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# AVIATION 5.0: CATALYST FOR WORKFORCE SUSTAINABILITY

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**Abstract.** This paper introduces Aviation 5.0 as an industry-specific instantiation of the Industry 5.0 paradigm, constituted by three interdependent principles: human-centricity, sustainability, and resilience, reinterpreted within aviation's distinctive operational, regulatory, and safety context. Building on the historical evolution from Aviation 1.0 to 4.0, and through a synthesis of Industry 5.0 literature and aviation-specific research, the paper develops a five-layer conceptual framework that structures the relationships between core principles, enabling technologies, aviation domains, system outcomes, and continuous alignment. Aviation 5.0 is explicitly distinguished from Aviation 4.0, which pursued efficiency through digital transformation, by its value-driven orientation: it asks not what technology can do, but what technology should do and for whom, within boundary conditions defined by safety primacy, internationally coordinated regulation, and certified human capital. The framework is applied to workforce sustainability as the critical domain where these principles are most urgently needed. Focusing on three core dimensions (workforce supply and continuity, training quality and adaptability, and worker well-being, inclusion and organizational support). The paper examines how demographic shifts, technological disruption, and declining career attractiveness threaten the industry, and demonstrates how enabling technologies can drive positive workforce outcomes across ecosystem levels. The paper concludes with policy, practice, and research recommendations to operationalize the framework globally, positioning Aviation 5.0 as a foundation for future empirical research and a catalyst for a more resilient, inclusive, and future-ready aviation industry.

**Keywords:** Aviation 5.0, human-centric, sustainability, resilience, workforce development, emerging technologies.

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## 1. Introduction

Each Industrial Revolution is characterized by significant changes in technology, production, and society brought about by groundbreaking innovations that redefine the way people live and work. Industry 4.0 focused on automation, digitization, and cyber-physical systems to improve efficiency and productivity. However, it lacked some fundamental human and environmental considerations, especially in addressing human well-being, sustainability, and system resilience. Industry 5.0 has very recently emerged to address these gaps, and shifting the focus from purely technological advancement to value-driven, human-centric innovation. Aviation, as one of the biggest and most complex global industries, faces challenges similar to the broader industrial context such as workforce shortages, environmental pressures, and rapidly evolving technology, as well as its own unique demands, including stringent safety requirements, international regulatory coordination and infrastructure dependency. Aviation 4.0's digital transformation lacks full integration of social and environmental priorities, making it inadequate to address global challenges. Drawing from Industry 5.0, this paper introduces the Aviation 5.0 framework which aligns aviation innovation with societal values. The paper first presents a brief historical roadmap from Aviation 1.0 to 5.0 to contextualize this evolution and focuses specifically on the relationship between this newly introduced framework and workforce development in the aviation industry. The paper explores enabling technologies and their applications across aviation domains. In particular, it is focused on workforce sustainability as it represents a major challenge within the industry and a critical domain where human-centric, resilient, and inclusive approaches are urgently needed. The paper aims to provide a strategic framework for guiding aviation toward a more inclusive, adaptive, and future-ready paradigm supporting workforce sustainability.

## 2. A brief definition of Industry 5.0

The need for Industry 5.0 arose from the changing societal and geopolitical landscape that resulted in a need to more effectively incorporate social and environmental considerations into technological innovation and production. Since 2015, there have been some efforts to define and introduce the Fifth Industrial Revolution. It was only after the European Commission formally introduced the concept through a series of discussions and documents in 2020–2021, that a growing interest in the Industry 5.0 framework emerged, both in academia and industry. This new framework is defined as an evolution and logical continuation of Industry 4.0 rather than a replacement or an alternative. Figure 1 summarizes the evolution from the first Industrial Revolution through to the Industry 5.0 paradigm. In contrast to previous Industrial Revolutions, Industry 5.0 is not technology-driven; rather, it focuses not on the technologies available, but on developing a new understanding of how technology can be leveraged to benefit society without compromising human well-being or the health of the planet. Thus, it is the first Industrial Revolution that can be characterized as value-driven, focusing not only on maximizing productivity and profits, but also on ensuring that technologies contribute to a more sustainable, inclusive, and human-centric future for all (Coelho et al., 2023; European Commission, 2021; Xu et al., 2021).

The core values of Industry 5.0 are identified as sustainability, human-centricity, and resilience. It redefines technology as an enabler, not a replacement for human capabilities. The main idea is to integrate advanced technologies such as artificial intelligence (AI), robotics and cyber-physical systems to promote sustainable, personalized, and efficient industrial processes. Human-centricity prioritizes human well-being, empowerment, and collaboration in industrial processes, shifting from mass automation to personalized, human-driven production. It creates safe, inclusive work environments that prioritize health, dignity, and privacy. Technology should serve people and society, adapting to industry workers' needs through continuous upskilling and reskilling for better career opportunities and work-life balance. Sustainability emphasizes respecting planetary boundaries and promoting sustainable practices in industrial production for long-term ecological balance. Resilience focuses on developing robust industrial systems that can withstand disruptions and support critical infrastructure during crises, requiring agile and adaptable technology (European Commission, 2021; Xu et al., 2021).

Through workshops with Europe's technology leaders, the European Commission identified the enabling technologies of Industry 5.0 as follows (European Commission, 2020):

- Human-centric solutions and human-machine-interaction technologies: Enhancing collaboration between humans and machines.
- Bio-inspired technologies and smart materials: Creating recyclable materials with embedded sensors and enhanced features.
- Real-time based digital twins and simulation: Modeling entire systems for better analysis and optimization
- Artificial Intelligence: Detecting causalities in complex systems to generate actionable intelligence.
- Cyber safe data transmission, storage, and analysis technologies: Managing data and ensuring system interoperability.
- Technologies for energy efficiency and trustworthy autonomy: Promoting sustainable energy practices.

This framework recognizes employees as investments critical to long-term success, not just costs. It emphasizes that industries must embrace societal shifts towards core values to attract and retain qualified workers and remain competitive. While Europe has led formalization efforts around Industry 5.0, these principles are globally relevant. However, disparities in access to enabling technologies, infrastructure, and training may pose challenges in low- and middle-income countries. Future efforts should explore adapting these frameworks to diverse regional contexts.

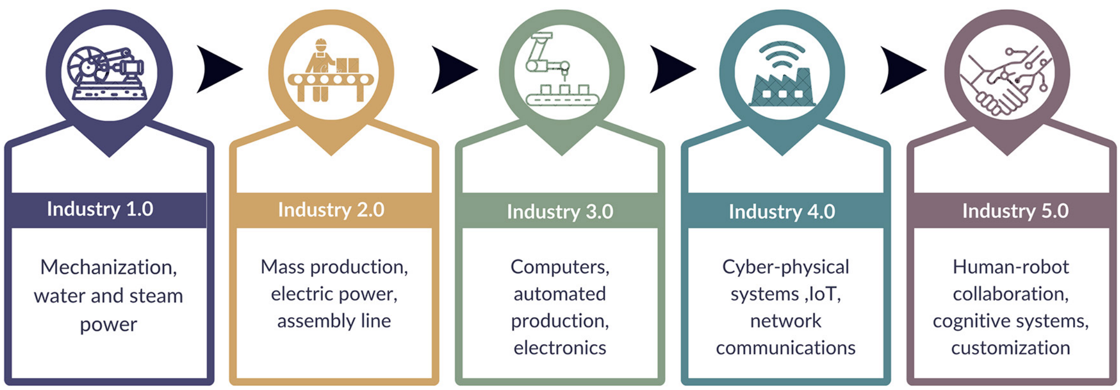


**Figure 1.** Industrial revolutions

## 3. Echoes in aviation: from Aviation 1.0 to Aviation 5.0

While the concept of Aviation 4.0 is increasingly recognized in academic and industry literature, often referring to the integration of Industry 4.0 technologies such as internet of things (IoT), cyber-physical systems, and big data into aviation operations, the full staged framework starting from Aviation 1.0 is not yet standardized (Valdes & Comendador, 2018; European Union, 2018; Büyüközkan et al., 2020; Kahraman & Aydın, 2022; Ballantine, 2024). To our knowledge, there is only Valdes and Comendador (2018) who framed these stages in terms of signal processing and automation. Their timeline offers a valuable technical perspective, but it lacks temporal anchoring and sociotechnical context (Valdes & Comendador, 2018). This paper builds upon their foundational structure and extends it by introducing Aviation 5.0 (Table 1).

Aviation has evolved in close parallel with successive industrial revolutions, moving through distinct stages of technological and operational maturation. Aviation 1.0 marked the shift from experimental flight to early commercial application (Colvin, 1993). Aviation 2.0 established structured international air transport networks and the first major airlines (Colvin, 1993; KLM Royal Dutch Airlines, n.d.; Valdes & Comendador, 2018). Aviation 3.0 ushered in the jet age and early digital integration, including fly-by-wire systems that fundamentally redistributed the role of the human operator from active control to active monitoring (Britannica, n.d.). Aviation 4.0 accelerated full digital transformation, with big data analytics, automation, collaborative decision-making, and AI beginning to reshape both operations and maintenance.

In this paper, Aviation 5.0 is conceptualized as the aviation-specific realization of Industry 5.0, grounded in three interdependent principles, human-centricity, sustainability, and resilience, adapted to aviation's unique operational, regulatory, and safety constraints. As a construct, it is distinguished from Industry 5.0 by three aviation-specific boundary conditions: first, the non-negotiable primacy of safety as an overriding systemic constraint that shapes how human-machine collaboration can be configured; second, the presence of a dense, internationally coordinated regulatory architecture that mediates the pace and form of technological adoption; and third, the structural interdependence of aviation's human capital whose certified competencies and psychological fitness are direct determinants of system safety.

Aviation 5.0 is distinct from Aviation 4.0 in that it is not technology-driven: whereas Aviation 4.0 sought efficiency and connectivity through digital transformation, Aviation 5.0 asks what technology should do, and for whom (Table 2). It reframes enabling technologies as instruments that must serve the well-being, adaptability, and long-term sustainability of the aviation workforce and the broader sociotechnical system, not merely its operational efficiency. Aviation 5.0 is not a completed state but a directional framework: a set of values and design principles that can guide decision-making across aviation domains, and against which policies, technologies, and workforce strategies can be evaluated. This paper makes a conceptual contribution through the development of a structured framework for Aviation 5.0, grounded in synthesis of literature across three bodies of knowledge, which is introduced in detail in Section 3.1.

The emergence of Aviation 5.0 is increasingly reflected in aviation policy and regulatory discourse. Human-centricity is evident in initiatives such as International Civil Aviation Organization's (ICAO) Next Generation of Aviation Professionals (NGAP) strategy, ICAO's Working Paper that focuses on integrating AI into ICAO's work programs, and European Union Aviation Safety Agency's (EASA) Artificial Intelligence Roadmap, which promote ethical AI integration and human-in-the-loop oversight (EASA, 2023; ICAO,

**Table 1.** Commercial aviation from Aviation 1.0 to Aviation 5.0

| Stage of Aviation | Characteristics |
|---|---|
| **Aviation 1.0 (1900–1919)**: Shift from invention to initial commercial application of flight. | Experimentation, with various designs and technologies being tested and the emergence of commercial aviation under visual flight rules, first scheduled commercial flight. |
| **Aviation 2.0 (1919–1950)**: Establishment of structured, global air transport networks and airline operations. | The first regularly scheduled international passenger flight, formation of airlines (KLM, Imperial Airways, Deutsche Luft Hansa), developments in aircraft design and scaled operations. |
| **Aviation 3.0 (1950s–2000s)**: Transition to jet age and early digital integration in aviation systems. | Development of modern jet engine, introduction of fly-by-wire control systems, the emergence of dependable and practical digital data processing and communication technologies that support informed decision making. |
| **Aviation 4.0 (2000s–2020s)**: Digitization of systems and processes with growing focus on efficiency and interconnectivity. | Initial efforts in full digital transformation across system. Data-driven efficiency with big data, automation and early discussions on AI implementation. Collaborative decision-making (CDM). |
| **Aviation 5.0 (2020–present)**: Human-centric, sustainable innovation addressing environmental and operational challenges. | Technologies like AI, VR/AR, and automation with a focus on workforce development and sustainability. Addressing the gap between human-machine interaction, challenges such as decarbonization, resilience, and adaptability in aviation. Personalized systems, workforce development, sustainable fuels, emissions reduction strategies. |

**Table 2.** A comparison of Aviation 4.0 and Aviation 5.0

| Dimension | Aviation 4.0 | Aviation 5.0 |
|---|---|---|
| Core orientation | Technology-driven transformation | Human-centred socio-technical transformation |
| Primary objective | Efficiency, automation, optimization, and productivity | Balanced optimization of efficiency, sustainability, resilience, and human well-being |
| Role of technology | Technology as the central driver of innovation | Technology as an enabler guided by human and societal principles |
| Human role | Humans adapt to increasingly automated systems | Technology is designed to support, augment, and empower humans |
| Workforce perspective | Focus on technical skills and operational efficiency | Focus on workforce sustainability, adaptability, inclusion, and well-being |
| Training approach | Standardized digital training and simulation | Personalized, adaptive, immersive, and lifelong learning systems |

2024, 2025). Sustainability efforts are reflected in ICAO's Long-Term Aspirational Goal (LTAG) for net-zero emissions by 2050, the integration of ESG principles into aviation operations, and ICAO's strategic objectives that align with the United Nations Sustainable Development Goals (Airports Council International [ACI], 2023; ICAO, n.d.-b, n.d.-a). Resilience considerations are similarly addressed by ICAO's Secretariat Report on Climate Adaptation and Resilience in International Aviation, and policy briefs from ACI that guide climate adaptation and disaster preparedness (ICAO, 2016; ACI, 2018).

At the operational level, Aviation 5.0 promotes a "technology for human" orientation in which technological systems are designed to augment rather than displace human capabilities. The framework emphasizes workforce safety and well-being, job satisfaction, and skills development alongside environmentally sustainable practices, such as green propulsion systems and carbon offsetting, to reduce the industry's carbon footprint on top of the integration of circular economy principles in fleet management and resource use. At the same time, it prioritizes organizational and technological adaptability to disruptions including climate change, pandemics, cyber threats, and geopolitical instability, while maintaining meaningful human involvement in safety-critical decision-making processes.

The enabling technologies of Aviation 5.0 are the same as those for Industry 5.0. Table 3 presents some example applications of each technology within the aviation context, though these applications are not limited to those listed and may evolve as technologies mature and integrate further into aviation systems. A growing body of aviation-specific research provides a strong technological foundation for the human-centric and sustainability-oriented objectives articulated in the Aviation 5.0 paradigm, even if not explicitly labeled as such. Studies on human-centered AI and human–machine teaming in aviation demonstrate how decision-support systems, adaptive automation, and explainable AI can augment operator capabilities, manage cognitive workload, and preserve human authority in safety-critical environments (Kirwan et al., 2024; Parasuraman & Wickens, 2008; Ziakkas et al., 2025). In parallel, research on digital twins, predictive analytics, and AI-enabled optimization highlights their role in improving resource efficiency, reducing emissions, and supporting sustainable operations in areas such as air traffic management, maintenance, and training (Geske et al., 2025; Yiu et al., 2021). Together, this literature indicates that enabling technologies already function as mechanisms through which human-centricity, sustainability, and resilience are operationalized in aviation systems, providing a solid empirical and theoretical foundation for the integrative framing proposed under Aviation 5.0.

While the successful implementation of these technologies is emerging, they are still at an early stage and remain limited in scope. Nevertheless, existing applications already illustrate how they can support the simultaneous realization of three core principles in aviation systems.

**Table 3.** Enabling technologies of Aviation 5.0

| Enabling Technology | Aviation 5.0 Application |
|---|---|
| Human-centric solutions and human-machine interaction | Advanced cockpits, intuitive air traffic control systems and personalized passenger services |
| Bio-inspired technologies and smart materials | Sustainable aircraft design and performance optimization |
| Real-time digital twins and simulation | Maintenance, flight operation optimization, and emergency scenario planning |
| Artificial Intelligence | Predictive analytics for flight operations and risk assessment, conflict detection and resolution, training simulators, personalized booking and dynamic pricing |
| Cyber safe data transmission and analysis | Secure handling of aviation data to prevent manipulation or loss |
| Energy efficiency and trustworthy autonomy | Green propulsion systems and reliable energy-autonomous sensors |

For example, Rolls-Royce uses its IntelligentEngine platform, a digital twin system, to continuously monitor how each engine performs in real time, taking into account operational and environmental conditions. The IntelligentEngine platform is powered by Microsoft Azure and Databricks, enabling advanced machine learning and predictive analytics to support both maintenance and sustainability goals (Olavsrud, 2021; Rolls-Royce, n.d.). The insights generated enable tailored maintenance strategies in aviation on a per-engine basis, extending time-on-wing by up to 50% and reducing the need for spare inventory. In this context, human-centricity is reflected in AI-assisted diagnostics that augment rather than replace engineering expertise, allowing for more informed and proactive decision-making. At the same time, condition-based maintenance minimizes unnecessary component replacement, improves operational efficiency, and has contributed to the reduction of over 22 million tons of carbon emissions, supporting sustainability objectives (Olavsrud, 2021). Additionally, data generated through such integrated analytics environments can support broader operational insights, including how aircrafts are flown and managed, enabling improvements in fuel efficiency and operational practices. Early fault detection further enhances system resilience by reducing unplanned downtime and strengthening operational continuity. Recently similar integrative effects are observed at the system level through platforms such as Airbus Skywise, which aggregates operational and maintenance data across fleets to support predictive maintenance and coordinated decision-making (Airbus, 2026). By enhancing situational awareness for engineers, operators, and planners, optimizing resource utilization, and enabling real-time responses to disruptions, such platforms demonstrate how enabling technologies can act as a unifying mechanism through which Aviation 5.0 principles are jointly operationalized.

More broadly, AI-supported tools are becoming increasingly widespread across aviation operations, including personalized booking and dynamic pricing, customer support and chatbots, facial recognition for check-in, baggage handling, AI-powered security screening, predictive maintenance, optimized flight operations and air traffic management, AI-powered cabin services, and lost luggage prevention (Friedman, 2025). In contrast, technologies such as green hydrogen propulsion systems, despite promising demonstrations like Airbus's ZEROe concept, remain in early development and face significant infrastructure and regulatory challenges before large-scale deployment (Airbus, 2024). Primary regulatory bodies in aviation, including IATA, ICAO, Eurocontrol, and EASA, are actively engaging with these developments, recognizing their importance for enabling a more human-centric, sustainable, and resilient aviation system (EASA, 2023; Eurocontrol, 2020).

These examples demonstrate that the components and capabilities associated with Aviation 5.0 are already emerging in practice, even though they are not explicitly conceptualized or implemented under this label. In other words, no current aviation system is deliberately designed as an "Aviation 5.0" system; rather, existing technologies and operational practices reflect partial and fragmented realizations of its underlying principles. Aviation 5.0, as defined in this study, therefore represents a conceptual integration of these developments into a coherent socio-technical framework that aligns technological innovation with human-centric, sustainable, and resilient system outcomes.

### 3.1. Aviation 5.0 as a conceptual framework

The conceptual framework rests on three bodies of literature. The first is the Industry 5.0 literature, including foundational policy documents from the European Commission and emerging academic work on the operationalization of human-centricity, sustainability, and resilience as industrial paradigm principles. The second is aviation-specific literature spanning technological transformation, human factors, workforce development, regulatory frameworks, and safety management, drawn from academic journals, institutional reports from ICAO, EASA, FAA, IATA, and Eurocontrol, and industry sources documenting current and emerging practices. The third is workforce sustainability literature from organizational behavior, occupational health, and human resource management, which provides the conceptual vocabulary and measurement indicators used to define and operationalize workforce sustainability as a construct in Section 4. The synthesis of these three bodies of literature was guided by the three Industry 5.0 principles, used as organizing categories to identify convergent themes. The resulting framework was developed through an iterative process of conceptual mapping: first positioning Aviation 5.0 as an industry-specific instantiation of Industry 5.0, then specifying the relationships between framework layers, and finally operationalizing the workforce sustainability dimension as the paper's primary analytical application. This approach follows the logic of conceptual framework development as described in theory-building literature, in which frameworks are constructed through structured synthesis rather than primary data collection, and are evaluated by their analytical clarity, internal consistency, and capacity to guide future empirical work rather than by their empirical validation at the point of introduction (Jaakkola, 2020; Oeij et al., 2024). The framework presented here is therefore explicitly positioned as a foundation for future empirical research rather than a replacement for it, and the paper's concluding section identifies the specific empirical questions that the framework generates and that subsequent studies should address.

Building on the conceptualization introduced earlier, Aviation 5.0 is operationalized in this paper as a structured framework that links principles, enabling technologies, and system-level outcomes. The framework can be understood as a structured construct for understanding how value-driven principles can be translated into aviation practices and evaluated through measurable outcomes. It explains core principles are operationalized through technologies and applied across aviation domains, while being continuously refined through feedback mechanisms. It is organized into five interconnected layers: core principles, enabling technologies, aviation domains, Aviation 5.0 outcomes, and continuous alignment. Figure 2 presents the framework schematically. The operationalization of Aviation 5.0 across these domains, and through the outcome and continuous alignment layers that follow, is structured by four interdependent ecosystem levels, following the analytical structure proposed by Oeij et al. (2024) and adapted to the aviation context. These ecosystem levels are not a property of the domains layer alone; rather, they function as a cross-cutting analytical lens that governs how domains are addressed, how outcomes are defined and measured, and how alignment is achieved in Layers 4 and 5. The scale at which an intervention is targeted determines what counts as a meaningful outcome and who is responsible for corrective action when gaps are identified. At the individual level, the framework addresses the aviation professionals, passengers, and other end users whose experiences, competencies, and interactions with technology ultimately determine whether Aviation 5.0 principles are realized in practice. At the organizational level, it addresses the airlines, air navigation service providers, maintenance and repair organizations, airports, training organizations and technology developers whose strategic decisions, investment priorities, and operational cultures shape the conditions under which Aviation 5.0 is implemented. At the industry level, it addresses the regulatory bodies, international organization whose frameworks, certification requirements, and sector-wide initiatives set the structural parameters within which organizations operate. At the societal level, it addresses the broader economic, environmental, and demographic contexts that determine the long-term conditions for sustainable aviation. This includes public expectations of safety and environmental responsibility, labor market dynamics, educational pipelines, and geopolitical factors that affect global connectivity and resilience.

The first layer defines what aviation should optimize for. It comprises the three core principles of Aviation 5.0, as inherited from the Industry 5.0 paradigm and reinterpreted within aviation's distinctive context, considering the boundary conditions mentioned earlier. In this sense, Aviation 5.0 functions as what Blumer (1954) termed a sensitizing concept, one that does not provide fixed prescriptions but offers directional guidance for approaching empirical and practical problems, a characterization explicitly adopted in parallel Industry 5.0 workforce research (Oeij et al., 2024).

The second layer identifies the technologies that enable these values. The relationship between the principles layer and the enabling technologies layer is one of mutual constraint rather than simple top-down determination. The principles guide technological deployment, while technological capabilities and limitations shape how those principles can be operationalized. Human-centricity demands that AI systems be transparent and explainable to human operators rather than functioning as opaque decision-makers. Sustainability demands that propulsion technologies, materials, and operational systems respect planetary boundaries and minimize resource consumption. Resilience demands that digital and autonomous systems maintain functionality and fail-safe properties under conditions of disruption, whether from cyber threats, extreme weather, or geopolitical instability. On the other hand, the current limitations of available technologies define the practical

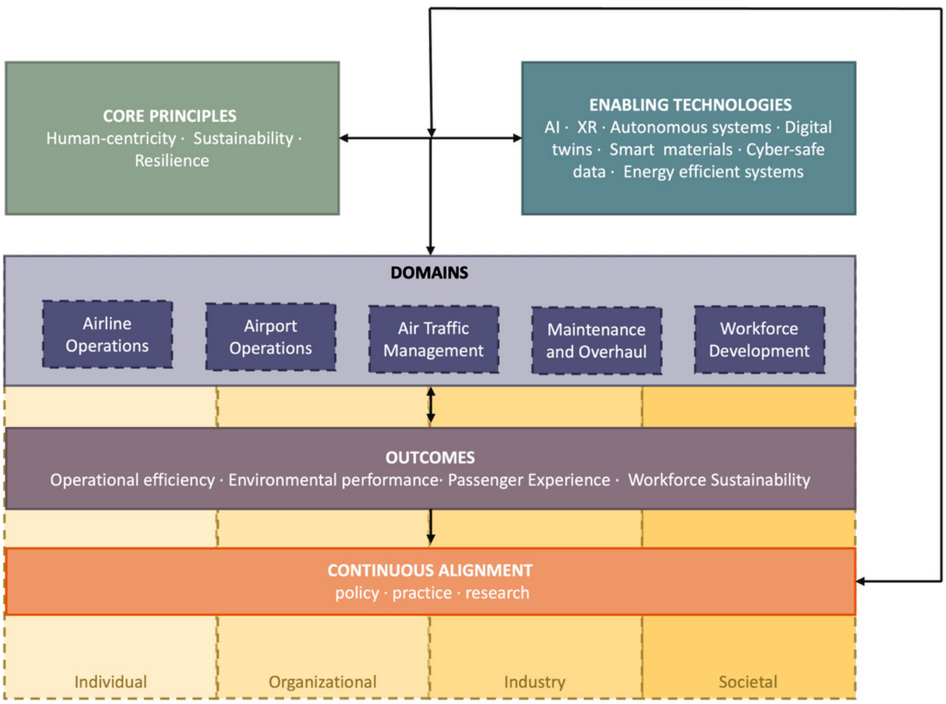


**Figure 2.** Aviation 5.0 conceptual framework

boundary within which principles can be realized at any given point in time. The human-centricity principle cannot demand full AI explainability in safety-critical flight operations if current interpretability methods cannot yet meet aviation certification standards. The sustainability principle cannot mandate hydrogen propulsion at operational scale if the supporting infrastructure and regulatory frameworks do not yet exist. The resilience principle cannot rely on fully autonomous systems if human oversight remains a certification requirement for safety assurance. This means that the framework is inherently dynamic. Importantly, these constraints and capabilities do not operate at a single scale: individual operators encounter AI limitations through interface design and workload, organizations encounter them through procurement and certification costs, industry bodies encounter them through regulatory readiness, and society encounters them through infrastructure availability and public acceptance, meaning that what is technically feasible is always ecosystem-level-dependent.

The third layer comprises the aviation domains and presents where these technologies are applied. Enabling technologies translate Aviation 5.0 principles into concrete outcomes across domains. The following examples illustrate this translation across domains, though the applications are not exhaustive and will continue to evolve as technologies mature.

In passenger experience and airport operations, efforts to promote human-centricity and sustainability can be enhanced by technologies such as human-centric solutions, human–machine interaction systems, AI, and cyber-safe data transmission and analysis. For example, biometric data and contactless technologies enable enhanced passenger experience, security and reduced congestion. At Dubai International Airport, biometric smart gates now verify travelers at security, immigration, and boarding gates without manual checks. Vancouver International Airport (YVR), Canada's first airport to launch biometric boarding, now allows travelers on select Air Canada flights and all US-bound flights to board without presenting a physical passport or boarding pass, simply by glancing at a facial recognition camera at the eGate. YVR has expanded this to 42 biometric-enabled gates, increasing boarding speed by 13 per cent. One's face is becoming their passport, ID, and boarding pass, easing multiple processes within air travel. Ninety-eight percent of airlines have either deployed biometric systems at terminals or have plans to do so and an industry standard is forming in real time. While biometric data and contactless technologies were introduced during Aviation 4.0 as part of the broader digital transformation, Aviation 5.0 builds on these foundations by embedding them within a human-centric, sustainable, and resilient framework (Regula, 2025; Sutton, 2025; CaraComp, 2026). Personalized services, such as customized offers, orders and adaptive and improved travel itineraries, further improve the travel process, ensuring a seamless and efficient airport experience. These innovations not only improve operational efficiency but also prioritize passenger well-being and safety.

For air traffic management and flight operations, Aviation 5.0 translates to more efficient, sustainable, and resilient air traffic management and flight operations. By leveraging AI technologies that support data-driven decision-making, aviation can mitigate its environmental impact by optimizing flight trajectories and reducing fuel consumption and emissions. With real-time digital twins, simulation, and AI, more effective and efficient predictive and optimization models facilitate reducing uncertainty, better planning, enhanced demand and capacity balancing, optimal resource deployment, and increased airspace capacity. Additionally, from a human-centric perspective emerging technologies like speech recognition models for air traffic controller assistance offer the potential to reduce controller workload, contributing to safer and more manageable operations.

In terms of airline operations planning and scheduling, a better matching of demand and supply is important to improve human-centricity, sustainability and resilience in air transportation services. Through data-driven, AI-enhanced decision tools that capture big data, both regular scheduling and disruption management can be conducted in a more effective way that enhances airlines' resource efficiency and passenger experience. As there is a shift in revenue management, from using preset fares and ancillaries along with booking class inventory control to quote any fare from a continuous range rather than being restricted to fixed classes, AI-based tools can enhance the efficiency of existing inventory by offering passengers more personalized options based on seat availability and ancillary services (Bülbül, 2025; Long & Belobaba, 2024). However, this shift toward dynamic pricing should align with Aviation 5.0's human-centric and ethical principles, ensuring that personalization does not lead to unjust disparities or discrimination.

Another significant domain is aircraft maintenance. As demonstrated by platforms such as Rolls-Royce's IntelligentEngine, AI-driven predictive maintenance enables early fault detection, reduces unplanned downtime, and improves operational efficiency through data-driven diagnostics. Digitalization and continuous monitoring streamline maintenance processes, leveraging data for efficiency and cost-effectiveness making use of cyber-safe data transmission and analysis technologies and AI (Eurocontrol, 2020; EASA, 2023).

Aviation 5.0 also presents significant opportunities for aviation workforce development. Human-centric solutions, human-machine interaction and simulation technologies can contribute to human-centric work and a resilient workforce. Extended Reality (XR) technologies, which encompass Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), offer immersive, interactive training environments that go beyond traditional methods. These technologies support adaptive and personalized learning experiences, enabling pilots, maintenance crews, and other operational personnel to train in realistic, data-driven scenarios at reduced cost. By simulating complex and high-risk situations in a safe environment, XR-based training has the potential to enhance decision-making, improve situational awareness, and increase overall preparedness across the aviation workforce (ICAO, 2023; Paul et al., 2025; Ross & Gilbey, 2023; VRPilot, n.d.; Loft Dynamics, n.d.). Most importantly Aviation 5.0 framework recognizes that employees are essential to long-term success. Hence, in this framework, workforce sustainability is a key focus, which is a major challenge today for the industry.

The fourth layer comprises the outcomes that Aviation 5.0 is designed to produce across its domains. Rather than optimizing for a single criterion such as efficiency or profitability, Aviation 5.0 pursues a system of interdependent outcomes that span operational, environmental, social, and human dimensions. Improvements in one dimension typically reinforce others. More sustainable operations enhance aviation's public legitimacy and career attractiveness. Better human-machine collaboration improves both safety performance and workforce well-being. More inclusive and equitable workplaces strengthen operational resilience. In addition, outcomes in Aviation 5.0 are not treated merely as end results, but as feedback signals that indicate whether principles and enabling technologies are operating as intended within and across aviation domains. Poor outcomes reveal misalignments, implementation failures, or capability gaps, thereby informing corrective adjustments to technologies, organizational practices, and policy priorities. What constitutes a meaningful outcome, and how it is measured, differs across the four ecosystem levels introduced in Layer 3. At the individual level, outcomes concern the well-being, competency development, and quality of experience of aviation professionals and passengers: indicators include mental health support utilization rates, time-to-proficiency in new roles, and self-reported job satisfaction as well as passenger-reported comfort and service satisfaction scores. At the organizational level, outcomes concern operational performance, workforce retention, and the ethical governance of technology: indicators include attrition rates disaggregated by demographic group, competency assessment outcomes, and AI audit results. At the industry level, outcomes concern sector-wide structural conditions: indicators include technology adoption and certification rates for AI and XR systems, harmonization progress across regulatory frameworks, and projected demand-supply gaps in occupational categories. At the societal level, outcomes concern aviation's relationship with the broader environment and labor market: indicators include emissions trajectories and sustainable fuel uptake, public trust indices, and the depth and diversity of educational pipelines feeding into the industry. This differentiation is not merely descriptive. It determines at which ecosystem level a corrective response must be triggered when outcome data reveals a gap, which is the function of the continuous alignment layer.

The fifth and final layer ensures continuous improvement based on outcomes. Continuous alignment functions as a structured feedback cycle: outcome data gathered across domains and ecosystem levels is evaluated against the three core principles, with identified misalignments or capability gaps triggering targeted corrective adjustments, to technology deployment, organizational practice, or regulatory standards, which are then re-monitored in the subsequent iteration. This layer addresses the claim that Aviation 5.0 is not a completed state but a directional framework requiring iterative refinement. It is at this layer that regulatory bodies update certification standards in response to emerging AI capabilities, that airlines revise training curricula in response to competency gap data, that airport operators adjust passenger service designs in response to inclusion audits, and that researchers identify the questions that the framework cannot yet answer. As Section 5.4 discusses, AI is developed and deployed by so many different actors that the "problem of many hands" arises. By systematically linking poor outcomes to a specific level of the ecosystem, Layer 5 provides a way to assign responsibility which is something aviation's accountability model demands but that AI's lack of transparency tends to obscure. The continuous alignment layer thus connects the framework back to the principles layer, not as a closed loop but as an ongoing process of value-driven adaptation.

This paper focuses on workforce sustainability in the workforce development domain where Aviation 5.0 principles are most urgently needed and least systematically developed. This domain serves as an illustrative case of Aviation 5.0 concepts. The following sections develop this application in detail, beginning with a formal definition of workforce sustainability and an analysis of the challenges currently threatening it, before examining the workforce development interventions that Aviation 5.0 makes possible and the strategic implications for policy, practice, and research.

## 4. Challenges in aviation workforce sustainability

The workforce is one of the most important drivers of efficiency and safety in the aviation industry. Human capital plays a crucial role in the industry, as organizations depend on individuals to function effectively. A healthy, motivated, and skilled workforce is essential for operational success.

Workforce sustainability is the capacity of an industry and its constituent organizations to continuously attract, develop, retain, and transition workers in ways that enable the workforce to perform its required functions effectively over time, without depleting human resources or compromising the ability of future generations to enter and thrive in the industry. It reflects both a system-level capability, ensuring alignment between workforce supply and evolving demand, and an organizational property, arising from workplace environments that support motivated, healthy, skilled, and adaptable individuals whose competencies are maintained and renewed through ongoing development (Karakhan et al., 2020; Kossek et al., 2014; Mui et al., 2025).

This definition integrates three core components. The first is workforce supply and continuity, which refers to the extent to which the workforce system maintains a sufficient and appropriately skilled labor pool to meet current and future operational needs. Its indicators include recruitment rates relative to attrition, training pipeline throughput, certification completion rates, and projected demand-supply gaps across occupational categories. The second dimension is workforce quality and adaptability which refers to degree to which workers possess current competencies and the capacity to acquire new skills as technologies, roles, and systems evolve. Measurable indicators include reskilling and upskilling participation rates, competency assessment outcomes, and the time-to-proficiency in new roles introduced by technological change. The third dimension is workforce well-being, inclusion, and organizational support which encompasses the conditions under which individuals can perform effectively and remain in the workforce over time, supported by equitable, healthy, and engaging work environments. Relevant indicators include mental health support utilization rates, occupational fatigue and burnout prevalence, attrition rates disaggregated by gender and demographic group, and representation of underrepresented groups across occupational levels. These three dimensions are interdependent: inadequate supply cannot be resolved without addressing well-being and inclusion, and adaptability cannot be achieved without investment in quality and a stable supply base (Karakhan et al., 2020; Kossek et al., 2014; Mui et al., 2025; Kefalidou et al., 2025).

These dimensions of workforce sustainability are increasingly under pressure, and these challenges must be addressed to ensure resilience, long-term safety and efficacy. The aviation industry continues to grow, rapidly recovering from the setback during the COVID-19 Pandemic. According to Boeing's Commercial Market Outlook 2024–2043, the aviation industry will require nearly 2.4 million new personnel by 2043, broken down as: 674,000 pilots, 716,000 maintenance technicians and 980,000 cabin crew members and these numbers do not include some other critical roles such as air traffic controllers and dispatchers (Boeing, 2024). With the growing demand and challenges in workforce supply, the aviation industry is experiencing a critical talent shortage across various roles, posing a significant challenge to workforce sustainability. Although this challenge was identified over a decade ago, it remains a major sustainability concern for the aviation industry (ICAO, 2011, 2024). This workforce demand is unfolding against a backdrop of structural vulnerabilities: an aging workforce, limited training capacity, and a persistent skills mismatch. Moreover, the rapid integration of automation, artificial intelligence (AI), and data-driven systems is reshaping job roles and competencies across the aviation value chain.

Major underlying drivers of workforce shortages in aviation can be grouped into three key areas: demographic and structural pressures, the impact of technological disruption on skills and job roles, and the growing difficulty of attracting and retaining talent. Each of these factors contributes to the workforce sustainability gap and highlights areas where targeted interventions are needed to build a more resilient and future-ready aviation workforce.

### 4.1. Demographic and structural pressures

The aviation industry is facing a critical demographic shift, with a substantial portion of its workforce, particularly pilots and maintenance engineers, approaching retirement age. It also continues to face persistent challenges related to a lack of diversity (Caraway, 2020; Marete & Wang, 2024). This is widening the gap between workforce supply and demand. The limited capacity of existing training systems, which are often constrained by high costs, lengthy certification processes, is also contributing to the challenge. The training pipeline remains slow and resource-intensive, making it difficult to scale up talent development in response to growing demand. Additionally, for some future careers, such as sustainable aviation fuel engineers, there is a potential lack of a training pipeline.

### 4.2. Skills mismatch and technological disruption

The aviation industry also faces challenges from rapidly advancing disruptive technologies that are reshaping work. Automation, AI, and digital systems transform existing roles, create new ones, and make some traditional functions obsolete. There is already a growing body of work on how these disruptive technologies will reshape the aviation workforce and the emergence of human-AI teaming. From air traffic controllers to pilots, aircraft technicians to ground personnel, studies foresee a reallocation of human expertise from routine execution to oversight, judgment, and emotional intelligence roles (Zaharia et al., 2021). Arrigoni and Cavagnetto (2023) highlight that the human role is not expected to change much from 2025 to 2030; human operators are still in charge of the majority of the tasks. However, the authors indicated that these five years are crucial for building trust between humans and AI in aviation, redesigning roles, and ensuring proper training for safe operation (Arrigoni & Cavagnetto, 2023). It is predicted that AI will evolve into a full team member by 2050 (Arrigoni & Cavagnetto, 2023). However, this increases the need for AI oversight, systems interpretation, and exception handling, giving rise to new responsibilities such as AI-system validation and predictive maintenance coordination (MoghadasNian, 2025). For instance, AI systems are expected to assist pilots with routine cockpit tasks such as frequency management and taxiing or support them in optimal decision-making in cases of emergencies. In air traffic control, AI can support conflict detection and communication transcription. This does not mean autonomous systems to eliminate pilots or air traffic controllers, but instead reconfiguring their role to be more supervisory, focusing on mission management and collaboration with intelligent systems. The evolution of cockpit roles (e.g., offloading monitoring tasks to external operators) will demand new models of human-AI teaming, making human-machine teaming a key competency. In technical domains such as aircraft maintenance, automation is replacing some diagnostic and repetitive tasks. Predictive maintenance tools powered by digital twins can support technicians and reduce their workload by transforming their role from manual diagnostics to proactive oversight. Traditional frontline roles like passenger service agents, flight attendants, and security agents will not be completely replaced, but will be augmented by technology, remaining vital for handling irregular scenarios and providing personal service. Automation in ground operations and passenger services is shifting staff responsibilities toward exception handling, promoting enhanced passenger satisfaction (Arrigoni & Cavagnetto, 2023; Abu Talib et al., 2025). This will require workers to adapt to new tools and processes while maintaining their core customer-oriented functions. These transitions mark a shift from routine-based work to resilience-oriented roles, where adaptability and critical thinking become essential. From a value-driven perspective, these transitions should not be viewed as replacements of human labor with technology, but rather as tools to reduce cognitive load, streamline repetitive tasks, and enable employees to focus on strategic, high-value functions. However, it is important to recognize the potential paradox: increased reliance on AI may inadvertently reduce opportunities for humans to practice these very skills. This concern, echoed in other domains such as medicine, underscores the need for deliberate strategies to maintain and cultivate critical thinking capacity. Training programs must not only teach technical competencies but also foster reflective judgment, ethical reasoning, and decision-making under uncertainty.

Automation and AI are not only transforming existing roles but also generating new ones. Abu Talib et al. (2025) highlight the rise of positions such as cybersecurity analysts, Unmanned Aerial Vehicle (UAV) managers, autonomous systems supervisors, and sustainability officers (Abu Talib et al., 2025). These roles demand hybrid skill sets that combine technical knowledge with systems thinking and ethical judgment. To meet these demands, workers must acquire new competencies, including data literacy, human-machine teaming, and adaptability (Golfetti et al., 2021). This transformation places a premium on reskilling and upskilling. Zaharia et al. (2021) emphasizes the need for aviation professionals to embrace interdisciplinary knowledge, spanning AI, ethics, sustainability, and digital literacy (Zaharia et al., 2021). Importantly, resilience in this context lies not only in technical preparedness but also in the ability to embrace change. To thrive in the Aviation 5.0 era, individuals and organizations must adopt an open and adaptable mindset as roles evolve and technologies become more integrated.

### 4.3. Career attractiveness

The aviation industry is facing a growing challenge in attracting and retaining new talent, particularly among younger generations. The COVID-19 pandemic significantly disrupted global aviation operations, leading to widespread layoffs and furloughs. These have impacted the perceived stability of aviation careers, especially in roles such as pilots, cabin crew, and ground operations staff, which were among the hardest hit during the crisis (Kearns, 2019; Han et al., 2021; Miani et al., 2021; Paramita & Sudhartio, 2022).

At the same time, generational shifts in workforce expectations are reshaping the labor market. Millennials and Generation Z increasingly prioritize flexible work arrangements, meaningful employment, and alignment with sustainability values (Deloitte, 2022). These cohorts are more likely to seek careers in industries that offer rapid career progression, digital innovation, and a strong sense of purpose, attributes that aviation has historically struggled to deliver (Bülbül et al., 2026). The rigid hierarchies, long training pipelines, and carbon-intensive image of the aviation sector contrast sharply with the agile, tech-forward environments of industries such as information technology, renewable energy, and logistics.

Without an attractive value proposition that addresses these evolving expectations, the aviation industry risks losing the next generation of talent to other sectors. These expectations align with the human-centricity, sustainability and resilience principles of Aviation 5.0. To remain competitive, aviation must rebrand itself as a future-oriented, inclusive, and socially responsible industry, one that not only embraces technological innovation but also invests in workforce well-being, diversity, and long-term career development.

Overall, with the increasing travel demand, aging workforce, training bottlenecks and the changing workforce dynamics, it is imperative for industry leaders to innovate workforce development strategies, embracing human-centric technological advancements to ensure long-term sustainability and resilience.

## 5. Workforce development through the lens of Aviation 5.0

The challenges identified in Section 4 affect all three dimensions of workforce sustainability defined in this paper. Workforce supply is pressured by retirements and limited training capacity. Workforce quality and adaptability are challenged by rapid technological change and evolving skill requirements. Workforce well-being and inclusion are affected by mental health pressures, the demands of working with AI systems, and the continued underrepresentation of some groups. Addressing these issues requires a coordinated framework that links principles, technologies, and workforce outcomes across the aviation system. Aviation 5.0 offers a timely and transformative framework and a new perspective on workforce development by aligning technological innovation with human-centric values.

Workforce development involves planning and implementing programs, policies, and practices to equip individuals with the knowledge, skills, and competencies needed

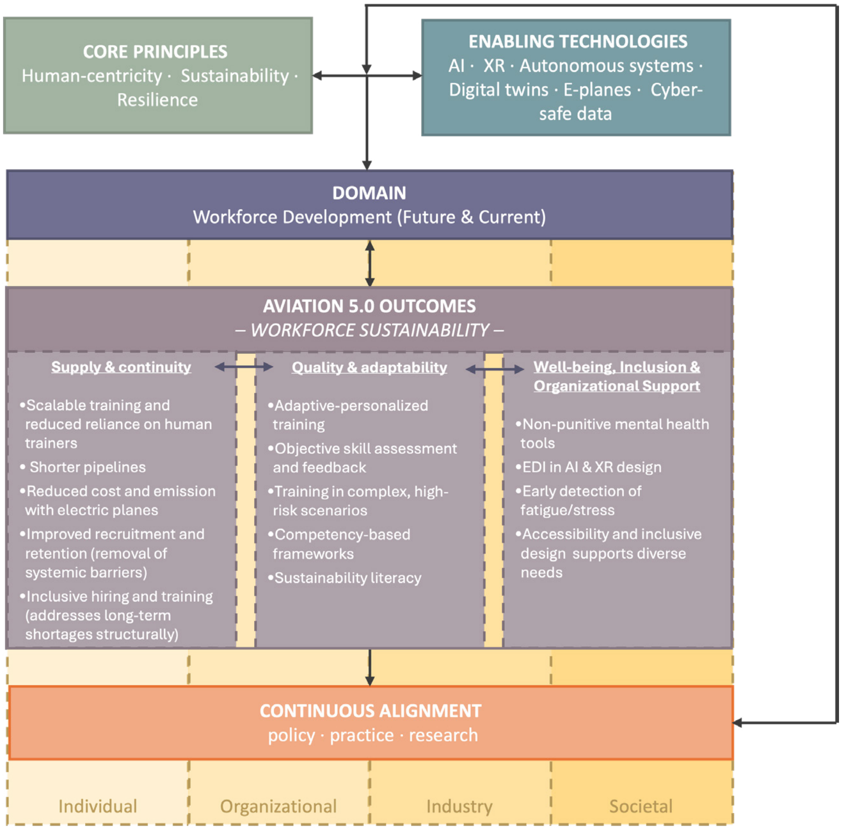


**Figure 3.** Aviation 5.0 for workforce development

for success in the current and future labor market. It includes preparing individuals for employment, providing learning opportunities to improve workplace performance, responding to changing workforce needs, and navigating career transitions. It addresses the needs of various groups, including young adults entering employment, currently employed individuals, and those transitioning to employment (Jacobs & Hawley, 2009).

Accordingly, the Aviation 5.0 framework developed in Section 2 is applied specifically to workforce development (Figure 3). Its logic operates as follows. The three core principles establish the normative criteria against which workforce strategies should be designed and evaluated. Human-centricity demands that workforce systems prioritize the well-being, personalization, and development of individual workers rather than treating labor as a cost to be minimized. Sustainability demands that the workforce pipeline be maintained across generations, that training and career pathways remain accessible and equitable, and that aviation's carbon-intensive image be transformed to attract talent aligned with environmental values. Resilience demands that the workforce possess the adaptability to absorb technological disruption, the organizational redundancy to withstand demographic shocks, and the institutional capacity to recover from crises such as pandemics.

Enabling technologies mediate between Aviation 5.0 principles and workforce outcomes through distinct mechanisms. Extended reality supports workforce adaptability through immersive and scalable training. AI and advanced analytics strengthen all three workforce sustainability dimensions by improving adaptive learning, predictive workforce planning, and mental health support. Digital twins enhance maintenance training and shift engineers toward proactive oversight roles. Cyber-safe data systems enable the ethical use of biometric and performance data while protecting worker privacy. Smart materials and sustainable aircraft technologies indirectly support workforce supply by improving aviation's environmental legitimacy and attractiveness to younger generations.

These technology-dimension relationships do not operate uniformly across the aviation system. Their effectiveness depends on where in the ecosystem interventions are targeted. At the individual level, the framework points toward personalized training, mental health support, and competency development. At the organizational level, it points toward inclusive recruitment practices, competency-based HR systems, and ethical AI governance in training and assessment. At the industry level, it points toward harmonized certification standards for XR and AI-based training, international coordination on workforce demand forecasting, and regulatory frameworks that support rather than penalize proactive mental health disclosure. At the societal level, it points toward educational pipeline development, public rebranding of aviation as a sustainable and inclusive career, and labor market policies that support workforce mobility and lifelong learning. This application of the framework across ecosystem levels directly reflects the cross-cutting architecture of Layers 3 through

5 described in Section 2. The scale of intervention determines both what constitutes a meaningful workforce sustainability outcome and which actors are responsible for alignment when gaps are identified.

The subsections that follow explore how Aviation 5.0 can reshape workforce strategies by fostering inclusive, adaptive, and future-ready talent ecosystems. It discusses innovative training methods, mental health and well-being, ethical considerations in human-machine interaction, and the imperative for equity, diversity, and inclusion (EDI) in building a resilient aviation workforce.

This paradigm shift calls for rethinking how aviation professionals are educated, trained, and supported. Workforce development in this context is not a linear pathway, but a dynamic, lifelong process aligned with rapid technological change and evolving human needs.

## 5.1. Innovative training strategies

Addressing workforce sustainability requires innovative training strategies. This includes enhanced training programs and the adoption of emerging technologies such as XR. Emerging research suggests that XR technology offers several key benefits for aviation personnel training, making it a valuable complement to traditional methods (Mavin et al., 2016). One significant advantage is the ability to simulate scenarios that are impossible to reproduce in traditional training, allowing users to train in safe, controlled environments with real-time feedback (Klotz & Stendal, 2023). Moreover, when integrated with psychophysiological monitoring tools such as eye tracking, heart rate variability, or neural activity, XR platforms can yield objective data about the learner's mental state, providing insights into workload, stress, fatigue, and engagement. These data streams can support adaptive training mechanisms aligned with competency-based frameworks.

A myriad of XR tools for aviation personnel pilot training, including cabin crew, pilot and maintenance personnel, have already been developed and commercialized by companies like CAE, Loft Dynamics, VRAI and VRPilot (ICAO, 2023; CAE, n.d.; Loft Dynamics, n.d.; VRAI Simulation, n.d.; VRPilot, n.d.). The addition of AI and machine learning enables real-time skill diagnostics, personalized feedback, and intelligent virtual instructors. These are key features supporting Aviation 5.0's inclusive, learner-centric vision that also help scale training delivery and address shortages of qualified human instructors. Implementing these technologies in training curricula can improve safety, reduce costs, enhance learning efficiency and minimize environmental impacts (Jensen & Konradsen, 2018; Lekea et al., 2021; Marron et al., 2024; Paul et al., 2025).

To fully leverage the benefits of emerging technologies such as AI, aviation personnel must also be equipped with foundational knowledge about these technologies. Understanding the capabilities and limitations of these systems is crucial for effective interaction and building appropriate trust and expectations. Trainings that integrate autonomous systems, cybersecurity measures, and human-machine interaction is critical in order to ensure safety (Abu Talib et al., 2025).

Complementing advances in simulation and XR-based training, innovations in aircraft technology also play a crucial role in reshaping training towards being more sustainable. Integrating electric aircraft into flight training also represents a meaningful step toward reducing aviation's environmental footprint. The Pipistrel Velis Electro, the first type-certified electric aircraft, has gained traction in flight schools for its low noise, reduced emissions, and operational efficiency. While enthusiasm is high, concerns remain around battery endurance and limited hands-on experience. However, the sector is optimistic, viewing e-planes as a catalyst for modernizing pilot training and aligning with broader sustainability goals (Edwards & Parker, 2022; Rizvi et al., 2024; Verdugo et al., 2025).

## 5.2. Employee wellbeing

Some of the most critical aviation professionals, such as pilots and air traffic controllers, operate in high-stakes, cognitively demanding environments where mental health and well-being are critical to both safety and performance. Aviation 5.0's human-centric perspective provides a framework for designing systems and policies that support the psychological and cognitive needs of employees throughout their careers, not just during training. While cognitive overload increases the risk of stress, fatigue, and human error, cognitive underload can result in boredom, disengagement and equally contribute to human error.

It is also worth highlighting that, as AI becomes more embedded in task allocation, it is essential to consider its impact on job satisfaction, perceived value of work, and self-esteem. The perception that AI technologies might replace jobs can create feelings of insecurity and irrelevance in the workplace. This can lower employees' self-esteem by making them feel less competent or obsolete, which in turn reduces motivation and job satisfaction. It is critical to also recognize these potential psychological effects, not just efficiency gains and build a supportive work environment, and provide training to reduce these negative effects (Ai, 2024). This will serve the interest not only the employees but organizations and society more broadly as psychological well-being and productivity are interconnected.

One of the most persistent and complex challenges in aviation is the stigma surrounding mental health among pilots. Despite growing awareness, many pilots remain reluctant to disclose psychological distress due to fears of losing their medical certification and, consequently, their careers, especially considering the high cost and time investment required to become a licensed pilot. While current aeromedical evaluations include mental health components, they often focus on detecting severe psychiatric conditions and may overlook more common but equally impactful issues such as anxiety, depression, and chronic stress. Moreover, the adversarial nature of some assessments can discourage pilots from seeking help, reinforcing a culture of silence. To address this, there is a growing consensus on the need for non-punitive, confidential, and proactive mental health support systems (Aerospace Medical Association Working Group on Pilot Mental Health, 2016; DeHoff & Cusick, 2018; Silva et al., 2022; Cross et al., 2024). These include:

- Self-assessment tools that allow pilots to monitor their mental health privately and regularly.
- AI-assisted protocols that interpret self-assessment results and guide pilots toward appropriate resources or interventions.
- Peer support programs that offer empathetic, pilot-led assistance without the fear of formal reporting.

The literature on pilot mental health reveals a structural paradox that Aviation 5.0 must directly confront. On one hand, human-centricity demands that aviation organizations invest in the psychological health of their workforce. On the other hand, aviation's regulatory architecture, specifically the linkage between medical certification and career continuity, creates a systemic disincentive for precisely the disclosure and help-seeking behavior that mental health support requires (DeHoff & Cusick, 2018; Silva et al., 2022). In other words, the very institutional structures that ensure safety at the system level actively undermine well-being at the individual level and thus safety at the system level. This is not a resolvable tension through technology alone. AI-assisted self-assessment tools and peer support programs can lower barriers at the margin, but they cannot eliminate the underlying certification dilemma without regulatory redesign. This points to a critical implication for the Aviation 5.0 framework: achieving the well-being dimension of workforce sustainability requires not only technological solutions but coordinated regulatory reform that decouples mental health disclosure from punitive career consequences, a reform that must operate at the industry and societal ecosystem levels rather than the organizational level alone.

Despite these promising directions, research gaps remain. There is an urgent need to validate the feasibility and usability of mental health self-assessment tools in operational aviation contexts as well as to develop AI-driven decision support systems that can provide personalized, evidence-based guidance while maintaining user privacy and trust.

## 5.3. Sustainability literacy in the workforce

Workforce development through the lens of Aviation 5.0 principles can also support the changing workforce landscape in aviation that emphasizes skills that correspond with sustainability objectives. Sustainability literacy is defined as the knowledge, skills, values, and dispositions needed to understand and address environmental, social, and economic sustainability challenges. It encompasses not only cognitive knowledge, but also thinking, ethical awareness and value-based decision making (Stibbe, 2009). Sustainability literacy in aviation involves having an understanding of environmental impact, regulations and policies, sustainable aviation technologies, operational efficiency practices and social aspects such as labor rights, diversity, accessibility and community engagement. Abu Talib et al. (2025) highlight that sustainability training is essential to provide professionals with the related skills and knowledge as sustainability becomes a major challenge within the industry (Abu Talib et al., 2025). Building sustainability literacy in the workforce is a cornerstone of Aviation 5.0, empowering professionals to integrate human-centric and environmentally conscious practices into every component of the aviation industry. To ensure sustainability literacy is embedded across the aviation ecosystem, training curricula should be developed for all personnel, from baggage handlers and cabin crew to maintenance technicians, pilots, and air traffic controllers, so that sustainability becomes a shared responsibility across all operational roles.

## 5.4. Ethics of human-machine interaction

There is no doubt that the enabling technologies have the potential to significantly enhance aviation safety and efficiency. However, as AI and automation become more embedded in aviation operations, ethical considerations around transparency, accountability, and trust should also be a top priority. According to the EASA, AI should not be viewed solely as a technical innovation but as part of a broader socio-technical system that must align with fundamental rights and societal values (EASA, 2023, 2024).

One of the most pressing ethical concerns is the need for transparency and explainability. For AI systems to be trusted and safely deployed in aviation, their decision-making processes and limitations must be understandable to human operators. This is particularly critical in high-stakes environments like flight operations and air traffic control, where timely and accurate interpretation of AI outputs can directly impact safety. The importance of safety assurance approaches tailored to AI's unique challenges is emphasized in the FAA's Roadmap for AI Safety Assurance. This document includes collaboration with industry and regulators to develop harmonized global standards (FAA, 2024). Similarly, the EASA Artificial Intelligence Roadmap 2.0 advocates a human-centered strategy for integrating AI, emphasizing the value of transparency, ethical alignment, and stakeholder collaboration (EASA, 2023).

Privacy and data protection also emerge as significant concerns, especially as AI systems increasingly rely on personal and physiological data. Surveys of aviation professionals have revealed discomfort with such data usage when transparency and informed consent are lacking. This underscores the urgent need for robust data governance frameworks that ensure ethical data collection, storage, and use. Bias and fairness represent another critical area of concern. AI systems trained on imbalanced or non-representative datasets risk perpetuating existing inequalities. These risks are especially serious in systems used for recruitment, training, and assessment, since there is a risk of replicating biases inherent in the data (Farahani & Ghasemi, 2024; Ferrara, 2024; Shuford, 2024).

Moreover, as AI becomes more autonomous and influential in aviation decision-making, the question of accountability becomes increasingly complex. When AI systems transfer decision-making from humans to algorithms, this creates responsibility and liability gaps because the system itself cannot be legally or morally liable. Kirwan (2025), underlines that, unlike today's largely manual or low automation operations, where the pilot is clearly liable, advanced AI creates a "double bind" for accountability (Kirwan, 2025). For instance, if an AI-generated recommendation leads to an accident, the human operator may be asked in court why they did not recognize that the advice was faulty. Or, if the operator deliberately ignores the AI and an accident occurs, the operator may be questioned for not following the AI's instructions. Porter et al. (2025) define this challenge as an exacerbated case of the "problem of many hands", the proliferation of actors across design, training, deployment, and monitoring, making it challenging to identify a single accountable party (Porter et al., 2025). This raises complex questions about legal and ethical responsibility. In cases where AI systems contribute to aviation incidents, it is unclear whether accountability lies with the developer, the operator, or the organization deploying the technology. Critical ethical consideration is the need for regulatory frameworks that mandate AI algorithm and data disclosure in the event of aviation incidents. As such, the EU's Artificial Intelligence Act introduces stringent regulations on high-risk AI systems, such as those employed in aviation, requiring transparency, traceability, human supervision, and conformity assessments to guarantee safety and accountability (EU, n.d.).

The literature on transparency, bias, privacy, and accountability all point to a fundamental problem: the assumption of human authority in aviation safety is incompatible with the opacity and distributed nature of current AI systems. Aviation's regulatory model assigns clear legal and moral responsibility to certificated human operators precisely because their decision-making is, in principle, auditable and explicable. AI systems violate both conditions: their outputs may not be interpretable even by their designers, and responsibility for their errors is distributed across developers, certifiers, operators, and deploying organizations in ways that existing liability frameworks cannot resolve (Kirwan, 2025; Porter et al., 2025). This is not merely a gap to be filled by better regulation. It represents a foundational tension between the logic of AI and the logic of certificated human authority on which aviation safety is built. For the Aviation 5.0 framework, this tension has a direct implication: human-centricity in human-machine interaction cannot be operationalized simply by requiring explainability or mandating human oversight. Regulators, operators, and the research community must collaborate to renegotiate human authority in safety-critical AI-assisted decision-making systems. The framework's continuous alignment layer is specifically designed to support this renegotiation.

Overall, the ethical deployment of these technologies in aviation requires a holistic approach that integrates technical safeguards with human-centric design principles. Transparency, fairness, privacy, and autonomy must be embedded into every stage of development and implementation to ensure that these technologies enhance, rather than compromise, the safety, equity, and integrity of aviation systems (Kirwan, 2025; Korentsides et al., 2024).

## 5.5. Equity, diversity, and inclusion (EDI)

The aviation workforce has historically lacked diversity, particularly in terms of gender, race, and socioeconomic background. Women, for example, represent less than 5% of commercial pilots globally (ICAO, n.d.-c). Aviation 5.0 presents a unique opportunity to embed EDI principles into the design of technologies, policies, and training systems from the outset.

The EDI literature, when combined with the workforce sustainability framework in this paper, indicates that diversity is not just an equity requirement but a structural condition for all three dimensions of workforce sustainability. At the supply and continuity dimension, the systematic exclusion of women and underrepresented groups from aviation pipelines constrains the available talent pool precisely when the industry faces its most acute demographic shortfall. The supply adequacy cannot be achieved without inclusion (Marete & Wang, 2024; Kefalidou et al., 2025). A workforce that is demographically narrow is simultaneously supply-constrained, adaptability-limited, and well-being-compromised. This means that EDI is not a separate pillar of Aviation 5.0 but a cross-cutting enabling condition: no dimension of workforce sustainability can be fully achieved without it. The implication for the framework is that EDI metrics must be integrated into the outcome indicators of all three workforce sustainability dimensions rather than tracked separately.

Human-centric design should prioritize accessibility, inclusive recruitment, and bias-free AI systems. XR training environments, for instance, must be designed to accommodate diverse physical abilities and learning styles. AI-driven hiring tools must be audited for fairness and transparency.

Policy recommendations include conducting EDI audits of training programs and AI tools, establishing inclusive design standards for XR platforms, and promoting diverse representation in leadership and innovation roles. These efforts are not only ethically imperative but also essential for building a resilient and innovative workforce. To truly address workforce sustainability, aviation must fully leverage the potential of all talent pools. Leaving out half the population not only limits opportunity but undermines the industry's ability to meet growing demands and innovate effectively. Inclusive practices are therefore not just a moral obligation but a strategic necessity.

While the interventions outlined in this section represent coherent responses to the workforce sustainability challenges, their implementation involves tensions that deserve acknowledgment. First, the efficiency gains promised by AI integration carry a deskilling risk: as routine cognitive tasks are offloaded to automated systems, human operators may lose opportunities to practice the very skills, situational awareness, judgment under uncertainty, manual override capability, that remain essential when AI systems fail or produce erroneous outputs. This paradox, documented in other high-stakes domains such as medicine and nuclear operations, requires deliberate training design that preserves human skill development rather than assuming technology will compensate for its own limitations (Arrigoni & Cavagnetto, 2023). Second, the scalability benefits of XR and AI-based training are unevenly distributed: the operators and regions that face the most acute workforce shortages are often those least able to absorb the infrastructure costs of these technologies, meaning that interventions designed to address supply adequacy may inadvertently widen existing inequalities between well-resourced and under-resourced aviation systems. Third, the personalization benefits of AI-powered mental health support and biometric feedback in training environments depend on the collection of sensitive personal data, creating a tension between the well-being and inclusion goals of Aviation 5.0 and the privacy rights of workers, a tension that data governance frameworks can mitigate but not eliminate. These trade-offs do not invalidate the interventions proposed here, but they do underscore that Aviation 5.0 workforce development requires ongoing critical evaluation rather than straightforward implementation.

## 6. Strategic implications for policy, practice, and research

Realizing the Aviation 5.0 framework requires navigating constraints that shape what is feasible and at what pace. Regulatory frameworks for AI and XR in aviation remain underdeveloped relative to technological change, creating certification and liability uncertainties (EASA, 2023; FAA, 2024). The evidence base for the safety and effectiveness of enabling technologies in operational contexts is still accumulating, and aviation's safety requirements mean adoption cannot outpace validation (Arrigoni & Cavagnetto, 2023; Ross & Gilbey, 2023). Organizational culture, particularly aviation's hierarchical structures and risk-averse norms, can slow technology adoption when workforce participation is insufficient. And socioeconomic disparities mean Aviation 5.0 adoption will be uneven across regions and operator sizes (European Commission, 2021; ICAO, 2024). The strategic directions below address each of these constraints directly, across policy, practice, and research.

To operationalize the vision of Aviation 5.0, a coordinated effort is required across industry, academia, and regulatory bodies. First of all, such a transformation cannot be put in place without regulatory alignment. It is important to align aviation regulations with the three key values of aviation 5.0: human-centricity, sustainability and resilience. This, for instance, could entail updating regulations, certification and licensing standards to integrate AI, XR and other emerging technologies. As discussed in the previous section, developing policies for transparency, accountability and explainability in AI systems used in aviation is another key step to be able to integrate them, without compromising safety and security. Another critical step is to support policies that address the aviation workforce's well-being and mental health. However, it is important to emphasize that, efforts in regulation and policy should encourage international harmonization of Aviation 5.0 standards to reduce global disparities.

From a practice perspective, the industry should take proactive steps towards embedding the principles of Aviation 5.0 into their processes, operations and organizational culture. For instance, this includes investing in designing systems that enhance the human roles, not replacing, through human-machine teaming technologies. Workforce development strategies should be revised to implement personalized, adaptive, competence-based training programs to address skill gaps and promote lifelong learning. An inclusive work environment should also be prioritized to accommodate diverse physical and cognitive needs. Additionally, operational efficiency and resilience can be strengthened by actively integrating emerging technologies such as digital twins and real-time decision support systems that mitigate disruptions and optimize performance.

In terms of research, there is a growing need for interdisciplinary studies that explore the socio-technical dynamics of Aviation 5.0. Future research should explore how trust is formed between humans and AI, especially in high-stakes operations. The effectiveness of XR-based training and biometric feedback in enhancing learning efficiency requires further exploration. The ethical implications of AI and automation in aviation should also be meticulously considered. Studies on new workforce development, training, upskilling and reskilling, strategies in the light of Aviation 5.0 principles and enabling technologies is also crucial. Finally, studies across countries and regions, while taking into account cultural, regulatory, and operational differences, is important to identify scalable solutions and ensure that Aviation 5.0 evolves in a way that's inclusive and effective worldwide. The following questions, while not exhaustive, represent the most directly framework-derived empirical priorities across the themes addressed in this paper.

Quality and Adaptability:

- How does the gradual expansion of AI autonomy affect human skill retention, situational awareness, and override capability over time?
- What training interventions best prepare aviation professionals for hybrid human-AI teaming roles, and how should competency frameworks be updated to reflect these roles?
- What are the measurable effects of XR-based training on time-to-proficiency, competency retention, and knowledge transfer to operational environments compared to traditional simulation methods?
- How does the integration of psychophysiological feedback (eye tracking, heart rate variability, neural activity) into XR training platforms affect learning outcomes and adaptive training design?

- How do aviation professionals form, calibrate, and lose trust in AI decision-support systems across different operational roles?
- How can aviation training pipelines be restructured to reduce time-to-certification and cost barriers without compromising safety standards?

Supply and continuity:

- How effective are XR simulators for reducing the environmental footprint and the cost of pilot training?
- How effective are electric aircraft as a tool for reducing the environmental footprint of pilot training, and what are the competency transfer implications for trainees transitioning to conventional aircraft?
- What factors most significantly influence the career intentions of Millennials and Generation Z toward or away from aviation, and how do Aviation 5.0 principles (sustainability, inclusion, digital innovation) affect those intentions?
- What is the cost-effectiveness threshold at which XR-based training becomes viable for smaller operators and training organizations in low- and middle-income countries?

Well-being, inclusion, and organizational support:

- What non-punitive mental health support models (peer support programs, confidential self-assessment tools, AI-assisted protocols) are most effective in operational aviation contexts, and what are the conditions for their successful implementation?
- How does increasing AI integration into task allocation affect job satisfaction, perceived professional identity, and self-esteem among different aviation workforce groups?
- What structural barriers most significantly limit the entry and retention of women and underrepresented groups across different aviation occupational categories, and at which ecosystem level are interventions most effective?
- How should legal and regulatory frameworks assign accountability when AI-assisted decision-making contributes to an aviation incident involving multiple developers, operators, and deploying organizations
- How do aviation professionals perceive the fairness, transparency, and explainability of AI systems currently deployed in their operational environments, and how do these perceptions affect adoption and compliance?

Addressing these questions will require collaboration across aviation safety science, human factors, organizational behavior, education research, ethics, and public policy. Taken together, they define a research agenda that is both generated by and necessary for the progressive validation and refinement of the Aviation 5.0 framework.

## 7. Conclusions

By grounding Industry 5.0 principles in aviation's distinctive constraints, this paper offers a replicable model for sector-specific adaptation of broader industrial paradigms. This paper introduces Aviation 5.0 as a conceptual extension of Industry 5.0, emphasizing core values of human-centricity, sustainability and resilience in aviation. By providing a historical roadmap from Aviation 1.0 to Aviation 5.0, the paper contextualizes technological and societal shifts, highlighting the evolution of aviation in parallel with industrial revolutions. In this scope the enabling technologies of Industry 5.0, such as AI, XR, digital twins, and smart materials, are mapped to aviation-specific applications across domains like air traffic management, maintenance, and workforce development, demonstrating their transformative potential. Workforce sustainability is identified as a critical challenge, and Aviation 5.0 was proposed as a strategic framework to address this challenge by guiding workforce development strategies in future aviation. Within this framework, this paper explores innovative training strategies, mental health support, ethical considerations in human-machine interaction, and the importance of EDI in building a resilient aviation workforce. The paper also outlines strategic implications for policy, practice, and research to support the operationalization of this paradigm across global aviation systems. Ultimately, Aviation 5.0 offers a future-oriented paradigm that aligns technological advancement with societal values, aiming to create a more inclusive, adaptive, and sustainable aviation industry.

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