phased transformation. Rather than attempting large-scale "big bang" deployments, airlines can stage their initiatives to align with incremental readiness improvements across pillars. This approach reduces risk, minimises operational disruption, and allows for continuous learning cycles that refine both the technical and human elements of transformation (Alnoor, Atiyah, & Abbas, 2024).

In practical terms, integrating insights from the 4Ts model and reverse engineering means that a technology decision is never just a technology decision. It is a decision about future workforce requirements, about the adaptability of supporting tools, and about the extent to which the transformation vision has been operationalised across the organisation. The most successful airlines are those that treat these considerations not as compliance checks but as strategic design principles (van de Wetering, Mikalef, & Pateli, 2021; PROS, 2024).

By integrating the 4Ts framework with a reverse engineering approach, airlines gain a comprehensive, interconnected perspective on digital transformation. This perspective highlights how strategic vision, technical capabilities, infrastructural readiness, and workforce competence must evolve in concert. Mapping these interdependencies enables decision-makers to prioritise interventions that yield benefits across multiple domains, avoid redundancy, and anticipate operational bottlenecks before they arise. Rather than addressing isolated problems in silos, this integrated view supports the design of coherent, system-wide transformation pathways that strengthen organisational agility, scalability, and long-term competitiveness in an increasingly digital aviation environment.

4. Critical Evaluation

This research makes a distinct contribution to the academic and industry discourse on aviation digital transformation. It shifts the analytical focus away from isolated technological innovations toward the systemic processes that determine their adoption, integration, and long-term sustainability. Existing literature has increasingly documented the implementation of solutions such as AI-enabled predictive maintenance, biometric passenger identification, and blockchain-based logistics. More recent studies highlight next generation retailing innovations like Offer and Order Management enabled through IATA's (International Air Transport Association) NDC and One Order standards, as well as dynamic pricing and digital twin applications (Amadeus, 2024; Ndhlovu, Makuyana & Dube, 2024; Sabre, 2024; PROS, 2024; IATA, 2023b; Mızrak & Akkartal, 2023; McGrath & McManus, 2020). However, most studies stop short of interrogating the organisational and cultural ecosystems in which these technologies must operate. Without that context, findings often overstate potential benefits and understate the operational and human constraints that can derail adoption (Vial, 2019; Trenerry et al., 2021).

The reverse engineering-based 4Ts framework addresses this oversight by explicitly situating innovation within a network of dependencies i.e. Transformation, Technology, Tools, and Talent where each domain interacts dynamically with the others. This represents a methodological and conceptual advancement over traditional change management approaches.

Conventional frameworks such as Kotter's 8-Step model or McKinsey's 7-S place strong emphasis on leadership, change execution, and organisational alignment (Kotter, 2012). While these models are valuable for structuring change initiatives, they often lack a diagnostic component for mapping operational interdependencies or uncovering technical constraints. The 4Ts framework goes further by integrating technical architecture, workforce readiness, and governance structures into a single evaluative model. This ensures that transformation strategy is not treated as an abstract vision but as a roadmap tethered to specific infrastructural and human realities (van de Wetering, Mikalef, & Pateli, 2021).

One of the framework's most important insights is that no single pillar can drive innovation in isolation. Technologies without supportive tools for instance, AI models deployed in an outdated Passenger Service System (PSS) will fail to deliver intended efficiencies (Sabre, 2024). Similarly, tools without skilled talent will be underutilised, and transformation strategies without cultural readiness risk being reduced to superficial compliance (Zaoui & Souissi, 2020). By explicitly recognising this synergy, the framework offers a corrective to piecemeal approaches, which often manifest as disconnected pilots, redundant system upgrades, or underperforming customer experience platforms.

From a methodological standpoint, the study distinguishes itself by combining qualitative and quantitative evidence in a way that mitigates common biases in transformation research. Many digital adoption studies rely heavily on executive self-reporting, which risks painting an overly optimistic picture of readiness and capability (Sebastian et al., 2017). By integrating 17 expert interviews with 393 global survey responses, this research generates a more balanced view, one that captures vertical misalignments between leadership perceptions and operational realities.

The finding that executives frequently believe digital tools to be "fully adopted" while frontline staff report limited usability and inadequate training is particularly telling. This reflects a perception gap frequently observed in transformation research: executives often equate system rollout with adoption, relying on deployment milestones or vendor reports, whereas frontline staff judge adoption through usability, workflow fit, and adequacy of training. When these elements are lacking, employees may underutilise tools, resort to workarounds, or disengage from digital processes altogether, resulting in superficial rather than substantive uptake (Sebastian et al., 2017; Ghobakhloo & Iranmanesh, 2021; Hizam et al., 2025). These gaps reveal a frequent oversight in digital transformation: assuming technology alone delivers value, while lasting benefits also depend on organisational readiness and human factors.

The diagnostic strength of reverse engineering lies in its ability to move beyond surface-level failure symptoms to uncover root causes. Issues such as vendor lock-in often stem not just from procurement decisions but from earlier architectural choices that limit interoperability and flexibility (Kabashkin, 2024). Similarly, technical debt, the accumulation of outdated systems and manual workarounds often reflects years of underinvestment in infrastructure rather than shortcomings in a single project. Skill deficits can arise not only from insufficient training but also from mismatches between hiring strategies and emerging digital demands (Wiblen & Marler, 2021; Banerjee & Sharma, 2024).

By tracing these problems back to their structural origins, the framework enables more targeted intervention design. For instance, an airline facing persistent delays in integrating ancillary revenue systems might discover through reverse engineering that the bottleneck lies not in vendor responsiveness but in its own lack of API governance protocols. This diagnostic depth positions the framework as both analytical i.e. capable of mapping systemic complexity and actionable i.e. offering concrete levers for change.

Another critical value lies in the framework's applicability across transformation phases. Unlike many models that are primarily prescriptive at the outset of change initiatives, the 4Ts reverse engineering approach remains relevant in mid-implementation and post-deployment audits. Airlines can use it to assess whether initial gains are sustainable, whether new bottlenecks have emerged, and whether the talent base remains aligned with evolving tools and technologies. This makes it not just a planning guide but a continuous improvement mechanism, similar in philosophy to lean management cycles but tailored to the complexities of aviation's digital ecosystems (Queiroz & Wamba, 2022).

The framework also helps mitigate the technology trap, the tendency to overinvest in headline-grabbing innovations without addressing the less visible infrastructural and cultural work required for success (Berman, 2012). This is particularly relevant in aviation, where the temptation to match competitors', digital offerings can lead to fragmented systems that burden rather than enable staff (Lavskaya et al., 2024). By enforcing a systemic readiness check before major investments, the approach protects against wasted capital and operational disruption.

Importantly, the 4Ts model and reverse engineering methodology also fill a research gap in longitudinal understanding. While many transformation studies capture a moment-in-time assessment, this approach lends itself to tracking evolution over multiple innovation cycles. This is vital for an industry in which regulatory changes, market shocks, and emergent technologies continually reshape priorities (Mızrak & Akkartal, 2023; Yıldız & Mazıoğlu, 2025).

In summary, the critical value of this research lies in its ability to bridge theoretical frameworks with operational realities. By embedding systemic analysis into transformation planning and execution, it equips aviation stakeholders with the tools to not only diagnose why change is failing but to design interventions that maximise the probability of success. In doing so, it advances both scholarly understanding and practical capability in one of the world's most complex and operationally demanding industries.

5. Conclusion

This study makes a substantive contribution to the evolving discourse on digital transformation in commercial aviation by presenting a reverse engineering-based framework anchored in the 4Ts model i.e. Transformation, Technology, Tools, and Talent. Unlike conventional, linear models of technology adoption, the 4Ts approach recognises that these domains do not exist in isolation but form a tightly interlinked system, where progress or deficiencies in one domain have cascading effects on the others. By viewing transformation as a mutually connected and iterative process, the framework provides aviation stakeholders with a comprehensive diagnostic tool. It supports the strategic planning, implementation, and expansion of innovation initiatives. At the same time, it ensures these initiatives remain closely aligned with operational realities (van de Wetering, Mikalef, & Pateli, 2021).

A central insight emerging from this research is that digital transformation extends far beyond the acquisition of new systems. The mere deployment of cutting-edge technologies whether in customer service, modern retailing, predictive maintenance, or operational planning, does not guarantee improved outcomes if the supporting processes, infrastructure, and workforce capabilities are not simultaneously aligned (Berman, 2012; Vial, 2019). By embedding reverse engineering principles into the transformation lifecycle, airlines can deconstruct existing workflows, identify interdependencies, and reveal hidden friction points that might otherwise derail the initiative. This diagnostic capacity makes the framework equally applicable at the pre-implementation, mid-course correction, and post-deployment evaluation stages.

The empirical findings reinforce the gap between adoption and integration. While most airlines surveyed have initiated some form of digital modernisation, often through investments in AI-driven customer engagement tools, mobile platforms, modern digital retailing or predictive maintenance systems, only a minority have achieved full integration across channels and operations. This shortfall is particularly evident in the disconnect between customer-facing digital innovations and backend operational systems, where legacy architectures, vendor lock-in, and siloed data environments inhibit the realisation of seamless service experiences (Sabre, 2024; Ndhlovu, Makuyana, & Dube, 2024).

The reverse engineering methodology proves valuable in mapping these integration barriers. By systematically auditing digital maturity and assessing alignment with enterprise-wide objectives, the approach enables airlines to realign fragmented initiatives into a coherent transformation strategy. This, in turn, enhances agility, fosters interoperability, and supports scalability, all of which are essential in an industry where market dynamics, regulatory pressures, and customer expectations evolve rapidly (Queiroz & Wamba, 2022; Yıldız & Mazıoğlu, 2025).

Survey and interview data underscore three critical enablers for successful transformation: cultural readiness, cross-functional collaboration, and leadership alignment. Without a culture that embraces continuous learning and adaptability, even the most sophisticated technological investments risk stagnation (Trenerry et al., 2021; Banerjee & Sharma, 2024). Cross-functional collaboration ensures that transformation objectives are shared across organisational silos, enabling a unified approach to both customer experience and operational efficiency. Leadership alignment, meanwhile, is crucial for ensuring that resource allocation, performance metrics, and change management strategies reinforce rather than conflict with transformation goals (Porfírio et al., 2021).

One of the key strengths of the reverse engineering-based 4Ts framework is its ability to surface hidden frictions, barriers that are not readily apparent in standard performance reports. For instance, a system considered 'fully rolled out' at the executive level may still encounter resistance in daily operations, where frontline employees struggle with practical issues such as training adequacy, workflow alignment, or tool usability. The framework helps surface these hidden frictions that traditional reports often overlook. Such misalignments are common in aviation, where the operational environment is complex, multi-layered, and heavily regulated (Sebastian et al., 2017). By highlighting these discrepancies, the framework empowers decision-makers to design targeted interventions that address root causes rather than symptoms.

The framework also has significant forward-looking value. While many transformation models are primarily reactive i.e. applied after a problem emerges, the reverse engineering approach can be integrated into future innovation cycles to pre-emptively identify risks and dependencies. This proactive capability allows airlines to pace transformation efforts, ensuring that readiness levels across all four pillars are synchronised before major deployments. By doing so, they can avoid redundant investments, reduce the likelihood of project failure, and ensure that digital initiatives reinforce rather than undermine long-term strategic goals (Ghobakhloo & Iranmanesh, 2021).

This research identifies several limitations that should be considered when interpreting the results. The aviation industry is currently facing rapid technological advancements, which implies that the trends highlighted in this study may change swiftly, potentially affecting the long-term relevance of some findings. Additionally, constraints related to time, funding, and the reliance on interviews may have shaped the depth and scope of the insights obtained. Such reliance on qualitative insights introduces the risk of perception bias, particularly in areas like cultural readiness or the extent of system integration. While the study utilised surveys and interviews to balance viewpoints from various stakeholders, future research could benefit from the inclusion of multi-source data triangulation, encompassing operational performance metrics, technology utilisation analytics, and customer experience indicators (Vial, 2019; Hizam et al., 2025). This would facilitate a more objective validation of perceived outcomes and help mitigate the risks of over-reliance on self-reported data.

A further limitation concerns the scope of the 4Ts framework. While it provides a useful diagnostic structure for examining digital transformation in aviation, it does not explicitly account for environmental, regional, or regulatory contexts. Transformation pathways are often shaped by these external factors. For instance, airlines in heavily regulated markets may face slower adoption due to compliance obligations, whereas carriers in emerging markets may struggle with limited capital but can sometimes leapfrog legacy infrastructure altogether, adopting modular, cloud-based solutions (Mızrak & Akkartal, 2023). The absence of such contextual integration limits the framework's universality. Future research could address this gap by adapting the 4Ts model to incorporate these dimensions, enabling more situationally aware and context-sensitive transformation strategies.

In closing, this article lays a foundational pathway for aviation stakeholders seeking to navigate digital transformation with clarity, cohesion, and strategic intent. By marrying the systemic interdependency mapping of the 4Ts framework with the forensic diagnostic power of reverse engineering, it provides both an analytical lens and a practical toolkit for aligning processes, infrastructure, and human capital. In doing so, it offers the aviation industry a route not merely to adopt technology, but to embed it in ways that sustain competitive advantage in an era defined by rapid technological change, shifting passenger expectations, and relentless operational pressures.

References

1. Airframe Designs (2018) What is aerospace reverse engineering? Available at: https://www.airframe-designs.com/ (Accessed: 02 August 2025).
2. Alnoor, A., Atiyah, A.G. and Abbas, S. (2024) 'Unveiling the determinants of digital strategy adoption in aviation', Global Journal of Flexible Systems Management, 25(2), pp. 243–260. Available at: https://doi.org/10.1007/s40171-024-00385-0
3. Amadeus (2024) 'How AI-based biometric algorithms are reshaping the travel experience', 3 November. Available at: https://amadeus.com/ (Accessed: 06 August 2025).
4. Annaç Göv, S. (2023) Air transportation management and the effects of digital transformation strategies. Bingley: Emerald Insight. Available at: https://www.emerald.com/ (Accessed: 27 August 2025).
5. Asif, I. (2013) Airline operational efficiency: A systems perspective [Special topic paper, Embry-Riddle Aeronautical University]. Academia.edu. Available at: https://www.academia.edu/ (Accessed: 11 August 2025).
6. Aroles, J., Cecez-Kecmanovic, D., Dale, K., Kingma, S.F. and Mitev, N. (2021) 'New ways of working: A critical review and research agenda', Information and Organization, 31(4), p. 100378. DOI: https://doi.org/10.1016/j.infoandorg.2021.100378
7. Auer, F., Lenarduzzi, V., Felderer, M. & Taibi, D. (2021) 'From monolithic systems to microservices: An assessment framework', Information and Software Technology, 137, Article 106600. DOI: https://doi.org/10.1016/j.infsof.2021.106600
8. Aviation Business Middle East (2024) 'How predictive maintenance is revolutionising the Middle East MRO industry', Aviation Business Middle East, 18 April. Available at: https://www.aviationbusinessme.com / (Accessed: 4 October 2025).
9. Aviation Week Network (2020) 'Airlines using predictive maintenance reap big benefits', Aviation Week Network, 5 April. Available at: https://aviationweek.com / (Accessed: 4 October 2025).
10. Banerjee, P. and Sharma, N. (2024) 'Digital transformation and talent management in Industry 4.0', The Learning Organization. DOI: https://doi.org/10.1108/TLO-10-2023-0183
11. Bansal, A., Panchal, T., Jabeen, F., Mangla, S.K. and Singh, G. (2023) 'Human resource digital transformation', Journal of Business Research, 157, p. 113611. DOI: https://doi.org/10.1016/j.jbusres.2022.113611
12. Berman, S.J. (2012) 'Digital transformation and business models', Strategy & Leadership, 40(2), pp. 16–24. DOI: https://doi.org/10.1108/10878571211209314
13. Brelje, B.J. and Martins, J.R.R.A. (2019) 'Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches', Progress in Aerospace Sciences, 104, pp. 1–19. DOI: https://doi.org/10.1016/j.paerosci.2018.06.004
14. Business Wire (2025) 'Lufthansa Group expands AI-based dynamic pricing with PROS', 28 January. Available at: https://www.businesswire.com / (Accessed: 9 September 2025).
15. Ciampi, F., Faraoni, M., Ballerini, J. and Meli, F. (2022) Digitalization and organizational agility.

Available at: https://research.vu.nl/ (Accessed: 18 August 2025).
16. DigitalDefynd (2025) 5 digital transformation in aviation case studies. Available at: https://digitaldefynd.com/ (Accessed: 12 August 2025).
17. DLA Aviation (2020) Reverse engineering in aerospace logistics. Available at: https://www.dla.mil/ (Accessed: 04 August 2025).
18. Engine Service Design (2021) Six ways to improve customer experience in aviation. Available at: https://www.linkedin.com/ (Accessed: 19 August 2025).
19. Exploring Digital Aviation (2025) 'Exploring the barriers and accelerators of digital adoption in aviation', 19 May. Available at: https://www.exploringdigitalaviation.com/ (Accessed: 13 August 2025).
20. Fedorov, R. and Perekrestov, V. (2025) 'Decision making framework for aviation safety in predictive maintenance strategies', Applied Sciences, 15(3), p. 1626. DOI: https://doi.org/10.3390/app15031626
21. Ghobakhloo, M. and Iranmanesh, M. (2021) 'Digital transformation success under Industry 4.0: a strategic guideline for manufacturing SMEs', Journal of Manufacturing Technology Management, 32(8), pp. 1533–1556. DOI: https://doi.org/10.1108/JMTM-11-2020-0455
22. Hess, T., Matt, C., Benlian, A. & Wiesböck, F. (2016) 'Options for formulating a digital transformation strategy', MIS Quarterly Executive, 15(2), pp. 123–139. Available at: https://aisel.aisnet.org/misqe/vol15/iss2/6 / (Accessed: 4 October 2025).
23. Hizam, S.M., Akter, H., Ahmed, W. and Sentosa, I. (2025) 'Assimilating talent centric approaches to digital workplace engagement behaviours', SA Journal of Human Resource Management, 23, p. a2947. DOI: https://doi.org/10.4102/sajhrm.v23i0.2947
24. International Air Transport Association (2018) Blockchain in aviation: Exploring the fundamentals, use cases, and industry initiatives. Available at: https://www.iata.org/ (Accessed: 09 August 2025).
25. International Air Transport Association (IATA) (2023a) Modern airline retailing – a business case. International Air Transport Association. Available at: https://www.iata.org/ (Accessed: 12 August 2025).
26. International Air Transport Association (IATA) (2023b) Servicing in New Distribution Capability (NDC) – where are you? International Air Transport Association. Available at: https://www.iata.org/ (Accessed: 14 August 2025).
27. International Air Transport Association (IATA) (2024) Insights from the IATA Publications 2024: The rise of the digital traveler. International Air Transport Association (IATA) Knowledge Hub. Available at: https://www.iata.org/ (Accessed: 17 August 2025).
28. Ieva, M. and Ziliani, C. (2018) 'Mapping touchpoint exposure in retailing: Implications for developing an omnichannel customer experience', International Journal of Retail & Distribution Management, 46(3), pp. 304–322. DOI: https://doi.org/10.1108/IJRDM-04-2017-0097
29. Ismail, M.H.A., Khater, M. and Zaki, M. (2017) Digital business transformation and strategy: What do we know so far? Working Paper, Cambridge Service Alliance, University of Cambridge. Available at: https://cambridgeservicealliance.eng.cam.ac.uk/ (Accessed: 10 August 2025).
30. Kabashkin, I. (2024) 'Digital Twin Framework for Aircraft Lifecycle Management Based on Data Driven Models', Mathematics, 12(19), p. 2979. DOI: https://doi.org/10.3390/math12192979
31. Kıyıklık, A., Kuşakcı, A.O. and Mbowe, B. (2022) 'A digital transformation maturity model for the airline industry with a self-assessment tool', Decision Analytics Journal, 3, p. 100055. DOI: https://doi.org/10.1016/j.dajour.2022.100055
32. Kotter, J.P. (2012) Leading Change: With a New Preface by the Author. Boston, MA: Harvard Busi

ness Review Press. ISBN 9781422186435. Available at: https://hbsp.harvard.edu/product/11116-PDF-ENG (Accessed: 4 October 2025).
33. Kovynyov, I. and Mikut, R. (2018) Digital transformation in airport ground operations. arXiv preprint arXiv:1805.09142. DOI: https://doi.org/10.48550/arXiv.1805.09142
34. Langer, A.M. (2023) Information Technology and Organizational Learning: Managing Behavioral Change in the Digital Age. 4th edn. CRC Press. DOI: https://doi.org/10.1201/9781003315896
35. Lavskaya, K., Barykin, S., et al. (2024) 'Digital platforms and ecosystems in air passenger transportations', in Barykin, S., Sergeev, S. and Bochkarev, A. (eds.) Digital transformation and global society. Cham: Springer. Available at: https://link.springer.com/ (Accessed: 07 August 2025).
36. Lee, D.S., Fahey, D.W. and Forster, P.M. (2021) 'The contribution of global aviation to climate change', Atmospheric Environment, 244, p. 117834. DOI: https://doi.org/10.1016/j.atmosenv.2020.117834
37. Lee, J., Lapira, E., Bagheri, B. and Kao, H.A. (2013) 'Recent advances and trends in predictive manufacturing systems in big data environment', Manufacturing Letters, 1(1), pp. 38–41. DOI: https://doi.org/10.1016/j.mfglet.2013.09.005
38. Ma, S., Flanigan, K.A. and Bergés, M. (2024) State-of-the-art review: The use of digital twins to support artificial intelligence–guided predictive maintenance. arXiv. DOI: https://doi.org/10.48550/arXiv.2406.13117
39. Matt, C. and Benlian, A. (2015) 'Digital Transformation Strategies', Business & Information Systems Engineering, 57(5), pp. 339–343. DOI: https://doi.org/10.1007/s12599-015-0401-5
40. McGrath, R.G. and McManus, R. (2020) 'Discovery Driven Digital Transformation: Learning your way to a new business model', Harvard Business Review, May–June. Available at: https://hbr.org/ (Accessed: 24 August 2025).
41. McKinsey & Company (2018) 'Walk before you fly: Capturing the digital opportunity in airlines', 28 June. Available at: https://www.mckinsey.com/ (Accessed: 23 August 2025).
42. Mızrak, F. and Akkartal, G.R. (2023) 'Strategic management of digital transformation processes in the aviation industry: Case of Istanbul Airport', in Rahman, S.A. (ed.) Cases on enhancing business sustainability through knowledge management systems. IGI Global. Available at: https://www.igi-global.com/ (Accessed: 28 August 2025).
43. Montero Guerra, J.M. (2023) 'Talent management in digital transformation', in Machado, C. and Davim, J.P. (eds.) Management for Digital Transformation. Cham: Springer, pp. 61–82. DOI: https://doi.org/10.1007/978-3-031-42060-3_3
44. Ndhlovu, E., Makuyana, T. and Dube, K. (2024) 'The state of hi-tech innovation in the global aviation industry', in Tourism and Hospitality for Sustainable Development, pp. 87–107. Springer. DOI: https://doi.org/10.1007/978-3-031-63069-9_6
45. Pantano, E., Priporas, C.V. & Dennis, C. (2018) 'A new approach to retailing for successful competition in the new smart scenario', International Journal of Retail & Distribution Management, 46(3), pp. 264–282. DOI: https://doi.org/10.1108/IJRDM-04-2017-0080
46. Pilon, R.V. (2023) Artificial Intelligence in Commercial Aviation: Use Cases and Emerging Strategies. Routledge. DOI: https://doi.org/10.4324/9781003018810
47. Porfírio, J.A., Carrilho, T., Felício, J.A. & Jardim, J. (2021) 'Leadership characteristics and digital transformation', Journal of Business Research, 124, pp. 610–619. DOI: https://doi.org/10.1016/j.jbusres.2020.10.058

48. PROS (2024) Airline offer and order management: A new era. Available at: https://pros.com/ (Accessed: 03 August 2025).
49. Queiroz, M.M. and Wamba, S.F. (2022) Managing the digital transformation: Aligning technologies, business models, and operations. 1st edn. CRC Press. DOI: https://doi.org/10.1201/9781003226468
50. Rozesara, M. (2023) 'A reverse engineering-based model for innovation process in complex product systems: Multiple case studies in the aviation industry'. Journal of Engineering and Technology Management, 69, p.101765. DOI: https://doi.org/10.1016/j.jengtecman.2023.101765
51. Sabre (2024) Why airlines must care about offer and order management. Sabre white paper. Available at: https://www.sabre.com/ (Accessed: 08 August 2025).
52. Salesforce (2022) 'State of Sales, 4th Edition'. Salesforce Research. Available at: https://www.salesforce.com/research/ (Accessed: 9 September 2025).
53. Schallmo, D.R.A. (2024) Digital disruption and transformation. Springer. Available at: https://www.springerprofessional.de/ (Accessed: 14 August 2025).
54. Sebastian, I.M., Ross, J.W., Beath, C., Mocker, M., Moloney, K.G. & Fonstad, N.O. (2017) 'How big old companies navigate digital transformation', MIS Quarterly Executive, 16(3), pp. 197–213. Available at: https://aisel.aisnet.org/misqe/vol16/iss3/6/ (Accessed: 4 October 2025).
55. Shiwakoti, N., Hu, Q., Pang, M.K., Cheung, T.M., Xu, Z. and Jiang, H. (2022) 'Passengers' perceptions and satisfaction with digital technology adopted by airlines during COVID-19 pandemic', Future Transportation, 2(4), pp. 988–1009. DOI: https://doi.org/10.3390/futuretransp2040055
56. SpringerLink (2022) Aircraft financial and operational efficiencies. Available at: https://link.springer.com/ (Accessed: 20 August 2025).
57. Stanton, I., Munir, K., Ikram, A. and El Bakry, M. (2022) 'Predictive maintenance analytics and implementation for aircraft: Challenges and opportunities', Systems Engineering, 25(4), pp. 404–416. DOI: https://doi.org/10.1002/sys.21651
58. Sun, X., Wandelt, S. and Zhang, A. (2022) 'A data-driven analysis of the aviation recovery from the COVID-19 pandemic', Journal of Air Transport Management, 109, Article 102401. DOI: https://doi.org/10.1016/j.jairtraman.2023.102401
59. Tan, J. H. & Masood, T. (2021) Industry 4.0: challenges and success factors for adopting digital technologies in airports. Pre-print, Ithaca, N.Y. DOI: https://doi.org/10.48550/arXiv.2112.14574
60. Tapia, F., Mora, M.Á., Fuertes, W., Aules, H., Flores, E. & Toulkeridis, T. (2020) 'From Monolithic Systems to Microservices: A Comparative Study of Performance', Applied Sciences, 10(17), article 5797. DOI: https://doi.org/10.3390/app10175797
61. Thums, J., Künzel, L., Klumpp, M., Bardmann, M.-M. and Ruiner, C. (2023) 'Future air transportation and digital work at airports – Review and developments', Transportation Research Interdisciplinary Perspectives, 19, 100808. DOI: https://doi.org/10.1016/j.trip.2023.100808
62. Trenerry, B., Ross, J., Fletcher, B.C., Renzaho, A. and Dow, B. (2021) 'Preparing workplaces for digital transformation: An integrative review', Frontiers in Psychology, 12, p. 620766. DOI: https://doi.org/10.3389/fpsyg.2021.620766
63. van de Wetering, R., Mikalef, P. and Pateli, A. (2021) 'Strategic alignment between IT flexibility and dynamic capabilities: An empirical investigation', arXiv. DOI: https://doi.org/10.48550/arXiv.2105.08429
64. Vial, G. (2019) 'Understanding digital transformation', Journal of Strategic Information Systems, 28, pp. 118–144. DOI: https://doi.org/10.1016/j.jsis.2019.01.003

65. Vuksic, V.B., Ivancic, L. and Vugec, D.S. (2018) 'A preliminary literature review of digital transformation case studies', in Proceedings of the 20th International Conference on Managing Information Technology, pp. 952–957. World Academy of Science, Engineering and Technology (WASET). DOI: https://doi.org/10.5281/zenodo.1474581
66. Westerman, G., Bonnet, D. & McAfee, A. (2014) Leading Digital: Turning Technology into Business Transformation. Harvard Business Review Press, Boston, MA.
67. Wiblen, S. & Marler, J.H. (2021) 'Digitalised talent management and automated talent decisions: The implications for HR professionals', The International Journal of Human Resource Management, 32(12), pp. 2592–2621. DOI: https://doi.org/10.1080/09585192.2021.1886149
68. Yıldız, B. and Mazıoğlu, V. (2025) 'The impact of digital transformation on innovativeness in airline companies: The role of agility and openness to change', Journal of Aviation, 9(2), pp. 454–466. Available at: https://dergipark.org.tr/ (Accessed: 16 August 2025).
69. Zamora Iribarren, M., Garay Rondero, C.L., Lemus Aguilar, I. and Peimbert García, R.E. (2024) 'A review of Industry 4.0 assessment instruments for digital transformation', Applied Sciences, 14(5), Article 1693. DOI: https://doi.org/10.3390/app14051693
70. Zaoui, F. and Souissi, N. (2020) 'Roadmap for digital transformation: A literature review', Procedia Computer Science, 175, pp. 621–628. DOI: https://doi.org/10.1016/j.procs.2020.07.090