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Status quo and challenges in air transport management research

Sebastian Wandelt^a, Constantinos Antoniou^b, Sebastian Birolini^c, Daniel Delahaye^d,
 Martin Dresner^e, Xiaowen Fu^f, Stefan Gössling^g, Seock-Jin Hong^h, Amedeo R. Odoniⁱ,
 Massimiliano Zanin^j, Anming Zhang^k, Hui Zhang^l, Yahua Zhang^m, Xiaoqian Sun^{a,*}

^a National Key Laboratory of CNS/ATM, Beihang University, 100191 Beijing, China^b TUM School of Engineering and Design, Technical University of Munich, Germany^c Department of Management, Information and Production Engineering, University of Bergamo, via Pasubio 7b, Dalmine (BG) 24044, Italy^d OPTIM Lab, National School of Civil Aviation (ENAC), Toulouse, France^e R.H. Smith School of Business, University of Maryland, United States^f Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China^g School of Business and Economics, Linnaeus University, Sweden^h G. Brint Ryan College of Business, University of North Texas, 1155 Union Circle 311396, Denton, Texas 76203-5017, USAⁱ Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, United States^j Instituto de Física Interdisciplinar y Sistemas Complejos IFISC, 07122 Palma de Mallorca, Spain^k Sauder School of Business, University of British Columbia, Canada^l Institute of public safety research, Tsinghua University, 100084 Beijing, China^m UniSA Aviation, STEM unit, University of South Australia, Adelaide, SA, Australia

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ABSTRACT

Air transport management research, concerned with all facets of aviation operations, policies, and strategies, is an essential element of making our aviation system more sustainable and preparing it for the challenges inherent to the present and future. Based on a data-driven categorization of almost 2,000 papers published on the subject, we discuss the status quo in air transport management research. Through our data-driven categorization we have identified 15 broad topics. For each topic, we provide a description of the state of the art and propose 2-3 challenges, respectively. Overall, our study provides a set of 35 challenges to the research community. Accordingly, we hope and believe that our study makes a valuable contribution, mainly by guiding the air transport management research community towards a delineated work plan on the research landscape of air transport as well as the present challenges, ultimately helping to improve the global air transport system.

1. Introduction

Throughout the 21st century, our inter-connected societies are characterized by rapid drive for globalization, time-sensitive business operations, and an increased amount of regional and international travel. Accordingly, air transportation remains critically important for mobility due to its unmatched speed, connectivity, and global reach. Specifically, air transportation does not only support economic growth through the efficient movement of goods and people (Button and Taylor, 2000; Zhang and Graham, 2020), but also fosters international cooperation as well as cultural exchange (Wensveen, 2023). Since its inauguration around 100 years ago, air transportation has become accessible to a broader population, connecting rather remote regions, and providing long-distance transportation affordable for a significant share of the population (Vasigh et al., 2018).

In recent years, the air transport system is facing a collection of major setbacks and pressures, which can be broadly categorized into three major types, as shown in Fig. 1. Presumably the most important concern of air transport to date is related environmental aspects in the context of *climate change* (Gössling and Humpe, 2020; Gössling and Upham, 2009; Lee et al., 2009; Ryley et al., 2020). Aviation makes a significant contribution to the emission of greenhouse gases, which drive global warming and climate change. Beyond such direct effects, air transport operations also contribute to the warming process by the formation of contrails and cirrus clouds (Schumann, 2005; Tesche et al., 2016). The induced related pressure from public perception and inherent responsibilities requires aviation stakeholders to commit towards sustainability, while still generating profits (Franke, 2007). Similarly, international organizations and governments are putting increasing regulatory pressure on the aviation industry, with the goal to significantly reduce its carbon footprint. The second major concern for air transport is the *aftermath*

* Corresponding author.

E-mail address: sunxq@buaa.edu.cn (X. Sun).



Fig. 1. Overview on major pressures on the air transport system in the year 2023.

of the COVID-19 pandemic, which is one of the deadliest pandemic outbreaks in human history, yet definitely the outbreak with the largest impact on the global aviation system; see [Abu-Rayash and Dincer \(2020\)](#); [Sun et al. \(2022, 2023d\)](#) for broad overviews and literature reviews on this subject. Grounded aircraft, emerging variants of concerns, highly volatile travel bans, and an under-prepared industry led to a chaotic period of nearly three years, whose peak was presumably the near standstill of the entire aviation system in March / April 2020; an unprecedented event in the history of aviation. While the aviation system has gradually recovered from the peak impact, see [Sun et al. \(2023b\)](#) for a data-driven study, with many airlines reporting profits and passenger records, the aftermath of the pandemic is still putting pressure on some parts of the system, especially concerning human resources and the need to identify and advocate alternate economic models for air transportation ([Gössling, 2020](#)). The third major concern for air transport is the presence of various *geopolitical conflicts* and diplomatic tensions, e.g., the Russia-Ukraine war, the strategic competition between the two superpowers China and the United States, as well as, and a general threat of protectionism and rejection of multilateral trade agreements, not only on aviation ([Standfuss et al., 2023](#)), but transportation in general ([Demiralay and Kilincarslan, 2019](#); [Zuan et al., 2021](#)). The downstream effects on the air transport system are various, including airspace disruptions ([Wang et al., 2023b](#)), increasing safety concerns due to military activities in conflict zones, technology restrictions ([Svik, 2020](#)), and supply chain failures. Air transport, a field concerned with all facets of aviation operations, engineering, policies, and strategies, has an instrumental role in overcoming the problems inherent to the three major pressures identified above, by helping to shape the future of the aviation industry through the generation of insights, innovative solutions, and data-driven recommendations; also under consideration of future challenges from urban air mobility ([Jin et al., 2024](#); [Wandelt et al., 2023c](#)); see also [Wang et al. \(2024\)](#) for a discussion of challenges on truck-drone-combined routing.

In this study, we discuss how the air transport research community may contribute shaping a better, more sustainable and resilient future for aviation undertaking. In order to achieve this goal, we first organize the air transport-related literature into a collection of major categories. For this purpose, we dissect the abstracts of nearly 2,000 related papers. Based on these abstracts, we derive a data-driven classification of the actual research; see the Appendix for a detailed description of the methodology; where each paper is assigned to exactly one cluster. Our classification contains 15 major clusters covering about 60% of all papers, as shown in [Fig. 2](#). These categories are summarized as follows:

- **Networks** (114 papers): Papers discussing the role of airline networks, connectivity of airports, regional studies with importance of specific routes in the air transportation system.
- **Benchmarking** (110 papers): Papers developing models and techniques for analyzing the efficiency and productivity of air transport stakeholders, e.g., airports and airlines.

- **Service quality** (99 papers): Papers with a focus on customer satisfaction, airline / airport service quality, region-specific perceptions, loyalty, and passenger complaints.
- **Choice behavior** (98 papers): Papers concerning airline choice, airport choice, mode choice, consumer preferences, willingness to pay, and other traveler choices such as airport shopping.
- **Regulation** (98 papers): Papers investigating the concepts of (de)regulation, liberalization, market concentration, consolidation, and other air transport economic developments.
- **ATC/ATM** (98 papers): Papers covering aspects of aircraft departure / arrival sequencing, delay prediction and propagation, trajectory optimization, as well as airport capacitation.
- **Environmental effects** (92 papers): Papers subsuming the areas of climate change, aircraft emissions, aircraft noise, aircraft electrification, and other sustainability-related subjects.
- **Safety** (92 papers): Papers covering aspects such as safety culture, safety evaluation, risk analysis, accident analysis and prevention, as well as near-misses and regulatory management.
- **Business models** (86 papers): Papers mainly concerned with the differentiation between full-service carriers and low-cost carriers as well as business versus leisure travel.
- **COVID-19** (51 papers): Papers concerned with the COVID-19 pandemic in the period 2020 to 2023 and its extensive impact on airlines, airports, passengers, and other stakeholders.
- **Airline alliances** (45 papers): Papers discussing the role of strategic airline alliances, code share agreements, antitrust policies, airline consolidation, and other cooperative aspects.
- **Security** (37 papers): Papers mainly concerned with the usage and improvement of screening procedures / technologies at airports, also covering some papers on aircraft security.
- **Cargo / freight** (34 papers): Papers covering topics such as air cargo demand estimation, air cargo routing and airport selection, as well as inter-dependencies with passenger transport.
- **Scheduling** (33 papers): Papers with a methodological focus on typical optimization problems, airline scheduling, aircraft taxi scheduling / gate assignment, and crew assignments.
- **Decision making** (24 papers): Papers using a wide range of multi-criteria decision making tools, such as Analytic Hierarchy Process (AHP), Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) and other variants in different air transport domains.

The remaining 40% of papers either induce rather smaller clusters or can be located on the intersection of multiple categories. Based on these 15 major air transport research categories, we identify the key challenges inside each category and discuss the need and potential for mitigation strategies. We conclude the discussion of challenges in air transport by providing a set of future research directions. We believe that our study makes a valuable contribution to the air transport research community and beyond, by guiding other researchers towards orchestrated work on present challenges and helping to improve our global air transport system. Our study is structured as follows. [Section 2](#) identifies

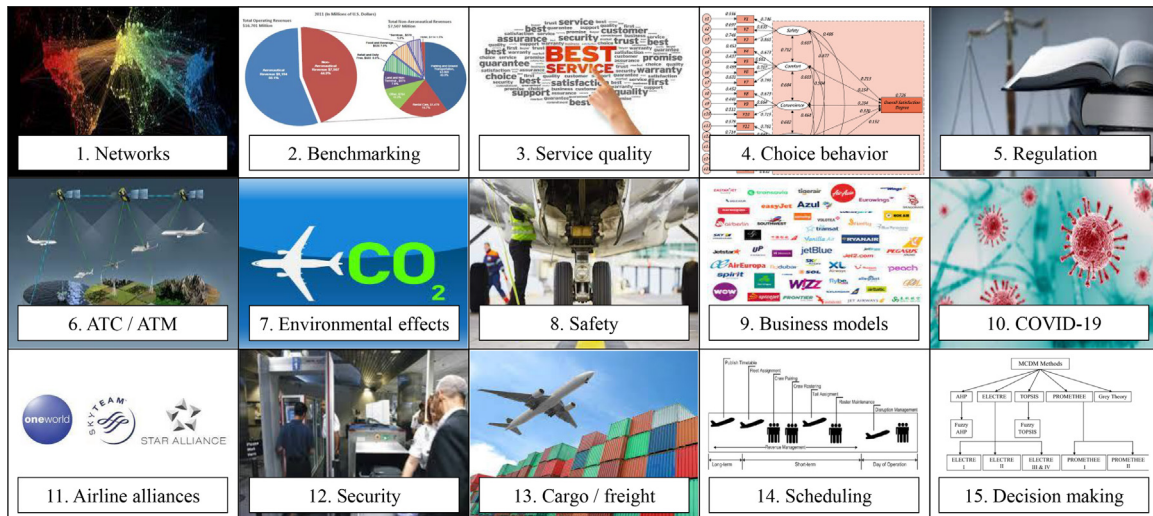


Fig. 2. Major categories of air transport research, ordered by the number of papers in each category (from upper left to lower right).

the key challenges in these categories as well as potential mitigation strategies and future research directions. Section 3 summarizes the major insights and concludes this study.

2. Status quo and challenges

This section discusses the status quo and most important challenges with respect to the 15 categories identified, having major impacts on the air transportation system. Each category represents a timely and informed recapitulation of each domain as in the end of the year 2023. The categories are discussed in decreasing order of the number of papers, i.e., following the numeration introduced in Figure 2.

2.1. Networks

Stemming from the classical field of statistical physics, the theory of complex networks has played a crucial role in the aviation system in the last two decades, facilitating the efficiency and safety of air travel, particularly in the context of identifying key components and improving air transport resilience; see Zanin and Lillo (2013); Zanin and Wandelt (2023) for reviews. From a methodological perspective, complex networks have emerged as modelling technique for understanding and measuring the resilience of the global air transportation system. By representing the connections between airports and airlines as networks, researchers and policymakers can gain profound insights into the system's structure, vulnerabilities, and potential failure points (Sun and Wandelt, 2021; Wandelt et al., 2023b), whose understanding is instrumental for devising strategies to successfully mitigate their impact of disruptions; also see Czerny and Lang (2023) on contracted networks useful for theoretical policy analyses. In recent years, there has been a divergence between both communities: Only very few papers published on air transport use recently developed techniques from network science, most research in statistical physics that rely on air transport data fail at understanding the underlying problems, and usually provide answers with limited operational value. Accordingly, it is time to re-join forces, following two key research challenges:

Challenge 1.1: How to better integrate a complex system's perspective into air transport management? Complex networks theory, and statistical physics in general, aims at providing descriptions of the macro-scale properties of a system even when the details of its micro-scale constituents are unknown. This can only be achieved through abstract representations devoid of all (prima facie) unnecessary details. To illustrate, the nodes of a typical airport network are abstract entities no longer associated to specific physical locations; and the result is a static

structure that lacks temporal evolution, even when such dynamic perspective is an important element of air transport Majhi et al. (2022); Rocha (2017). Results obtained through an over-simplified network representation must then be translated back to the higher-dimensional space of air transport management, a process prone to pitfalls and errors (Wandelt et al., 2023d).

Challenge 1.2: How to account for multi-layers and higher-order structures in air transport management? The dynamics of the air transportation system develops over diverse operational layers, including e.g. different airlines, airspaces, weather, and passenger / cargo. While each layer has its unique characteristics and interactions, they are also coupled, such that adverse weather events may affect flight operations, and these in turn the mobility of passengers. Such dependencies make it crucial to explicitly model interactions as distinct layers within a multi-layered network framework; see (Aleta and Moreno, 2019; Cardillo et al., 2013; Xu et al., 2023b). Additional complexity stems from the fact that those interactions are typically not of a pairwise nature, but rather form higher-order relationships - the simplest example being a passenger connecting multiple flights, thus creating a relation between many elements simultaneously. This could be tackled by the recent concept of higher-order networks (Bianconi, 2021; Bick et al., 2023).

2.2. Benchmarking

Benchmarking has been a useful tool used by industry practitioners, regulators as well as academic researchers in the aviation sector. Aviation authorities and industry organizations, such as the Airports Council International (ACI) and Skytrax, offer a wide range of benchmarking reports, e.g. on different sets of yearly / bi-yearly benchmarking reports on concessions, financial, infrastructure needs, service quality. Virtually all those reports rely solely on Key Performance Indicators (KPIs) associated with a particular aspect, and therefore they do not offer a comprehensive view of an organization's overall performance, or the patterns behind performance variations. For example, the same airport's service indicators may vary significantly between off-peak vs. peak time; the same airport's per employee revenue could significantly change before and after outsourcing major operations, even though there is no change in the airport's operations. Although such KPI analysis offers convenient and timely performance measurement of a particular aspect of airlines and airports, it does not provide reliable guidelines on overall or long-term pattern. The latter is often addressed by comprehensive benchmarking analysis, many of which on the efficiency and productivity of airlines and airports.

Three methods have been extensively used for the measurement of efficiency and productivity in the aviation industry, namely Data Envelopment Analysis (DEA), Stochastic Frontier Analysis (SFA), and Total Factor Productivity (TFP). Standard DEA and TFP are non-parametric analysis which does not rely on econometric estimations. This would avoid the need of specifying parameters and (implicit) assumptions for empirical estimation. However, this does not always lead to reliable analysis even though in many cases the methodologies per se are fairly straightforward. While existing studies offer rich insights into different aspects of the aviation industry, major improvements are needed to overcome challenges. For example, another major challenge is the control of service quality and product differentiation. It has been empirically validated that there are significant product differentiation between Low-Cost Carriers (LCCs) and Full-Service Carriers (FSCs) (Fu et al., 2011a), which involve significantly different costs and inputs. Treating an Available Seat Kilometre (ASK) from an LCC and an FSC equally will clearly favour an LCC's efficiency score. In fact, the same problem occurs when one treats one ASK of business / first class service the same as one ASK of economy service. In theory with sufficient number of observations of different airlines, DEA and SFA could partially overcome such a problem by allowing for different frontiers for various types of airlines. Still, it is difficult to clearly interpret the benchmark results across different (types of) airlines. It is also difficult to control the effects of factors beyond managerial controls, such as geographic locations of an airline's hubs, regulations such as open-skies policy, airport slot control, government assistance including subsidies received during the COVID-19 pandemic, emission control policy, airport-airline vertical arrangements (Cui et al., 2016; Fu et al., 2011b; Yang et al., 2015). Many fundamental issues remain to be addressed in the literature.

Challenge 2.1: How to increase the dissemination of reliable, comprehensive and detailed benchmarking data? It is often difficult to get comprehensive and detailed data even for publicly listed firms that are obliged to prepare annual report, let alone for small and regional airports (Liebert and Niemeier, 2013); see also Pauwels et al. (2024) for a recent overview on how to uniformly define a regional airport. In addition, both airlines and airports produce multiple outputs, such as passenger services, cargo services, commercial services (e.g., duty free sales, food and beverage, extra luggage, lounge use etc.). Since there is significant joint production (i.e., the same aircraft / runway may be used for both passenger and cargo operations), it is not always clear how to reasonably assign revenue (cost) to individual output (input).

Challenge 2.2: How to properly take into consideration the existence and reporting of subsidiary firms? More and more airlines are establishing subsidiary or affiliated airlines using the so-called Airline-within-Airline (AinA) strategy (Homsombat et al., 2014), whereas many airports are owned and managed by airport groups (Oum et al., 2003). It is often difficult to precisely collect / match data for inputs and outputs used by specific firm / decision-making unit. Whereas virtually all those methods are capable of handling the cases with (incomplete) subsets of inputs and outputs, it is not always clear what are the most important inputs and outputs to include, and to what extent the results could reveal the true performance of the target airlines and airports.

2.3. Service quality

Service quality has been a research focus in the air transport research community since its strong association with the aviation businesses' competitive advantage and profitability. Relevant research mainly covers the service quality of airports, airlines and the services of suppliers to airports and airlines in different geographic locations, with Asia and Europe being the most extensively researched area (Zhang et al., 2023c). The service quality of airlines in different development stages with different business models is also well researched. Most of the research papers examining the service items follow the process of a passenger's travel journey from pre-departure activities such as ticket booking, to activities at the departure and arrival airports (e.g. Jiang and

Zhang (2016)). There is no sign of dwindling interest in this area. Instead, the number of studies in air transport service quality has been increasing at a faster pace in recent years. This is largely due to the dynamic nature of the air transport industry, and the fact that air passengers' expectations have been constantly changing and shifting, driven by technological advancement, increasing awareness of the environmental problem and continuously high demand for air travel, especially in the post-pandemic period (Zhang et al., 2023c). These changes have provided new incentives, topics and contexts for air transport researchers to keep growing the body of knowledge in air transport service quality to meet the need of the industry.

Research in air transport service quality has followed a variety of theoretical frameworks and the most commonly used ones include SERVQUAL, AIRQUAL, fuzzy set theory, theory of planned behaviour, Service quality and brand equity theories, expectancy-performance theory, cognitive network theory, important-performance analysis, and psychological capital and service behaviour. Structural Equation Model (SEM) including factor analysis is the single most frequently used empirical method, followed by econometric models and fuzzy set related methods (Cao et al., 2023). In recent years, it has been common to use online survey tool to collect data for convenience and cost saving. It is argued that today's online survey software is well designed with sophisticated functions to produce accurate and representative data (Batterham, 2014). Social media platforms such as X (Twitter), Facebook and various tourist review websites, have been an important research data source where researchers can use user-generated content such as online customer reviews to understand passengers' opinions and preferences, which, to some researchers, are more truthful and unbiased (Park et al., 2020). Despite the fact that air transport service quality is a well-researched area, new challenges and research directions still exist. Two important challenges are:

Challenge 3.1: How to measure and capture new service quality dimensions due to the new and evolving trends? For example, airlines have adopted digital technologies and provided digital products to digital passengers. It is not known if the digital services offered match the needs and expectations of the travellers. Clearly, not all passengers are comfortable with the new technologies. These include senior citizens, and technology illiterate passengers. Some recent studies have included digital tangibles in the research framework. However, this remains to be an under-researched area. In addition, passengers are facing a greater risk of personal information leak in the digital age and there is a lack of research into the passengers' privacy and cybersecurity concerns associated with the proliferation of technology-enabled services.

Challenge 3.2: How to establish a link between service quality and long-term goals, e.g., efficiency vs. sustainability? The current research in air transport service quality concentrates on increasing passenger satisfaction, retention and loyalty through quality services. Little attention has been paid to establishing the link between service and aviation businesses' long-term goals such as improved efficiency and profitability (Zhang et al., 2023c). In recent years, greater emphasis has been placed on developing Corporate Social Responsibility (CSR) of a business, which includes environmental, social and economic responsibilities. The CSR activities can enhance a firm's reputation, influence the customer's perception of the service quality received, which can, in turn, strengthen air passengers loyalty and retention (Dijkmans et al., 2015; Kuo et al., 2016). Studies linking service quality and these long-term performance variables are still lacking in air transport research.

2.4. ATC / ATM

Research on Air Traffic Management (ATM) has generated literally thousands of published papers over the years - including a count of 98 in JATM alone. A few examples of well-studied and important problems that still deserve much attention include: Delay mitigation through a combination of operating and scheduling practices (Jacquillat and Odoni, 2015; 2018); equitable and passenger-centric

Air Traffic Flow Management strategies (Barnhart et al., 2012; Jacquilat, 2022); 4D trajectory planning (Dal Sasso et al., 2019); flexible and dynamic airspace design (Schultz et al., 2019); airspace sectorization (Zhang et al., 2023a); governance, regulation and economics of ATM (Arblaster, 2018; Efthymiou, 2023). Recent developments such as advanced air mobility concepts and AI-based approaches and tools have opened an enormous set of possibilities for innovative and impactful ATM-related research, including climate change and environmental issues at both the planning and operations levels (Matthes et al., 2020). We list a few major challenges below:

Challenge 4.1: How to set the declared capacity at slot-coordinated airports? The problem of setting the declared capacity of “coordinated” (or “Level 3” or “congested”) airports is of critical importance, as the declared capacities determine the supply of slots at these approximately 200 airports that handle nearly 50% of the world’s air passengers and include practically all the airline hubs outside the United States. The setting of declared capacities is a complex task that requires determining the optimal trade-off between volume of demand served, on one hand, and air traffic congestion, on the other, while taking into consideration the full range of operating conditions (weather, traffic mix, etc.) and the daily and monthly demand profiles at the airport (Rodríguez-Sanz and Rubio-Andrada, 2023).

Challenge 4.2: How can environmentally efficient trajectories contribute towards sustainable air traffic? For 50 years, technological innovations, mainly at the level of engines, materials and aerodynamics, have made it possible to reduce the consumption of airliners by approximately 60%, however, kerosene remains a major issue for airlines not only in terms of cost but also environmental impact which is becoming increasingly restrictive. Having effective trajectory calculation algorithms then becomes a determining factor for airlines (Courchelle et al., 2019). In order to ensure capacity of the airspace, traffic is structured at the vertical level (flight levels), at the lateral level (airways network) but also at the temporal level (speed regulation). The optimal vertical profile of an airliner consists of a continuous climb and descent. In the horizontal plane, aircraft try to optimize their trajectories based on the wind field, but they are forced to follow a network of routes which structures the traffic for the controllers in order to ensure the capacity of the control sectors. If all traffic were operated in such a way as to optimize kerosene consumption (optimal routes depending on the wind, optimal vertical profile, and optimal speed profile), it would be impossible for controllers, with current tools, to effectively manage this type of traffic and the airspace would reach very quickly its capacity.

Challenge 4.3: How can we push the envelope for ATM automation with better trajectory prediction systems? Many efforts have been done in the past in order to develop decision support tools to help controllers to manage the traffic and then to enhance the capacity of the system (Kuchar and Yang, 2000). Unfortunately, no algorithms have been deployed in operations and this challenge has to be investigated in future research to develop decision support tools to help controllers to manage more aircraft in the airspace and then to improve the overall capacity of the air transport system. Such algorithms being used at the tactical level, the real scientific challenge is linked to the demonstration that such algorithms are trustable and can be accepted by the operators. Such automation will also help controllers to manage greener trajectories without reduction of the airspace capacity. Many efforts have been done in the past for improving the performances of the operation prediction even by Machine Learning (Yepes et al., 2007), but trajectory prediction remains one main challenge for improving the performances of the air traffic management system.

2.5. Choice behavior

Passenger choice models serve as tools for airlines in understanding, predicting, and exploiting the existing, dynamic travel preferences of travelers. Such models are often built upon sophisticated mathemat-

ical frameworks and behavioral theories, and are an integral part of airline optimization processes, revenue management systems, and service offerings. Passengers’ decisions are driven by a complex interplay of cognitive and affective factors, including ticket price, flight schedule, travel time, safety records, and service quality. These attributes are being weighted according to their individual preferences and past experiences to derive an optimized decision. The Discrete Choice Model (DCM) is a rather widely used method. Earlier studies utilized the Multi-Nomial Logit Model (MNL), a specific DCM technique, to study airline selection due to its good performance, efficiency and interpretability. Traditional DCM approaches may not be deployed for the non-linear large samples, whose assumptions do not hold in some real applications. Therefore, researchers have developed various other models as well, e.g., integrating machine learning (Lhéritier et al., 2019; Mottini and Acuna-Agost, 2017) and big data (Mottini et al., 2018). There exists a set of challenges for choice behaviour, summarized as follows.

Challenge 5.1: How can airlines develop more informed and reliable passenger choice models? Concerning the heterogeneity of market segmentation and consumer preferences, airlines should optimize the supply side to meet passenger demand, given their insufficient responses, e.g., concerning traveler needs demonstrated throughout the COVID-19 pandemic. A simple data-driven history-based prediction model did not lead to informed and timely response strategies, leaving airlines in the dark regarding actual (and changing) passenger demand. It would be rather short-sighted and unsustainable, if airlines simply return to using their traditional modeling and prediction techniques, simply because they seem to work again after the strong recovery seen by the aviation industry in the year 2023. To achieve this goal, recent methodological advances should be further disseminated, e.g. machine learning / data driven approaches (Sun et al., 2023c), and optimization.

Challenge 5.2: How can we further develop and improve multi-modal passenger choice models? Multi-modal choice behavior, i.e., the choice between air and other modes, has seen a considerable increase in interest in recent years. This development is mostly spurred by the emergence and development of high-speed railway systems (Li et al., 2024; Román et al., 2007). For instance, China has the largest high-speed railway network in the world, with more than 40,000 km in length. This strong competition has forced airlines to drop prices significantly and even quit formerly-profitable markets, in face of significant demand shifts. There is a need to develop better, holistic models which take into account various factors, in order to explain the dominance of high-speed railway for distances larger than 1200 km; a competition range which was unthought of one decade ago.

2.6. Regulation

The airline industry was at the forefront of public policy reforms with respect to liberalization of regulatory policies: namely, the bellwether deregulation of US domestic markets in 1978 (Bailey et al., 1985). Following US deregulation there has been a worldwide move away from government regulation towards liberalization of air services and “open skies”. After a three-packages process starting from the late 1980s, the EU created, in 1997, a Single Aviation Market (SAM) similar to the deregulated US domestic market or the Australia-New Zealand SAM: that is, any EU-registered carrier has the right to operate flights between or within any of the - then - fifteen EU member countries, as well as in Norway and Iceland (Button et al., 1998). National ownership rules have been replaced by EU ownership criteria, and airlines have been given freedom to set fares, with safeguards against predatory pricing through EU competition policy rules. So far, these changes do not apply to extra-EU agreements. The unleashing of airline competition has led to a number of strategic actions being taken by airlines in a liberalized competitive environment, including mergers and consolidation, competition over frequency and scheduling, hub-and-spoke network formation, international alliance agreements, and development

of low-cost carriers (LCCs) (e.g., [Borenstein \(1989\)](#); [Finger and Button \(2017\)](#); [Levine \(1986\)](#)). There exists an active literature that aims to understand the rationales - and welfare implications - behind these various strategic actions that were ultimately set in motion by enhanced competitive forces leading to, among others, lower fares, better services, increased traffic, and more competitive carriers (e.g., [Borenstein \(2005\)](#); [Clougherty and Zhang \(2009\)](#); [Fu et al. \(2010\)](#); [Morrison and Winston \(2010\)](#); [Zhang et al. \(2023b\)](#)).

Challenge 6.1: How can we achieve further progress towards completely free trade in airline services? Unlike many other industries, air transportation is regulated internationally, in the form of a huge number of bilateral air service agreements. Progress has been made since the early 1990s: a number of Open Skies Agreements (OSAs) have emerged among countries. The OSAs are noted to have substantially enhanced international airline competition, but to involve a number of exclusions with regard to competitive activity including cabotage. Thus, OSAs still fall well short of establishing completely free trade in airline services. A recent study by [Tan et al. \(2024\)](#) investigated the question of whether US travelers would benefit from entry by foreign airlines, by simulating the effect of cabotage based on LCC competition in the US and EU markets. Their simulation shows that an EU LCC's entry in US markets would generate a modest \$1.6 billion annual welfare gain to travelers. The analysis is based on a case of unilateral cabotage (only the US government granted cabotage rights to foreign airlines). While US travelers gain, it is not sure about the impact on US carriers' profit. Furthermore, it is uncertain if other countries would reciprocate, thus leading to a comprehensive cabotage policy that allows entry of all foreign carriers in all countries. This global cabotage scenario would be an expanded version of the EU SAM. While this global open-skies regime is unlikely to be achieved in the near future given both the large asymmetry between the US / EU and Asia, and the current geopolitical climate of trade protectionism and the de-globalization/re-shoring trend, more studies on assessment and implementation would be needed.

Challenge 6.2: How to better integrate air cargo into air transport research and policy-making processes? [Tan et al. \(2024\)](#) considered global cabotage only for the passenger market. Global cabotage may be much more easily achieved for the cargo market. In general, air cargo represents an often neglected area of air transport, as passenger transport has often taken precedence both in terms of policy and scholarship. Yet air cargo has grown substantially over the past decades - and it was much less disrupted during the COVID-19 pandemic than the passenger transport - and its relative importance with respect to passenger transport has accordingly increased. A crucial distinguishing feature of air cargo transport is the need for more multilateral routing structures, thereby requiring the fifth/seventh-freedoms and cabotage that allow cargo to go through domestic points and third countries, and to consolidate through regional cargo hubs. These needs are largely ignored by the current system of bilateral agreements, however. While some efforts have been made to separate cargo from passenger transport and then bring cargo regulation to the WTO level, the prevalence of wide-bodied aircraft in Asia (where cargo and passengers are intertwined) represents a significant impediment to this policy breakthrough.

Challenge 6.3: What additional insights can be obtained through airline-airport vertically integrated analysis? Another area of research that had been neglected until the last two decades is the need to consider airports and airline-service in an integrated manner. As discussed in, e.g., [Basso and Zhang \(2007\)](#), airports and airlines cannot be treated separately in analyzing competition and regulation in air transport sector. This is consistent with (for example) [Drukker and Winston \(2024\)](#). They find, in the US context, that travelers flying out of metropolitan origins with at least three airports pay lower fares, ceteris paribus, than travelers flying out of metropolitan origins with only one airport; but that fares from metropolitan origins with exactly two airports are higher compared with fares out of single-airport metropolitan origins. They attribute this somewhat surprising result to the channel by which three or more airports reduces fares is by generating ad-

ditional airline competition. Fully considering the vertical nature of airline-services and airports appears then to be a fruitful area of future research.

2.7. Environmental effects

Air transport has grown rapidly in recent decades, and so have concerns regarding its various environmental impacts. Chief among these are longstanding sustainability issues such as noise and local air quality, as well as the more recent attention that is being paid to climate change. Noise and air pollution have health implications for populations living near airports, and have been investigated mostly in local and national contexts ([Wolfe et al., 2017](#); [Zhu et al., 2011](#)). The more pressing topic in the global policy context is aviation's contribution to climate change. This line of research has focused on the quantification of radiative forcing effects of carbon dioxide, nitrous oxides, and contrails ([Lee et al., 2021](#)), and, more recently, challenges for net-zero aviation ([Dray et al., 2022](#)). These include propulsion technologies and sustainable aviation fuels ([Su-Ungkavatin et al., 2023](#)); the energy, water and space requirements of new fuels ([Fiorini et al., 2023](#)); as well as policies supporting the transition to more sustainable air transport ([Larsson et al., 2019](#)). Related issues also include air transport planning and management (infrastructure, itineraries, flightpaths) and aviation economics (carbon taxes, cost of new fuels, subsidies) ([Gössling and Humpe, 2023](#)). There is also an emerging literature on the implications of climate change for air transport, for example because of adverse weather conditions or sea-level rise, and opportunities for adaptation ([Burbidge, 2018](#)). As air transport is expected to grow rapidly in coming years, these questions will gain importance. This makes it likely that two interlinked research areas will gain attention:

Challenge 7.1: Which barriers need to be overcome to advance a more sustainable aviation sector? The transition to net-zero is usually discussed in terms of new technologies, fuels, or energy requirements. While these topics will remain important for decades to come, many other barriers exist that have so far been largely unexplored. This starts with the definition of 'net-zero' and the complexities of measuring and avoiding CO₂ / non-CO₂ radiative forcing. There are limitations to the upscaling of biogenic fuels, the considerable energy requirements to produce fuels such as hydrogen or e-fuels, and implications for aircraft designs and supply infrastructures. As sustainable aviation fuels are significantly more expensive, there is also a cost issue that demands attention ([Gössling and Humpe, 2023](#)).

Challenge 7.2: How can new business models and policy designs support sustainable aviation? The global air transport system operates at marginal profitability, much of which is reliant on premium class sales that drive up energy consumption. Distributional aspects (frequent fliers), structural issues (bonus programs), and policy failures (non-taxation of CO₂) have considerable relevance for profitability and demand patterns, as well as the sector's energy consumption growth. There is consequently a role for politics in forcing the sector to adopt new technologies and fuels, and for the sector to discuss new business models. As political attempts to improve the sustainability of the sector have already led to resistance, lobbying and greenwashing, research is also needed into finances, debt of airlines, implications of subsidies, and the role of aircraft manufacturers in driving up capacity ([Becken and Carmignani, 2020](#)).

2.8. Safety

Aviation safety is a cornerstone of reliable and swift air services, is continually researched and optimized. The breadth of these studies spans various domains such as structural safety, fire safety, accident investigation, airport logistics, risk management, human factors, avant-garde technologies, as well as computational and experimental methodologies. These integral studies aim to enhance aircraft design safety, ensure reliable operations, and improve stakeholder decision-making pro-

cesses. Muecklich et al. (2023); Tepylo et al. (2023); Wang et al. (2023a); Wiegmann and Shappell (2001) offer comprehensive reviews of the relevant literature in the aforementioned fields, particularly focusing on research advancements from the 1960s to present. It encapsulates key contributions from the US, China, and UK - the three front-runner countries in aviation safety research, characterized by a high number of related publications and a marked intensity of author collaboration. This part offers valuable insights into the multidisciplinary nature of aviation safety research, identifies significant contributors to its progress, and demonstrates the dynamic evolution of advanced safety technology. Currently, research hotspots in the field include air traffic control, risk assessment, human factors, and accident investigations. There is, however, the potential for undervalued or overlooked aviation safety challenges existing within the available literature and government-funded projects. By identifying these potential focal points, future studies could home in on them to build upon existing efforts. Additionally, a set of three key research challenges is important for air transport safety. Given the evolving nature of technology and the aviation landscape, it is critical to keep updating investigation methodologies, incorporating the latest research findings into accident investigations. The identified safety challenges necessitate a joint effort from academia, industry stakeholders, policymakers, and regulatory bodies. Proactive collaboration is crucial to addressing these challenges, identifying knowledge gaps and research priorities, and providing insights for future research directions.

Challenge 8.1: How can we integrate new technologies into aviation safety management? The integration of state-of-the-art technologies such as automation systems, data-driven decision-making tools, and machine learning into aviation operations poses significant challenges. Concerns arise about these integrations and their overall influence on safety. The key challenge lies in seamlessly incorporating these technologies to enhance, not inhibit, established safety protocols. The introduction of advanced ICT technology raises the potential for emergent risks not anticipated during design and testing stages. Interaction between different technological components can lead to unexpected breakdowns or generate cascading effects. Furthermore, the pursuit of increased airspace capacity necessitated by escalating air traffic engenders a surge in airspace complexity. With the airspace shared by commercial, general, and unmanned aviation, it necessitates meticulous coordination to prevent potential collisions and incidents. This intricate environment can introduce safety risks around airspace capacity planning and real-time management, which may require advanced solutions to address effectively.

Challenge 8.2: How can we redefine roles / responsibly accounting for human factors in training and operation? Recent accidents have triggered a paradigm shift in aviation safety, necessitating a reassessment of the roles and responsibilities of stakeholders, specifically pilots and air traffic controllers; see Wandelt and Wang (2024) for a recent review on the pressing challenges concerning hiring and retention of the air transportation workforce. As these individuals increasingly take on supervisory and data management roles, the risk of miscommunication, confusion, and decision-making errors mounts. Integration into advanced traffic control systems requires aviation personnel to adapt to novel procedures, interfaces, and decision-support tools. This can lead to an increased cognitive workload and a steep learning curve, thereby heightening the risk of errors due to human performance limitations. The next generation of technology aims to alleviate these concerns. Techniques such as natural language processing, advanced ICT technology, and human error prevention systems are being developed to mitigate errors and enhance efficiency. The challenge lies in effectively incorporating these advancements into training and operations to successfully minimize human errors.

Challenge 8.3: How can more effective and efficient accident investigations be performed? Accident investigations bring a unique set of challenges due to inherent complexities and occasionally scant evidence. These investigations are crucial as they identify the causes of accidents and the interactions between aircraft safety operations and en-

vironmental variations. Given the intricate engineering systems, structural designs, and advanced materials in an aircraft-including those in the luggage-investigators must constantly develop their technical skills to effectively deal with potentially hazardous materials. Organizing and analyzing evidence requires a meticulous approach that respects the objective laws of accident occurrence and progression. Establishing links between accident traces, physical evidence, and human evidence, and understanding their spatial and temporal relationships are key in creating logical constructs of accident sequences.

2.9. Business models

Business strategists teach that there are two main business models that a firm can follow: low-cost or differentiation (Porter, 1997). A low-cost provider, by definition, has the lowest costs among competitors and can compete in a market by charging the lowest prices. Other companies need to compete by offering differentiated products or services. Airlines have been grouped into these business models with low-cost carriers (LCCs) competing with low fares and network or full-service carriers (FSCs) offering differentiated products; for example, airport lounges, pre-selected seats, and business-class comfort, e.g., Urban et al. (2018). To achieve their low-costs, LCCs have adopted operational practices to improve efficiencies, including limiting the variety of flight equipment to reduce maintenance and repair costs, reducing turnaround times at gates to maximize profit-generating flying times of aircraft, reducing seat pitch to squeeze more passengers onto an aircraft, and flying point-to-point routes to eliminate the complexities inherent in hub-and-spoke systems. Researchers have pointed out that these two business models, LCCs and FSCs, do not fit all airlines, e.g., Moir and Lohmann (2018). In the United States, for example, there are many carriers operating as regional affiliates of the FSCs, focusing on low-density feeder routes using regional aircraft. Europe has a history of significant charter operations, with charter carriers focusing on flights from Northern Europe to Southern sun destinations. In Asia, the carrier-in-a-carrier concept has been employed as a business model by firms that operate both FSCs and LCCs, thus segmenting their markets. In Europe, multi-brand operators fly aircraft under several different brand names offering differentiated service levels. Finally, there are various types of cargo airlines, including integrators that sell door-to-door services to package shippers. Moreover, researchers have used operating characteristics and demand factors to classify carriers into FSCs, LCCs or other categories (Pereira and Caetano, 2015). Other researchers have written about the convergence between LCCs and FSCs, with LCCs adding features normally associated with FSCs, such as seat selection and hub connections, and FSCs mimicking the LCCs, for example, by offering cafeteria pricing, where passengers must pay for amenities, once included in the ticket price (Daft and Albers, 2015). Airlines that offer features from both LCC and FSC operations have been termed hybrid carriers. Although there has been considerable research on airline business models, there are important questions that remain under-studied. Suggested areas for research include the following:

Challenge 9.1: What are the environmental impacts of the different business models? FSCs typically operate with two- or three-class seating configurations, often including extra-wide seats for high-paying business travelers. The FSCs, therefore, fly routes with fewer available seats than the LCCs. Thus, the environmental impact, per passenger, of an FSC flight is likely to be higher than the environmental impact for an LCC flight. But LCCs often fly short routes, with a high number of take-offs per day. These short-haul operations burn jet fuel and contribute to CO₂ emissions and ambient noise pollution around airports. Therefore, research assessing the relative environmental impacts from these types of business models may provide useful information to public policymakers, airport operators and environmental researchers.

Challenge 9.2: How do multi-brand operations impact public welfare? Airlines have adopted business models with multiple brands, including airline-in-airline concepts where a single firm operates both

FSCs and LCCs. These multi-brand operations may provide convenience to customers, but can also lead to industry concentration, potentially driving fares higher. An assessment of the public welfare impacts of multi-brand operations would be welcome.

Challenge 9.3: How to develop competitive models under consideration of the true cost of travel? Finally, researchers have historically examined the intensity of airline competition based on yields or published fares. But these yields and published fares have increasingly diverged from the true cost of travel due to separately priced amenities, including seat selection and checked luggage. These ancillary costs are especially prevalent with LCCs. Thus, researchers could calculate the elasticities of these amenities and construct competitive models between various types of carriers based on the true costs of travel.

2.10. COVID-19 pandemic

The COVID-19 pandemic has not only led to unprecedented impacts on the aviation system, but also to the aviation literature; see Sun et al. (2022) for broad reviews on this subject. There exist three major types of conceivable papers concerning the pandemic: a) Investigating the (negative) impact of COVID-19 on aviation, b) discussing the recovery process and its ramifications, and c) preparing for the next epidemic / pandemic outbreak. The current status of the literature is heavily skewed towards a). Even in the year 2023, one can still see papers appearing which analyze the very early interactions of COVID-19 back to the year 2020. Nevertheless, it is important to emphasize that the negative impact has been rather well understood by now, at least concerning the short / midterm consequences. Accordingly, it is time to put a much stronger focus on b) and, presumably the most important types of paper, c). In line with this focal shift, two major research challenges regarding COVID-19 and future epidemic / pandemic outbreaks are:

Challenge 10.1: How long will the aftermath of COVID-19 have an impact on the aviation system? Major parts of the aviation system have recovered from the impact of COVID-19 in Summer 2023; other places, however, still have significantly reduced connectivity, e.g., the international market of China. Accordingly, it would be interesting to answer how long it takes for a full recovery, and what such a recovery is like. Specifically, how did the competitive landscape of airlines change under ramifications of state aids and different pandemic strategies? Understanding the differences and their drivers is an important part of research for deriving the lessons learned; see Sun et al. (2023a); Wu et al. (2023).

Challenge 10.2: How can we reduce the impact of future epidemic outbreaks proactively? While the tools provided by statistical physics, mostly based on compartmental disease spreading models, are rather mature by now, it seems like they do not consider societal aspects and economic trade-offs sufficiently. The experience with the COVID-19 pandemic, with presumably rather ineffective border closures, has shown that one needs to consider sentiments in the population as well as financial and other health-related consequences when making decisions. Therefore, we see a need to develop more optimization-driven tools which balance the trade-offs between minimizing the impact of a potential Disease X and reducing the negative impact on population and economics; see Ding et al. (2021); Liu et al. (2024); Scheelhaase et al. (2022); Sun et al. (2021); Xu et al. (2023a).

2.11. Airline alliances

The competition between firms has evolved from firm versus firm competition to something that can be described better as *group versus group competition*, in terms of such as supply chains and strategic alliances (Rowley et al., 2004). The airline industry is presumably one of the dominating examples for this phenomenon, in addition to pharmaceutical and chemical, as well as automation industries (Seo, 2020), mainly because these alliances not only create values to customers, but

also enhance profit opportunities for the partners (Oum and Park, 1997). Airline alliance formations have mainly increased in presence of various external factors, such as globalization, deregulation, and privatization; see Amankwah-Amoah and Debrah (2011); De Man and Luvison (2019); Morrish and Hamilton (2002); Park and Zhang (2000) for seminal papers on the subject. The benefits of participating in an airline alliance are manifold, including an extended network, higher cost efficiencies, collaborative marketing efforts, streamlined operations, as well as combined loyalty programs. As of today, three major airline alliances in the world are: Star Alliances, SkyTeam, and oneworld. Alliances in air transportation are rather stable, mainly due to the fact that the cost of leaving a strategic alliance increases as the partners work closely by investing time and resources to enhance mutual benefits. Accordingly, China Southern leaving SkyTeam in 2020 is a rather rare event nowadays. In addition, the opportunity cost of finding another airline partner increases rapidly as many airlines have found durable alliance partners (Oum and Park, 1997). The increasing presence of low-cost carriers in major air transport markets has led to a situation in which, unaligned low-cost airlines have operated 31% of global airline capacity, nearly double that of the largest alliance - Star Alliance - which operated 17% (June 2022 to May 2023)¹.

Challenge 11.1: Are micro alliances a potential development scenario out of stable alliance networks? During the COVID-19 pandemic, airlines often had serious problems trying to attract customers, in the presence of changing lockdown rules and flight bans. During this period, airlines have been creating so-called micro-alliances (Garrow et al., 2021) which are more temporary and at a smaller scale than traditional alliances. The major differences of these micro-alliances are agility, flexibility and granularity, i.e., the ability to forge alliances and create contracts at the level of single seat or customer instead, compared to year-long contracts or code-sharing agreements. The research community should develop models and optimization techniques accordingly, as well as derive empirical analyses of such micro alliance phenomena.

Challenge 11.2: How will the future development of low-cost carriers challenge alliances structures? The business model of low-cost carriers is fundamentally different from traditional airlines in an alliance and the strategies used within global alliances are usually not beneficial to low-cost carriers. The reason is that low-cost carriers have an extreme focus on optimizing their operations, reducing a number of services, and using secondary airports, with the goal to offer significantly low fares on regional flights. This is rather contrary to what alliances typically propose (e.g., long-haul destinations / coverage, access to lounges, higher service quality, etc.). With the continuing growth of low-cost carriers around the world and a younger generation which is potentially significantly less loyal and more price sensitive, the question arises whether (and how) these low-cost airlines will be able to put further pressure on existing alliances, until a point, where the current three-major-alliance-equilibrium might break apart. Similarly, it will be interesting to see whether earlier attempts to build low-cost carrier alliances will be more successful in the future.

2.12. Security

An increasingly challenging subject for air transport is security, with criminal groups continuing to exploit novel, high-tech methods in an attempt to attack airports and aircraft. Securing air transport does not only enable and foster international relations, promotes economic activities, but also facilitates the free flow of cargo, making aviation security a critical element in maintaining global peace, stability, and prosperity. In order to ensure the safety of air transport operations and all stakeholders, including passengers, crew, and airport staff, it is essential that aviation security protocols are well-designed and implemented, reflecting knowledge on the latest threats and take proactive measures to mitigate poten-

¹ <https://www.oag.com/blog/where-next-airline-alliances-partnerships>

tial risks (Gillen and Morrison, 2015). The list of effective aviation security measures is long, and includes stringent passenger screening, crew / staff background checks, advanced intrusion technologies, and international collaboration; see Gkritza et al. (2006). On the other hand, passengers at large airports often face disruptions due to long security lines, complexity of rules and sometimes invasive processes. The major turning point for aviation security in recent decades was the 9/11 terrorist attack, which exposed striking vulnerabilities, and has drastically transformed aviation security protocols worldwide (George and Whatford, 2007; Seidenstat, 2004). The response was a paradigm shift in airport and airline security, largely driven by the foundation of the Transportation Security Administration (TSA) in the United States, including the implementation of body scanners, restrictions on liquids and sharp objects, and the reinforcement of cockpit doors (Lyon, 2006). Since 9/11, aviation security focuses on proactive measures to prevent similar incidents, while accepting the potential downstream effects in passenger (in-)convenience and disruption likelihood (Stewart and Mueller, 2014). Two of the most important security challenges in air transport are discussed below.

Challenge 12.1: How to maintain security levels while reducing disruptions? One major challenge for future air transport operations is to ensure a sufficient level of security, while reducing the effects and extent of disruptions, i.e., striking a balance between thorough security checks and passenger convenience remains a priority. In this context, researchers and industry stakeholders need to acknowledge that there exists no uniform passenger and that different passengers have different expectations, perceptions, and performances at security checkpoint (Kirschenbaum, 2013). Future studies could increase the extent of realism by introducing uncertainties as well as more realistic passenger behavior, especially in light of the perceived increase in *unruly* passengers. At the same time, while implementing passenger-specific security processes, one needs to prepare for legal arguments concerning discrimination of specific travel groups; a challenge which should be addressed by policy-oriented studies.

Challenge 12.2: How to evolve towards global coordination and unified implementation of security standards? Air transport is a global, inter-connected industry with heterogeneous stakeholders. Accordingly, achieving consistent, high-level security designs and implementations worldwide requires international cooperation and coordination among governments and air transport authorities; as well as trust between states and their agencies; see Wong and Brooks (2015) for a review of issues in security screening. While 9/11 has led to a de-facto harmonization of various security standards, there are some indications of trend changes. For instance, the United Kingdom is aiming to ease airport security rules concerning the carriage of liquids and electronics starting from June 2024. It will be interesting to see whether this technology-driven move is the start of a race for more passenger convenience and higher throughput at airports and whether this change will reduce the security levels at airports and in-flight.

2.13. Cargo / freight

Air cargo is crucial in the supply chain and the globalized economy (Hong et al., 2018). Competition for air cargo is fiercer, with other transport modes offering new products (Association, 2018) and one-stop supply chain solutions. The air cargo market comprises combination carriers, all-cargo carriers, and integrators (Boeing, 2022b). Air cargo's challenges and weak growth trends are ongoing and more observable for combination carriers than all-cargo carriers and integrators (Business, 2017). The role of integrators (DHL, FedEx, UPS, etc.), global freight forwarders, and new logistics service providers is increasing, such as Amazon Prime Air (Hong et al., 2023). The air cargo growth rate worldwide has decreased since 2010 to around 4.1%, compared to 6% decades ago (Boeing, 2022a; 2022b).

Challenge 13.1: How can combination carriers improve competitiveness? The biggest challenges that led to the air cargo growth rate

not being sustained are the economic recessions, changes in product characteristics (Fisher, 2003), dissimilarities, and lack of economies of scale between the passenger and cargo service networks (Reis and Silva, 2016). Combination carriers that provide cargo services should incorporate better supply chain strategies for their client's long-term needs rather than simply focusing on transporting cargo from airport to airport (Hong et al., 2023; Hong and Zhang, 2010). A joint venture between heavy air cargo providers and supply chain solution providers (integrated carriers or global retailers) could be a solution to expand, as is the case with AeroLogic, a joint venture with LH and DHL and the partnership between Atlas Air and Amazon.com's Prime Air. Collaboration to balance supply and demand could reduce dissimilarities between passenger and cargo transport businesses (Hong et al., 2018).

Challenge 13.2: How do freight forwarders and integrators consolidate efficiently? Integrators and freight forwarders provide comprehensive logistics services for their customers. Therefore, integrators' strategic and operational importance is high for shippers' production and commercial processes (Onghena et al., 2014). Integrators have expanded their business with mergers, acquisitions, and cooperative strategies to obtain economies of scale and density. The integrator's pursuit of developing strategies concentrated in the air cargo industry will continue with network robustness (Bombelli, 2020) and provide opportunities to create effective customized solutions (Tsai et al., 2021).

2.14. Scheduling

The air transport industry is currently one of the largest worldwide, characterized by intricate processes, capital-intensive resources, various stakeholders, and numerous interacting players. Within this domain, scheduling problems naturally arise in various areas and play a pivotal role in establishing safe and efficient operations. The continuous development of effective optimization-driven scheduling tools has consistently captured the attention of academics and practitioners (Barnhart et al., 2003), and their widespread adoption today stands as a fundamental pillar of modern air transport systems.

Airlines tackle scheduling problems throughout their entire planning process, from months in advance to just a few days before operations, covering tactical issues such as flight scheduling and fleet assignment, all the way down to operational decisions such as crew scheduling and tail assignment (see Belobaba et al., 2015, for a review). Contributions in this domain initially focused on addressing each problem independently and developing solution methods that scale to the growing size of real-world airline networks. More recently, increasing attention has been given to integrating sequential stages and improving the integration with predictive methods aimed at anticipating key inputs, such as demand at the tactical level and delays at the operational level, demonstrating enhanced capability to yield superior decisions (Birolini et al., 2021; Cacchiani and Salazar-González, 2017).

Many challenging scheduling problems also arise in airport and air traffic management, primarily aimed at better aligning capacity with demand to ensure safe operations and achieve efficient allocation of increasingly scarce resources. These encompass, but are not limited to, schedule coordination, often achieved through slot allocation mechanisms, traffic flow management, aircraft sequencing, runway scheduling, and gate assignment (e.g., Daş et al., 2020; Ribeiro et al., 2018; Wang and Jacquillat, 2020). Similar to the airline domain, recent contributions have focused on combining different perspectives, both vertically (considering sequential problems together) and horizontally (considering multiple resources simultaneously) to mitigate the shortcomings and incompatibilities stemming from the solution of independent problems. Moreover, endeavours have been devoted to enhancing the capture of multiple objectives expressed by different stakeholders and proposing improved solution methods and algorithms that align with practical deployment requirements. Despite the numerous efforts made since the early development of scheduling tools (dating back to the mid-20th century), scheduling problems in aviation have continued to gar-

ner growing attention. This trend is expected to persist in the future, primarily addressing the following challenges:

Challenge 14.1: How to fully harness the potential of machine learning and AI in scheduling problems in aviation? In recent times, advancements in computing technology, analytics techniques, and data availability have fostered the use of Machine Learning (ML) methods in combination with operations research techniques (Bengio et al., 2021). The use of ML in scheduling problems is no exception. Supervised ML methods has the potential to improve predictions, hence leading to more effective predict-then-optimize approaches (e.g. Birolini and Jacquillat, 2023). ML can also expedite the resolution of challenging combinatorial problems by narrowing down the solution space (e.g. Rashedi et al., 2023), replacing some heavy computations by fast approximations or aiding in the configuration of algorithms (e.g. Ding et al., 2023). ML can also be prescriptive, offering alternative approaches to tackle repetitive scheduling tasks (e.g. Razzaghi et al., 2022). Early works exploring the potential of combining ML and traditional optimization techniques have shown promise but have not fully explored the extensive range of possibilities. To further upscale the integration of ML and optimization in aviation scheduling problems, the investigation of model interpretability and effective mathematical integration is considered a particularly important avenue for research.

Challenge 14.2: How to develop schedules that are as adaptive as possible? A predominant characteristic of scheduling problems in aviation is their strong interdependence with upstream and downstream stages and the need to revise decisions multiple times across the planning horizon. This, in turn, calls for methods that are adaptive, providing solutions at a given time that can be easily adjusted or revised later based on emerging information and improved visibility into uncertain inputs (Sherali and Zhu, 2008; Yan and Ghate, 2022). While many scholars have focused on integrating one or more sequential tasks, this is typically accomplished through integrated models that often overlook the costs associated with recourse actions or in general lack a comprehensive consideration of rescheduling options. In this regard, the development of dynamic methods that better account for the multi-stage nature of scheduling processes or frame them as sequential problems is seen as a promising future direction.

Challenge 14.3: How can scheduling practices be effectively improved and leveraged to promote sustainability? Scheduling problems in aviation have traditionally neglected the explicit consideration of environmental factors, instead prioritizing economic or efficiency objectives. However, next to new technologies and sustainable fuels, improving scheduling practices offers an additional and complementary means to achieve the aviation industry's ambitious environmental goals. Future efforts are therefore sought, with a focus on effective strategies for integrating environmental considerations into scheduling problems. Beyond individual agents' planning, from a policy perspective, this also encompasses the investigation of collaborative and incentive schemes to foster solutions that effectively balance economic, social, and environmental targets. Lastly, it is crucial to account for new technologies and their operational demands, which in turn necessitate tailored scheduling techniques and create opportunities for innovative operational concepts (Hou et al., 2021; Justin et al., 2022; Mitici et al., 2022).

2.15. Decision making

Many processes and decisions underlying air transport require the consideration of a wide range of constraints and objectives from multiple stakeholders (airports, airlines, passengers, air service providers), leading to a set of different, potentially conflicting criteria. Even an individual air transport stakeholder by itself faces situations with numerous alternatives, incomparable benefits, and uncertainties. Accordingly, there is a need for applying Multi-Criteria Decision Making (MCDM) methods to help decision makers to find satisfactory solutions. There exist various methods in the literature, mostly extensions of Analytic Hierarchy Process (AHP) and Technique of Order Preference Similarity

to the Ideal Solution (TOPSIS), with an increasing focus on uncertainties and fuzziness in recent years. Typical examples for the application of MCDM in air transport include studies on service quality, aircraft selection (Sun et al., 2011), and financial performance analysis. The following challenges remain for decision making in the context of air transport:

Challenge 15.1: How to measure and identify true methodological advances on MCDM methods? Papers using MCDM in air transport have an increasing math-aspect in recent years, where the description of the preliminaries and methodology significantly outweighs the evaluation and actual managerial / policy-related insights. In such an environment, it becomes difficult to appreciate the found rankings / results based on the simple fact that they are different from related works (often using simpler methodologies). Accordingly, there is a need to provide comprehensive evaluation of methods and their results on standard air transport problems, enhanced with a discussion on why the results are different and which results are preferred under which circumstances.

Challenge 15.2: Can MCDM methods be applied at a broader range and for wider problems in air transport? A review on research applications, covering the years 2000 to 2018, has revealed that MCDM is mostly used for airline-related purposes so far and that evaluation is the most commonly purpose. The reason for this observation is unclear, presumably a combination of data availability and research interest / cooperation. There clearly exist many more opportunities to apply MCDM, on airports, air traffic management, as well as for passengers. Accordingly, we encourage a broader usage of methods in the air transport domain.

3. Conclusions

In this study, we have derived a categorization of major air transport research topics. Based on the identified 15 categories, we make two major contributions. First, we describe the current state of the art in each category, supplemented by seminal papers in the field. Second, we provide a set of 2-3 open research challenges for each category; all challenges are summarized in Table 1. These challenges, while being specific to each category, reveal a few common themes, which are summarized below:

- 1. Towards sustainability of air transport** (Challenges 3.2, 4.2, 7.1, 7.2, 9.1, 14.3): Achieving sustainability is essential for air transportation, due to its real as well as perceived environmental impact. Practices for increasing sustainability, e.g., alternative fuels, efficient aircraft design, and operational strategies, aim to reduce emissions and will allow the industry to prepare for the future. Given that public awareness of environmental concerns grows over time, adopting more sustainable practices becomes vital for air transportation's long-term viability, aiming to find a balance among economic growth, efficiency, and environmental responsibility.
- 2. Consideration of additional, more realistic aspects** (Challenges 1.1, 2.2, 3.1, 6.2, 6.3, 8.2, 9.2, 11.1, 13.1): Some of the challenges concern novel perspectives and the consideration of additional aspects in research. Often, the consideration of a wider perspective, contrary to a too-specialized / narrow analysis, will lead to novel managerial insights. Examples for such wider considerations include new service quality dimensions, integrated analysis of passenger and cargo transport, as well as novel forms of airline interactions / alliances. Similarly, the cross-border analysis of stakeholders, such as an airline-airport vertically integrated analysis is promising to deliver novel managerial insights.
- 3. Development of novel models and methodologies** (Challenges 1.2, 4.2, 5.1, 5.2, 8.1, 9.3, 14.1, 15.1): In order to reach its goals, air transport requires novel and innovative methodologies / models, mainly due to its complexity and evolving landscape. The major need for such technological advancements, including big data and artificial intelligence, particularly in the area of large-language models

Table 1
Summary of the key challenges for air transport.

ID	Challenge for Air Transport
1.1	How to better integrate a complex system's perspective into air transport management?
1.2	How to account for multi-layers and higher-order structures in air transport management?
2.1	How to increase the dissemination of reliable, comprehensive and detailed benchmarking data ?
2.2	How to properly take into consideration the existence and reporting of subsidiary firms ?
3.1	How to measure and capture new service quality dimensions due to the new and evolving trends?
3.2	How to establish a link between service quality and long-term goals , e.g. efficiency vs. sustainability?
4.1	How to set the declared capacity at slot-coordinated airports?
4.2	How can environmentally efficient trajectories contribute towards sustainable air traffic?
4.3	How can we push the envelope for ATM automation with better trajectory prediction systems?
5.1	How can airlines develop more informed and reliable passenger choice models?
5.2	How can we further develop and improve multi-modal passenger choice models?
6.1	How can we achieve further progress towards completely free trade in airline services?
6.2	How to better integrate air cargo into air transport research and policy-making processes?
6.3	What additional insights can be obtained through airline-airport vertically integrated analysis ?
7.1	Which barriers need to be overcome to advance a more sustainable aviation sector ?
7.2	How can new business models and policy designs support sustainable aviation?
8.1	How can we integrate new technologies into aviation safety management?
8.2	How can we redefine roles / responsibly accounting for human factors in training and operation ?
8.3	How can more effective and efficient accident investigations be performed?
9.1	What are the environmental impacts of the different business models ?
9.2	How do multi-brand operations impact public welfare ?
9.3	How to develop competitive models under consideration of the true cost of travel ?
10.1	How long will the aftermath of COVID-19 have an impact on the aviation system?
10.2	How can we reduce the impact of future epidemic outbreaks proactively?
11.1	Are micro alliances a potential development scenario out of stable alliance networks?
11.2	How will the future development of low-cost carriers challenge alliances structures ?
12.1	How to maintain security levels while reducing disruptions?
12.2	How to evolve towards global coordination and unified implementation of security standards ?
13.1	How can combination carriers improve competitiveness?
13.2	How do freight forwarders and integrators consolidate efficiently?
14.1	How to fully harness the potential of machine learning and AI in scheduling problems in aviation?
14.2	How to develop schedules that are as adaptive as possible?
14.3	How can scheduling practices be effectively improved and leveraged to promote sustainability ?
15.1	How to measure and identify true methodological advances on MCDM methods ?
15.2	Can MCDM methods be applied at a broader range and for wider problems in air transport?

(Wandelt et al., 2023a), are due to the increasing demand, need for operational efficiencies, the aim to reduce environmental impacts, and gradually enhancing passenger experiences, while maintaining safety standards. In addition, emerging factors such as climate change require adaptable frameworks to ensure sustainability and compliance.

We hope and believe that our work will be guiding almanac for the community and helps to provide a clear view on open challenges and interesting directions for future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Sebastian Wandelt: Writing – original draft, Writing – review & editing. **Constantinos Antoniou:** Writing – original draft, Writing – review & editing. **Sebastian Birolini:** Writing – original draft, Writing – review & editing. **Daniel Delahaye:** Writing – original draft, Writing – review & editing. **Martin Dresner:** Writing – original draft, Writing – review & editing. **Xiaowen Fu:** Writing – original draft, Writing – review & editing. **Stefan Gössling:** Writing – original draft, Writing – review & editing. **Seock-Jin Hong:** Writing – original draft, Writing – review & editing. **Amedeo R. Odoni:** Writing – original draft, Writing – review & editing. **Massimiliano Zanin:** Writing – original draft, Writing – review & editing. **Anming Zhang:** Writing – original draft, Writing – review & editing. **Hui Zhang:** Writing – original draft, Writing – review & editing. **Yahua Zhang:** Writing – original draft, Writing – review & editing. **Xiaoqian Sun:** Writing – original draft, Writing – review & editing.

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Appendix A

Our classification is mainly based on papers published in the Journal of Air Transport Management (JATM), a peer-reviewed journal publishing research on the air transportation. Covering a period of three decades, we have downloaded 1997 abstracts from the journal's webpage². We use a recently proposed technique called t-distributed stochastic neighbor embedding (t-SNE). We have chosen t-SNE, given its strength to visually present a set of objects originating from a high-dimensional space, by mapping of objects into a two-dimensional space; see Hinton and Roweis (2002) for the development of a stochastic neighbor embedding and Van der Maaten and Hinton (2008) for a t-distributed variant with the goal of visualization. Each paper abstract is represented as an individual vector, whose components correspond to words appearing in the abstract. This leads to a matrix of term frequency-inverse document frequency features, which can be considered a statistical measure intended to identify how important a word is to a specific abstract, compared to the whole collection of abstracts.

² A few papers do not have abstracts, mostly concerning non-scientific contributions, e.g., book reviews.

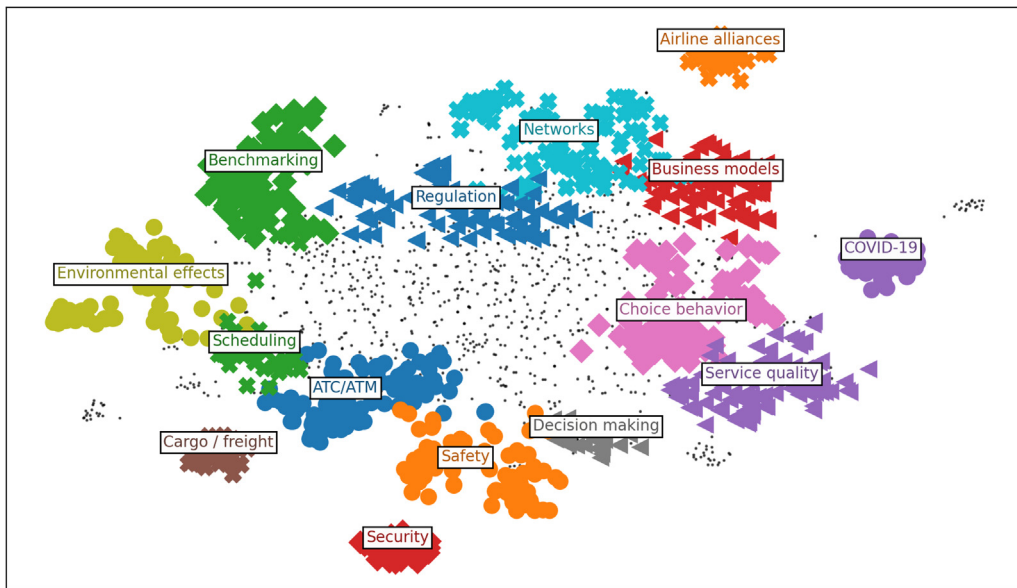


Fig. 3. Each data point represents an abstract of a paper. Categories are highlighted by labels and individual colors. Papers not assigned to category, mostly located towards the center of the figure, are visualized as black dots.

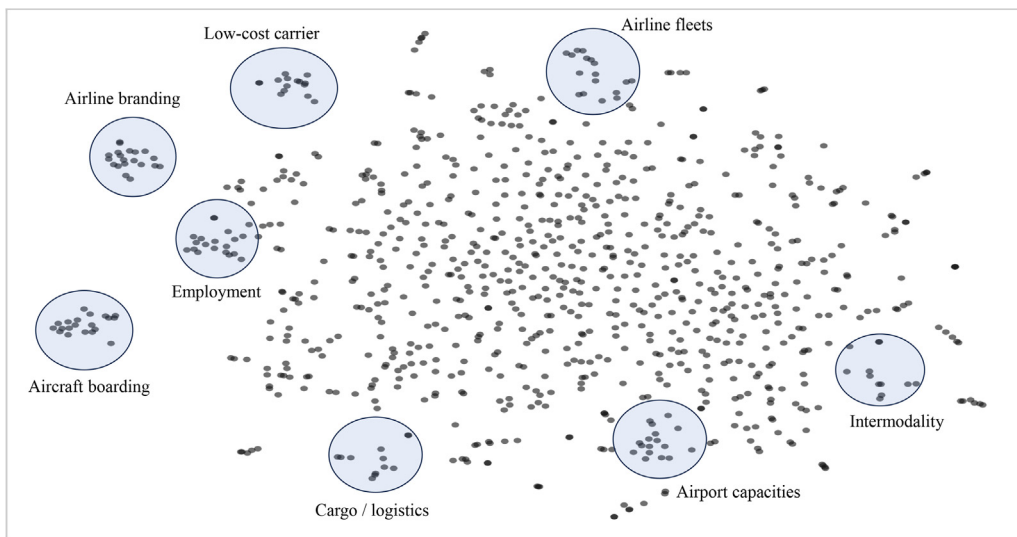


Fig. 4. Result of a repetitive t-SNE transformation for papers not being assigned to any of the 15 categories.

We have transformed these abstracts using t-SNE and obtained a two-dimensional embedding. The result of the embedding with labels attached to clusters is shown in Fig. 3. In total, we were able to derive 15 major categories.

Overall, these 15 categories cover about 60% of all papers published in the journal. The remaining papers cannot be assigned reasonably well to one of these clusters based on the abstract word importance measure. We have also performed an additional experiment where we repeatedly run t-SNE on these unassigned papers only, to see whether additional clusters emerge in absence of the other dominating clusters. Fig. 4 shows the results of this experiment. We can see that there are very few, and mostly smaller clusters, supporting the hypothesis that these remaining papers are indeed covering either subjects on the edge between existing clusters or constitute rather narrow research subjects on their own; not being covered by a significant number of JATM papers.

Fig. 5 visualizes the evolution of the 15 identified categories over the last three decades. The y-axis corresponds to categories and the x-axis to years. The color intensity of a cell correlates with the number of papers published in that category / year combination, with darker colors indicating a larger number of papers. We can see that a few categories are of high relevance to the journal rather early, e.g., papers in regulation have mostly been published in the first 20 years of the journal. Other categories peaked out intermediately, e.g., research on business models and benchmarking. The most recent categories with a larger number of papers are ATC/ATM and COVID-19. There exist very few categories which have received continuous and balanced attention from researchers over the years, most notably maybe the categories *Networks* and *Airline alliances*. The reason for this observation is presumably due to shifts in research / public interests as well as changes in the journal leadership / editorship.

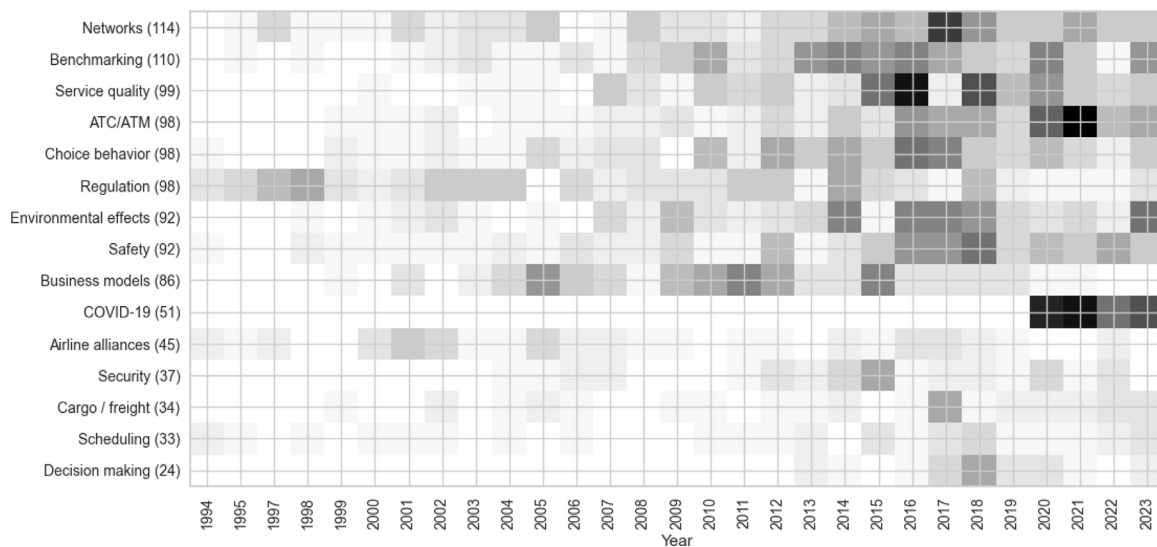


Fig. 5. Temporal distribution of papers in each category.

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