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Technological and educational challenges towards pandemic-resilient aviation

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**ARTICLE INFO**

**Keywords:**
- Air transportation
- COVID-19
- Technologies
- Education
- Challenges

**ABSTRACT**

While COVID-19 has devastating effects on aviation, several recent studies have highlighted the potential of the pandemic-induced break for rethinking air transportation, hopefully orchestrating changes towards the construction of a more pandemic-resilient aviation system. Here, pandemic-resilient means that aviation stakeholders can sustain the impact of an epidemic or pandemic outbreak through a more informed reallocation of their resources and more collaborative decision making, while being able to minimize the impacts of external events. Our study contributes to the literature by discussing the challenges associated with technological innovation and education of aviation professionals, on the way towards pandemic-resilient aviation. We discuss issues surrounding technologies for smarter aircraft, smarter airports, and smarter airlines. While technology ensures long-term competitiveness and sustainability, an often-ignored source of challenges are human resources and education. COVID-19 has uncovered and magnified the effects of severe concerns with the current aviation education system, which need to be solved by extended skill sets, modern technology, and better career perspectives. Without properly addressing these technological and educational challenges, the aviation industry likely misses an distinct opportunity for restructuring towards pandemic-resilient aviation.

**1. Introduction**

Aviation has witnessed a decade of tremendous growth, the number of passengers in commercial aviation had doubled between 2005 and 2019. The ongoing COVID-19 pandemic, however, has reminded aviation professionals how fragile success can be. The fragility is partially caused by efforts to make the aviation system more efficient and more profitable, increasing the risk of devastating failure. From an epidemiological perspective, it has been known for a while now that air transportation is one major driver for the spread of diseases, since aircraft enable conquering extreme distances before reaching incubation time (Brockmann and Helbing, 2013). This fact has been reported based on several earlier disease outbreaks, e.g., for SARS (Likhacheva, 2006; Bowen and Laroe, 2006), MERS (Zaki et al., 2012; Gardner et al., 2016), and Ebola (Bogoch and et al., 2015; Read et al., 2014). On a local scale, these earlier outbreaks had devastating effects, but it took COVID-19 to turn an epidemic outbreak into a full pandemic. COVID-19 is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and was first identified at the end of 2019 (see Zhang et al. (2020), for the role of air transportation in the initial spread of COVID-19 as a local epidemic). On March 11th, 2020, the World Health Organization (WHO) had declared COVID-19 officially as a pandemic (World Health Organization, 2020). By the end of June 2021, a total number of 182 million cases had been confirmed and more than 3.9 million fatalities reported, making COVID-19 one of the worst pandemics in recent history.

In addition to the direct impact on health, COVID-19 has had devastating effects on the aviation industry (Suau-Sanchez et al., 2020). An unprecedented reduction of flights (Nakamura and Managi, 2020; Sun et al., 2020), entire fleets being grounded (Adrienne et al., 2020), aviation workforce layoffs (Miani et al., 2021), a puzzle of country-wise flight bans and recoveries (Sun et al., 2021b), are the characteristics of probably aviation’s biggest crisis; see Sun et al. (2021c) for a recent review on the impact of COVID-19 on aviation. Despite the negative impact of COVID-19 and the ongoing struggle of aviation stakeholders for survival, several researchers have argued that now is the ideal opportunity to rethink and redesign aviation (Macilree and Duval, 2020;
The list of potential avenues for improvement is long, including the following key directions. First, a transition towards more climate-friendly operations will not only save our planet, but also can attract the millennials as customers and members of the aviation workforce. Second, with the excessive grounding of aircraft, reconsideration of business models, and pressure to reduce operating costs, there is huge potential for airline re-fleeting, leading to more fuel-efficient models and reducing the capital expenditure on new aircraft. Third, the time of reduced operations allows for rethinking of daily operations and processes, for instance, by increasing efforts towards digitization and automation in the industry. Finally, policy makers and regulators could consider how to guide all stakeholders towards a resilient aviation future.

To the best of our knowledge, the challenges surrounding technological innovation and education of aviation professionals due to COVID-19 have not been thoroughly discussed in the literature. Solving these challenges can help to reach the goal of pandemic-resilient aviation. Here, pandemic-resilient means that aviation stakeholders can sustain the impact of an epidemic or pandemic outbreak, by a more informed reallocation of their resources and more collaborative decision making, while being able to minimize the impacts of external events. In this study, we fill this gap in the literature and discuss a collection of challenges which are inherently attached to reaching the goal of pandemic-resilient aviation. These challenges are mostly aligned along the term smart. While this term has very broad meaning, we intend to narrow down the usage of smart towards two specific connotations: operated by automation and having a high degree of (mental/operational) ability. Accordingly, we use the word smart as an umbrella term for novel technologies, operational approaches, and a high degree of resilience.

The first part of this study concerns the usage of emerging technologies. As COVID-19 has revealed several severe problems with our current aviation system, the momentum should be used to push technological innovation. We discuss challenges surrounding technologies such as smarter airports, smarter aircraft, and smarter airlines. While technology ensures a long-term competitiveness and sustainability, an often-ignored source of challenges are human resources and their education. We discuss challenges concerning the educational practices for aviation professionals including the development of an extended skillset required in education, effective distant learning, increased gamification, and more flexible career options. We believe that without properly addressing these challenges, the aviation industry likely misses an important opportunity for restructuring towards being sustainable and pandemic-resilient. Recent advances in vaccination efforts across several countries and governments’ serious consideration to reopen borders will further push the envelope towards a restart ofaviation. The time has come to implement changes, making use of the COVID-19-induced reprieve before it is too late.

2. Technological challenges

The aviation industry is heavily built around technology, be it embedded in aircraft, enabling efficient airport handling, performing effective air traffic management, or for the sake of attracting passengers and improving their travel experience. The proliferation of novel technologies in aviation is a tedious process, mainly due to the global role air transportation takes in our society, which requires successful negotiation across a wide range of stakeholders with various cultural and professional backgrounds. Accordingly, identifying shared benefits for all stakeholders is often the key on achieving technological and regulatory advancement. In this section we describe a set of selected technologies and how they have the potential to contribute to a pandemic-resilient aviation system, through lessons and insights learned from COVID-19. Specifically, Section 2.1 investigates technologies concerned with smarter aircraft, Section 2.2 discusses technologies related to smarter airports, and Section 2.3 focuses on the selected technologies involving digitization of aviation. Fig. 1 provides an overview on the structure of this section.

2.1. Smarter aircraft

The design and construction of a novel aircraft type comes with tremendous expenses. For instance, Airbus spent approximately 25 billion USD to develop the A380 (Nelson, 2021); it was the biggest investment the manufacturer had ever made. While the design and production process led to many novel and long-lasting technologies, the overall project of the A380 is ultimately coined as a failure. The reasons for the failure are manifold; see Dorfler and Baumann (2014) for a discussion. One of the major reasons is presumably that airlines over-estimated their ability to fill more than 500 seats on connections that are being served multiple times a day (Nelson, 2021), together with severe financial and logistical challenges for airports (Forsyth, 2005); at the Dubai International airport more than one billion USD was spent for turning it into A380-ready. Such examples show the high risk involved in developing new aircraft technologies. Developing a new aircraft type is a strong bet into the future, for manufacturers as well as airlines. Aircraft manufacturers incur high costs for research and development and may face decade-long certifications with uncertain outcome (De Florio, 2016). Airlines are highly profit-driven, and they benefit from maintaining business as usual (Daft and Albers, 2015) as well as re-fleeting according to changes in demands and operations (Hu and Zhang, 2015); see Oguntona et al. (2019) for a recent survey of aircraft types usage and cabin layout among full-service carriers and low-cost carriers for the years 2000–2016. Accordingly, one could argue that under the turbulences of a pandemic, neither of these two stakeholders would be willing to risk considerable, let alone revolutionary, changes towards aircraft design. On the other hand, during times of reduced demand/operations, forced re-fleeting, and extensive government bailouts, the aviation industry should think long term (Macilree and Duval, 2020; Wilson and Chen, 2020; Suau-Sanchez et al., 2020; Gössl et al., 2021b). Below, we discuss the inherent challenges for future evolutionary/revolutionary aircraft design and cabin layout in a post-COVID-19 world and how policy makers could help to address them.

First, we discuss short-term changes which can be described as evolutionary design and layout changes. While the drop in passenger flights during early parts of COVID-19 was unprecedented, seeing levels of up to 90% reduction, cargo traffic was affected significantly less. With the ongoing pandemic, an increased need for cargo transportation, mainly due to rising e-commerce and the demand for medical supplies, coincided with the grounding of thousands of passenger aircraft. It did not take too long, until some airlines used aircraft originally built for passenger transportation and turned them into variants of freight aircraft. Some airlines have left the passenger area empty while filling only the belly of an aircraft with cargo and other airlines have removed all seats from passenger areas and reserved them for cargo transportation. Lufthansa reportedly was the first to name these converted aircraft as preighters (merging the two terms passenger aircraft and freighters)\footnote{https://www.airlinerwatch.com/2020/05/preighter-new-name-found-by-lufthansa.html.}. Whether or not the cargo success story will last beyond the current COVID-19 pandemic is uncertain. Arguably, if there was an extreme need for more cargo aviation, then one would have recognized this before the pandemic as well (Leopardi, 2021). The conversion of aircraft is a welcomed business for not only airlines but also other aviation stakeholders, e.g., companies originally focused on aircraft maintenance. This process, however, comes with regulatory problems. Turning the purpose of an aircraft also has an impact on the safety regulations and the granted use during certification. For instance, the European Union Aviation Safety Agency (EASA) has recently announced...
to limit the flight time of preighters to 2000 flight hours until the end of 2021. EASA argues that the cargo placed at passenger areas significantly increases the risk of fire. This example reveals again how slow processes in aviation can be: These preighters were flying for more than a year, until EASA realized that there is a need for regulation. Notably, here airlines created a de-facto situation first, due to extreme business needs. Usually, intended changes require prior year-long standardization and certification. Moreover, this example highlights how arbitrary regulatory decisions can be: Where does the number of 2000 flight hours come from? If there was a real general threat, preighters should be grounded. If the threat comes from specific materials, the transport of such material should be forbidden in preighters. People uninvolved into such decision making find it hard to follow such seemingly arbitrary policy decisions. There is a need for science-driven decision making and communication.

Unless the epidemiological situation worldwide changes significantly, aviation will likely reencounter a series of bans and recoveries, maybe not as strong as those in March 2020. Accordingly, airlines need to remain flexible regarding their markets and (short-term) business focus. Whether the increase in cargo operations is long-term, needs to be seen. Preighters do contribute to airlines’ flexibility and efficiency, e.g., see Hong and Zhang (2010). In the future, airports and aircraft could be designed/adapted to hybrid operations, where airlines can make more seamless transitions between passenger and cargo operations. This not only comes with technological challenges, including convertible aircraft-use areas as well as improved ground handling operations, but also comes with inherent regulatory challenges as well as future pandemics or other similar shocks. It is difficult to assess the long-term commitment aviation regulators would make to such hybrid operations, mainly due to outstanding safety concerns.

The tremendous uncertainty of long-distance flights during COVID-19, amplified by unanticipated border closures due to sudden outbreaks, could lead to other changes in business models for airlines (see also the discussion in Section 2.3), with implications on aircraft design. Traditionally, airlines have few interactions between revenue management and scheduling; this has changed significantly during the pandemic, due to the race for market opportunity (Garrow and Lurkin, 2021). The recovery of domestic markets was significantly faster than those of international, long-distance markets, and also significantly less volatile. Less volatility means easier to plan for airlines and eventually more profit under recovery (Gudmundsson et al., 2020). If the re-focus on domestic, short-distance travel is lasting, then this will naturally have an impact on aircraft design and fleeting decisions. Along the same line of thought, an open question is whether hub operations will be reduced as a side-effect of the pandemic; consolidating the business models followed by low-cost carriers. This might lead to novel, unique route profiles, such as ultra-long haul (Bauer et al., 2020). During the peaks of COVID-19, many airlines have reduced their maximum load factor to about two-third, in an attempt to guarantee minimum distance thresholds suggested by IATA, often by leaving the middle seat (if present) empty. Several forecasts predict that the leisure market will recover much earlier than the business market, given the increased availability of video conferencing and stricter considerations of travel needs by companies. This change, as well, challenges airlines. For instance, does it make sense to remove traditional business classes and rather provide further (class/price) distinctions for leisure passengers? In essence, the major question (in the short run) is which technologies could be used to turn the existing aircraft (interior) design into becoming pandemic-resilient. There is an urgent need for airlines to better understand how passenger behaviour has changed during the pandemic. Other evolutionary changes concern the use of smarter materials, e.g., shape memory alloys, piezoelectric materials, and carbon fiber reinforced polymer (CFRP), which build the backbone for recent advances in aircraft technologies (Sharma and Srinivas, 2020). Moreover, augmented reality in flight decks might soon enhance the pilot experience and spatial awareness in difficult situations, by augmenting the real world with an overlay of smart visual annotations (Abeyratne, 2020a). Similarly, crew and flight attendant operations inside an aircraft is likely supported by IOT-driven devices, compared to the paper printouts common nowadays.

In terms of evolutionary changes, i.e., within a time frame of 20–50 years, the potential for technology changes regarding smarter aircraft are huge. First of all, there exists much research on fundamentally-different aircraft designs for several decades now. For instance, blended wing body designs could reduce the fuel reduction significantly, contributing to aviation becoming more climate-friendly. In addition, larger passenger seating areas in blended wing bodies supports the idea of rethinking the interior of an aircraft, through a better consideration of passenger experience and social distancing. In nowadays single-aisle aircraft, there will always be a non-neglectable degree of interactions between larger passenger groups, which leads to (perceived) danger and threats. Governments and policy makers should push these designs now, and bind their funding and implementation to conditions leading towards pandemic-resilient aviation. While the aviation industry has made some improvements in the past decades, for instance, regarding the use of composite materials, synthetic fuels (Gossling et al., 2021a), modern manufacturing methods, and turning hardware functions into software.

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![Fig. 1. Overview on technological challenges and major solutions towards pandemic-resilient aviation.](image-url)
now it is the time to rethink at a larger scale, compared to performing business as usual. If it turns out that existing airlines and equipment manufacturers are reluctant to perform investments and upgrades, there needs to be a better support for novel, less conventional players, be it in terms of funding or certification reliefs. Overall, governmental support towards smarter aircraft should be bound to the realization of important societal goals and policies (Abate et al., 2020; Gossling, 2020).

### 2.2. Smarter airports

Throughout recent decades, there has been an increasing pressure on airports to be competitive (De Neufville and Neufville, 1995; Rothkopf and Wald, 2011; Tuchen et al., 2020). The competitive strength of an airport depends mainly on how many passengers consider an airport beneficial as a choice for traveling, given other substitutable airports (Forsyth and Dwyer, 2010). In the last decade, however, airports have become multi-services business organizations, whose non-aeronautical revenue is often larger than those revenues generated by the original business model of transporting passengers (Zhang and Czerny, 2012). Given the extensive competition among airports, airport services and their quality are critical for an airport’s success (Mainardes et al., 2021). One major element for the quality of service is the airport processing time, quantifying the time between arrival at the airport and departure; given that passengers are rather sensitive regarding waiting times (Sezerre and Gomes, 2020). Accordingly, many airports and airlines have participated in an IATA initiative called Fast Travel program, whose goal was to create uniform standards and recommended practices for how to speed up various phases of passenger processing, including check-in, luggage handling, document checks, and security checks. Notably, the Fast Travel program was terminated in the year 2019, just before the start of COVID-19, given that IATA considered the project mature and self-progressing. IATA started to focus on the One ID program,5 whose goal is twofold: First, it aims to ensure efficient and secure data flow between passengers, airlines, and governments. Second, it focuses on delivering a touchless/contactless passenger experience. Both goals presumably are instrumental to raise passenger confidence in air travel to relaunch the aviation industry in a sustainable post-COVID-19 era (Serrano and Kazda, 2020). Below, we discuss the inherent challenges towards smarter and touchless airports, highlight which technologies show potential for solving these challenges, and how policy makers could support the mature implementation of technologies in practice.

The ultimate goal of smarter airports is a document-free and touchless airport experience which is based on global identity management and tracking. In essence, passengers will be able to identify themselves at intermediate check points across the airport through effective, resilient biometric recognition services (see also the discussion in Section 2.3 related to Industry 4.0). Technologies which enable such a smart airport vision are based on the following three key ideas. Originally, a lot of research and testing had been performed on RFID technology, where a cellular network of passive RFID receivers, combined with far-field active RFID tags could be used for, e.g., luggage tracking (Shehib et al., 2016; Baasirah and Elleithy, 2019) or security checks (McCoy et al., 2005). The major limitation of this technology is that there is still a need for physical hand-over process of these RFID tags. Under pandemic consideration the major goal is to eliminate contact among passengers and airport staff. Accordingly, RFID has a promising future mainly for luggage tracking, but it will unlikely be a long-term, effective solution for passenger tracking. The second candidate technology is touchless fingerprinting. Traditional fingerprint detection comes with several problems, centered around the challenge to map a 3D finger to a 2D plane, which introduces distortions, noise, and inconsistencies on the captured fingerprint image (Farziale, 2006). In the last decade, researchers have developed touchless approaches which eliminate these problems. These innovations, however, come with new issues, mainly centered around incompatibility with (established) touch-based fingerprinting and the problem of detecting fake profiles; see Priesnitz et al. (2021) for a review of touchless fingerprinting projects.

The third candidate technology is based on gesture and face recognition. Massive advances in deep learning over images have led to a leap of reliability to detect and identify people and their gestures based on high-definition camera systems (Phillips et al., 2009). These high-definition camera systems could also be used for contact-less scanning of passports and health screening. Another promising technology is voice-based recognition; compared to the earlier technologies, voice recognition is still in its infancys and the required reference profile data are not available to airports; fingerprints and biometric face profiles, together with semi-mature processing techniques, are already available today. We conjecture that the mid-term future will likely see multimodal biometric recognition systems emerging, centered around high-definition cameras, which fuse different biometric modalities while improving prediction rates and achieving significantly increased robustness (Samarin et al., 2021). Along these lines, mobile phones might provide further support in verifying and guiding passengers from the point of entry at the airport to the boarding gate. However, it should be noted that a human workforce will never be fully eliminated from airport processing, since there is always a need for a backup in case the technology fails, for instance, physical presence or at least tele-presence. Similarly, highly-automatic processing still requires physical security backups in case some passengers are not cooperative. To sum up, the actual passenger handling and guidance at touchless airports will be done by machines and technology, but humans will have to supervise the correct execution.

The digital transformation of airports has seen significant advances in recent years, but COVID-19 has shown that there is more that needs to be done to reach pandemic-resilient aviation. The ultimate objective, which is to achieve a fully interoperable system that connects airports, airlines, and governments, is not established. The Internet of Things (IoT) promises to further push the envelope towards such a system (Zhang, 2020; Hyun, 2020), by permanently connecting a huge set of devices to the Internet and enabling them to communicate independently. There is an increased need for taking technologies from the research lab to practical use at airports. The current momentum around COVID-19 should be used by policy makers and operators to enable and implement such emerging technologies, for a sustainable future (Tonne, 2020). Just to give an example on how the pandemic affected passenger attitudes: Before the pandemic, passengers would have a hard time to understanding the purpose of using touchless gestures for controlling a terminal or self-check-in system (Iqbal and Campbell, 2020); with the experiences of the pandemic and its implications, passengers are likely keen on trying such options, in order to be able to travel safely.

Once the verification and tracking of passengers can be handled in a touchless manner, smarter airports still have hard challenges for their generation of non-aeronautical revenues. To predict how airports could be made smarter, one would need to first understand better what exactly caused the reduction in non-aviation revenues. To the best of our knowledge, there is no consensus on this question in the literature, yet. A primal contribution is the enforcement of social distancing during all stages of passenger processing at airports. Another reason is the fear inherent with passengers during the overall process of taking a flight, given that aviation has been connected with the spread of COVID-19. Moreover, several airport shop operators anticipated the mid-term effects of COVID-19 and simply closed-down operations. While the interaction between airport and city shopping and its implications for airport regulation were recently discussed in the literature, e.g., (Kidokoro et al., 2016; Czerny and Zhang, 2020), the integration strategies have yet been proposed and discussed. One viable solution specific to the shopping experience is the integration of city shopping with airport procedures. For instance, one could envision a system in which

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4. https://www.iata.org/whatwedo/passenger/fast-travel/Pages/index.aspx.
5. https://www.iata.org/en/programs/passenger/one-id/.
passengers’ shopping bags are transferred to the airport and automatically loaded into the aircraft, without further interaction needed by the passenger. Such an improved experience and exploring related options have huge potential to stipulate the recovery of non-aeronautical revenues. Finally, it should be noted that not all effects of COVID-19 are negative on the non-aeronautical revenues of airports. For instance, it has been reported that passengers increasingly use cars over public transit to go to the airport. Revenues from car parking and car rental could partially compensate from losses in other areas. Airport operators and policy makers need to streamline their recommendation to provide a well-thought and consistent smart airport experience; a set of scattered, half-hearted solutions are not likely to prepare airports for the next pandemic.

2.3. Smarter airlines

One of the major challenges for airlines nowadays - and also in a pandemic-resilient future - is to successfully move towards digitalization, accompanied with several highly relevant technologies. Since the beginning of industrialization, several major leaps can be observed, commonly abbreviated as industrial evolutions. The first three such revolutions include mechanization, electrification, and digitalization. While the first two revolutions were clearly present in the aviation sector, the third industrial revolution largely took place outside the aviation world. The benefits of digitalization (particularly the use of modern software and the Internet) was clear to most aviation stakeholders; yet, the aviation industry was long reluctant to leave their well-trodden paths. The reasons for this reluctance are various, most likely contributors were presumably a) the idea that one should not change a running system and b) unlikely appearance of novel competitors on the horizon. Only once low-cost carriers started to exploit digital technologies, a wider share of traditional aviation stakeholders signed up as well. Accordingly, it took aviation almost to the edge of the fourth industrial revolution, commonly labeled Industry 4.0 (Vaidya et al., 2018; Ghobakhloo, 2020), to gradually shift their attention to a major digitalization of their processes; see Abeyratne (2020a) for an overview and discussion of the digital age in aviation.\(^6\) Digitalization does not comprise a single technology on its own, but it can be considered a collective umbrella (Kuisma, 2018) for a wide range of complementary technologies, sometimes overlapping with the ideas behind Industry 4.0. From the aviation perspective, the two foremost technology groups during this transition period are data science and artificial intelligence. Below, we discuss the inherent challenges for these technologies during the pandemic and in a post-COVID-19 world, and how policy makers could help to address them.

The benefits of data management and data science for airlines are threefold: 1) increasing revenue by better understanding the demand and customers, 2) increasing the performance in comparison to other players in the market, and 3) increasing the safety based on more accurate operational data. IATA started to support the idea of better data management and analysis through a set of programs, e.g., IATA Direct Data Solutions\(^7\) (access to global airline market data), PaxIS\(^8\) (passenger-focused aviation data), AirportIS\(^9\) (for airports’ air service development projects), and OAG-Analyzer\(^10\) (for airline schedules). The more airlines join these efforts, the more valuable is the access to the overall data repository. Accordingly, in recent years, data regarding aviation has been increasingly made available in individual repositories, mostly spurred by usage of the above mentioned centralized data collection efforts, new players in the data aviation market based on ADS-B, and other open source datasets. As an illustration, see Sun et al. (2021a) for a comparative analysis of customer catchment areas between airports and high-speed railway stations using some of the open data.

Accordingly, one can safely claim that throughout the pandemic, there was an abundant ocean of data available to airlines. Yet, it seems like the available data did not (directly) help them to avoid the disaster. The major explanation for this fact is rather simple; and it has been observed by IATA more than a decade ago already: Airlines are sitting on a vast resource of valuable passenger data. The challenge is to use it effectively.\(^11\) The massive amount of data comes with a set of problems, which were not properly addressed before and during the COVID-19 pandemic. First, airlines still face tremendous challenges when it comes to uniquely identifying passengers, unless they have enrolled for one of the major frequent flyer programs. Identifying the same customer at different touch points (travel agency, website, phone, check-in) is not yet possible in a reliable way. Moreover, when data from different sources is fused together, a huge jungle of privacy laws need to be considered, laws which vary by regions. Therefore, the integration of distinct datasets without conflicts is a huge problem. Second, even if all data is available in a single, consistent repository, getting (correct) answers is tremendously challenging. On one hand, managerial aviation stakeholders are used to (small) Excel files and handy reports, not dealing with Gigabytes or Terabytes of raw data per day. On the other hand, unless a highly-optimized infrastructure is implemented, even simple queries can incur extremely high execution times. Therefore, operating such large datasets requires well-trained experts. Traditionally, these jobs would be filled by computer scientists, in recent years, the specialized track of data science has emerged. A few airlines have gradually realized this necessity for experts, e.g., Easyjet announced two years ago that it wants to become the most data-driven airline in the world,\(^12\) by hiring a team of data scientists. However, building up the human resources and technical infrastructure takes time. Finally, such an approach requires decision makers who understand the ramifications which come with data generated by data scientists; this data often comes with inconsistencies, uncertainty, modeling errors, and many more.

Another reason for why airlines are failing to be pandemic-resilient is the over-reliance on historical patterns (or aggregated data). In essence, passenger demand is highly predictable at times without disruptions, following very strong seasonal and spatial patterns. Therefore, in undisrupted times, airlines can operate large parts of their business as a safe bet into the future; particularly exploiting existing monopolies on routes or their hubs. During the COVID-19 pandemic, however, this strategy did not work out: All historical models were suddenly invalid. In absence of working models, operators found it extremely difficult to make informed decisions. And instead of actively working towards a better understanding of the pandemic and its dynamics, some airlines were busy requesting bailouts and offering tickets for flights without timely refunds, essentially making the passengers pay for market experiments.\(^13\) Therefore, we recommend that airlines should employ novel technologies, based on modern simulation and data science techniques which are less history-agnostic, being able to pick up trends more quickly (Garrow and Lurkin, 2021). With such novel models, airlines will be able to predict demand independently of their business as

\(^6\) Now Industry 4.0 is building on the Third, the digital revolution that has been occurring since the middle of the last century. It is characterized by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres.

\(^7\) https://www.iata.org/en/services/statistics/intelligence/direct-data-solutions/.

\(^8\) https://www.iata.org/en/services/statistics/intelligence/paxis/.

\(^9\) https://www.iata.org/en/services/statistics/intelligence/airportis/.

\(^10\) https://www.iata.org/en/services/statistics/intelligence/oag-analyzer/.

\(^11\) https://airlines.iata.org/analysis/airline-data-know-your-passengers.

\(^12\) https://www.marketingweek.com/easyjet-ceo-data-driven-airline/.

\(^13\) Lufthansa reportedly had a stock of more than one billion Euro from non-refunded tickets in Summer 2020. While the airlines stated officially that there refunding system does not support swift and automatized returns, the reason for not returning was presumably a financial motivation - at the expense of their customers.
usual. Research-wise such demand prediction and simulation is well understood, and all the required data is available to airlines.

With the Internet of Things, there comes a vision of a Global Aviation Intranet (ICAO, 2020), which connects various stakeholders from different domains, consisting of a collection of novel commercial network services and is mainly based on public Internet technologies. Opening up access to such an intranet to global providers, including non-aviation stakeholders, raises a wide range of security and performance requirements. The required standards and recommendations need to be developed in a timely manner, to eliminate the lack of integration in today’s point-to-point communication infrastructures with sparse connectivity. Once such a connected system is established, the above data management challenges will need to receive even more attention, to address the abundant amount of exchanged data. In addition, there will be outstanding requirements on the security/trust layer of such an open system. For instance, measures need to put in place which avoid cyber threats, e.g., flight plan forging, operator impersonation, and other data manipulation. There is a need for increased human and automated oversight in such a global system.

The second computer science-driven technology with huge potential to have a disruptive impact on airlines is artificial intelligence. In fact, artificial intelligence (or machine learning) is highly related to the data issue discussed above: The inherent goal of machine learning techniques is to identify and possibly explain patterns in complex data. A few examples from the scientific literature where aviation problems are solved by artificial intelligence include arrival time prediction by multi-cells neural networks (Wang et al., 2018), long/short-term memory for airline sentiment analysis (Naseem et al., 2019), fuel consumption prediction (Li, 2010), and faster aircraft design (Azizi Oroumieh et al., 2013). The degree of implementation in aviation companies is rather low - despite being motivated for more than 30 years (McMullen, 1987), presumably due to the dominance of simple, easily-interpretable models prevalent in the aviation industry (Maheshwari et al., 2018). In addition, some aviation processes have extremely high standards on safety and reliance, particularly under unforeseen circumstances. By design, artificial intelligence methods are trained and evaluated on previously-seen samples. Once such a model encounters an unseen real-world situation, its reaction is often unpredictable, let alone explainable. A rather vivid, psychologically-motivated example is the usage of artificial intelligence for autonomous control of aircraft: In case of a forced landing, should the artificial agent perform the landing in a school playing field or the gardens of a retirement home (England and Phippard, 2019)? Such decisions involve multiple ethical and technical considerations, which are unlikely performed with minimally invasive impact. Accordingly, using artificial intelligence as a support to humans is conceivable, but a fully-automated system is unlikely to emerge at this point. In a more general sense, today’s aviation largely relies on human involvement at all levels, including maintenance, air traffic control, or flight deck management. This makes a short-term transition difficult towards an entirely artificial intelligence-driven solution (Abeyratne, 2020b).

Data science and artificial intelligence are undoubtedly indispensable technologies for airlines while moving towards a sustainable aviation future. Policy makers are required to set ramifications accordingly, to allow for these technologies to be used effectively and in a timely manner. Specifically, we see the following areas with high potential for improvement.

1. There is a need for better and more realistic regulation of data privacy and global identifiers. In times when most social media companies have created quasi-identifiers for large parts of the online population, it seems inadequate to block airlines from doing so, due to national concerns. Particularly, with the ongoing vaccination efforts, there is a need to verify identities of passengers throughout the whole flight process. This opportunity should not be missed by policy makers to generate a better use of personal identifiers in aviation.

2. We advocate for a better understanding of the processes underlying data science. The idea of having a click-and-go spreadsheet-based product for analyzing terabytes of heterogeneous data is unlikely to turn out well soon. The aviation industry needs to appreciate that this task requires experts, and decision makers need to understand the ramifications and limitations of using excessive historical data to derive novel insights. Especially at the leadership level, the terms data science and artificial intelligence should not only be buzzwords, but leaders should set guidelines and be aware of their company’s exploitation of these technologies.

3. Much of aviation data is hidden behind a paywall, which means that it is extremely difficult for the scientific community to push the envelope for significant leaps leading towards universal insights, better frameworks, and insightful, working systems. Policy makers and operators need to find ways to join forces with the research community in order to make research progress feasible and affordable. A major challenge is how to incentivize airlines to publish their data. Given that individual airlines are too afraid of losing a competitive edge, IATA is likely the right player here. IATA should steer a process of gradually releasing data to the public, while reducing possibly negative impact on individual airlines.

4. Regarding the application of artificial intelligence, again, we perceive a strong dispersion between academic papers and what is done in an operating environment. Policy makers should define standard tasks and evaluation measures, for which researchers can implement and evaluate solutions based on artificial intelligence; ideally trained on publicly available data. By doing so, airlines can directly see the benefits of novel solutions contrary to their own. In addition, a seminal discussion on ethical considerations and consequences of artificial intelligence is due.

3. Educational challenges

During the past century, a fundamental shift in engineering education took place, describing a set of transformations: 1) from practical emphasis to analytical emphasis, 2) outcome-based education, 3) engineering design, 4) a combination of education, learning, and social behaviour research, towards 5) integrating information, computing, and communication technology in engineering education. The next shift has appeared on the education horizon and is related to the transition towards Industry 4.0, which requires proficiency in technology and information (Ramirez-Mendoza et al., 2018; Hernandez-de Menendez et al., 2020). Approximately two-third of pupils entering primary school these years will perform jobs which do not even exist yet (World Economic Forum, 2017). Regarding the required skill set, there is an observed, important mismatch between the education providers and their customers. While 74% of universities believe that their graduates are adequately prepared for entry level positions, only 35% of employers and 38% of students think so (Lappas and Kourousis, 2016). As long as universities fail to acknowledge and improve their shortcomings in practice-oriented education, the pathways towards a better education are blocked.

It is natural, that aviation will not be left out from these transitions, particularly, since the whole aviation industry has to catch up regarding digitization. Despite the existence of earlier epidemic outbreaks, regarding research on the impact of epidemics and pandemics on aviation, students and universities’ responses are rather limited (Miani et al., 2021). The reason is presumably the rare nature of such extreme events, which makes stakeholders and policy makers believe that they are of low interest. Time will show whether and how COVID-19 changes the education research landscape. Obviously, COVID-19 had unprecedented direct impacts on the aviation workforce, including tremendous job losses and also organisational closures and restructuring of human resources; see Albers and Rundshagen (2020) on how airlines restructured during the COVID-19 pandemic. In addition, the pandemic has placed a high burden on pilots to maintain their flight proficiency. According to
Aviation Safety Reporting System data analysis, the number of pilot-reported incidents increased by 1000% during the pandemic (Olaganathan and Amihan, 2021).

Universities and other education providers have an outstanding responsibility to helping graduates manage the associated impacts and better prepare them for the changing industry (Miani et al., 2021). Several aviation-related jobs are likely to switch from an active and tactic-oriented role to a role that is rather focused on monitoring and strategic decision-making (Goletti et al., 2021). For example, these transitions will likely be first visible in areas of air traffic management, where human operators will supervise and guide the work of computational intelligence. Other technology-induced, emerging occupations in aviation are summarized below, see Knowledge Alliance in Air Transport (2018) for details:

**Design and operation of automated vehicles:** The future of aviation will likely see many smaller, semi-automatic vehicles, e.g., for preemptive aircraft maintenance and luggage handling. The operation of such vehicles will be highly automated and need to be programmed and supervised by specifically-trained aviation personal.

**AI and data engineers:** With an ongoing integration of artificial intelligence and data science techniques into aviation, there will be an extraordinary need in engineers to develop, operate, and maintain such systems. These engineers need to have expert knowledge not only in aviation but also computer science.

**Privacy protection analysts:** If the future of aviation is to be successfully built on data and integrated systems, there will be an increasing need for experts in the area of privacy protections; not only from a technical perspective, but also include legal ones.

**Cyber security experts:** With the increase in the dissemination of integrated and adaptive systems, cyber security will become a major topic, given that the underlying data and application programming interfaces need to be partially connected to the public.

**Climate change experts:** Given the extraordinary initiative for climate change and the role of aviation, especially across younger people, i.e., the future aviation workforce, companies will have to seriously consider the issues around climate change, likely by recruiting and publicizing the existence of specialized experts in this area.

These new jobs, together with yet-unknown jobs on the aviation horizon, will require a rethinking of aviation education. Many aviation-related jobs, e.g., pilots and maintenance personnel, have outstanding requirements on graduate students. A traditionally highly-selective recruitment process mismatches a highly bewildered cohort of high school and undergraduate students, who have seen the potential for extreme volatility of the aviation sector and its effects on aviation professionals. The supply of qualified aviation workforce was already predicted to be insufficient pre-COVID-19; forecasts indicated that a shortage of ten thousands of maintenance personnel and pilots is expected in the following decades (Zaharia et al., 2021b). Therefore, the current momentum of COVID-19, provides outstanding opportunities to revise curricula and make them future-safe and sustainable (Carnevale and Hatak, 2020); specifically since recent research showed that students recognize the need for further skill development (Miani et al., 2021), and accordingly are presumably keen on participating in the transformation process. Below, we describe the education-related major areas in which we see enormous potential for change in the next few decades. We focus on an extended skill set (Section 3.1), the use of modern techniques in education (Section 3.2), and increasing career perspectives (Section 3.3). Fig. 2 provides an overview on the structure of this section.

### 3.1. Smarter skills

The skill set required for future aviation graduates is tightly connected to the inherent transformation of the industry (Lappas and Kourousis, 2016). COVID-19 has shed light on several skills which might turn out critical for the future work force, in order to obtain pandemic-resilient aviation. A major skill required for the workforce driving the future of aviation is the ability to deal with uncertainties and probabilities correctly; which is a long understudied problem in civil engineering (Chou et al., 1995; Goyal et al., 1997). In essence, the COVID-19 pandemic was the black swan event that several researchers had predicted to happen (only nobody knew the exact date), while the aviation industry completely missed out on preparations. The reasons for aviation not being prepared to predictable surprises are various (Burbidge, 2013), including economic considerations and lack of information/guidance. One extremely fundamental problem here is the inability to anticipate the likelihood and huge impact of such rare events (Aven, 2013). Accordingly, we advocate for a better preparation of students in terms of making long-term decisions under the impression of the unlikely. Similarly, the overall reaction to COVID-19 over time has shown that large parts of the population, be it educationally trained or not, lack fundamental knowledge about simple concepts such as exponential growth, phase transitions, and other basics of mathematics and statistical physics. To create an aviation workforce which can prepare their companies for a pandemic-resilient future, there is an urgent need to teach such skills during undergraduate education. Along these lines, aviation stakeholders need to be better trained in system thinking, by taking into consideration non-trivial interactions between a system’s components, instead of being focused on optimizing a single component.

Another major skill that was shown to be underdeveloped...
throughout the COVID-19 pandemic is the ability to deal with virtual and augmented reality (Brown et al., 2021). This begins with simple, yet chaotic video conference setups - which hold until more than one year after the outbreak. Future technologies will raise the entry barriers for employees regarding virtual and augmented reality significantly. Especially under social distancing constraints and travel restrictions, physical access to meetings and aviation devices will always be a problem. It can be expected that many tasks which require physical access today will be executed by small, semi-autonomous vehicles or robots in the future leading to novel learning opportunities (Miani et al., 2021). These robots need to be controlled and supervised by humans; who are interacting with the environment by means of virtual and augmented reality (Macchiarella and Vincenzi, 2004). The required skills target human-machine and machine-machine interaction as well as acquiring new ways of understanding spatial and temporal representations. Without such a skill set, the automation of aviation will be significantly slowed down, as physical presence will outperform such remote working in a profitability-driven industry.

Apart from these technical skills, we see a set of soft skills necessary to enable pandemic-resilient aviation. Several of these skills have been formulated as important before the pandemic. But it seems like their integration into education has not seen sufficient success yet. Among others, sustainable aviation requires a sense of social responsibility, which at first sight goes diametrically opposed to being profit-oriented. The latter observation is presumably one of the major reasons why aviation stakeholders are reluctant to prepare for a sustainable future. However, given tremendous shifts in the society, especially among the younger generations, the future customers of airlines will be rather sensitive to issues such as climate impact and sustainable mobility. Accordingly, it is conceivable that airlines will be forced to change business models, in order to attract and keep these younger customers loyal. In fact, one could imagine a scenario in which one of the players (be it an existent or a new player) rushes towards this increasingly growing market of sustainability-aware individuals, driven by various social and personal drivers (Wallis and Loy, 2021). And - despite all environmental considerations - these younger generations will have strong desires to travel after the COVID-19 pandemic. Therefore, the argument of profitability should not be used against change in aviation; but this change should be supported by increasing the relevant social skills across the aviation workforce. At the same time, it has been reported that aviation managers need a greater level of business acumen (Tisdall and Zhang, 2020), in order to enable pandemic-resilient aviation.

The last two skills which we want to highlight concern cultural awareness and communication/consensus finding. The ongoing COVID-19 pandemic has highlighted one large societal trend: our global world is developing a tendency towards a regain of strong nationalism; a crisis always comes with shifts in context (Falleti and Lynch, 2009). COVID-19 can be considered as a multi-layer disease, where the medical disease caused by the virus is accompanied by a disease-spreading from the failure of institutions and shift of contexts (Woods et al., 2020). It comes as no surprise that the failure of institutions and the political virus are always linked. It can be expected that many tasks which require physical access today will be executed by small, semi-autonomous vehicles or robots in the future leading to novel learning opportunities (Miani et al., 2021). These robots need to be controlled and supervised by humans; who are interacting with the environment by means of virtual and augmented reality (Macchiarella and Vincenzi, 2004). The required skills target human-machine and machine-machine interaction as well as acquiring new ways of understanding spatial and temporal representations. Without such a skill set, the automation of aviation will be significantly slowed down, as physical presence will outperform such remote working in a profitability-driven industry.

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3.2. Smarter learning

Historically, aviation has seen three larger generations of education training, which can be referred to as apprenticeship (1903-1929), simulation (1929-1979), and safety (1979-today); see Kearns (2016) for a review. The outcome of the third generation is the effective use of all available resources leading to the goal of safe and efficient flight operations (Jensen, 1997; Helmreich and Merritt, 2000). Distance learning has a huge potential to herald the start of a fourth generation of education training in the aviation sector. This observation is not new; it is haunting aviation for around two decades now (Raisinghani et al., 2005; Scarpellini and Bowen, 2018). Nevertheless, distance learning has not seen the long-expected breakthrough in aviation. The reason is presumably threefold. First, such distance learning courses vary dramatically in quality, with the poorest courses usually being directly converted from classroom presentation, without considerations of different learning environments (Kearns, 2016); and the transformation potential attracts players who use it as moneymaking schemes (Scarpellini and Bowen, 2018). Second, preparing online material well requires tremendous time, effort, and financial backing by the teachers; resources which are often not available under business as usual. Third, the motivation for distance learning is mainly driven by the stimulus of technology availability (Tarryn Kille and Murray, 2015; Moore and Kearsley, 2012), not because the major aviation stakeholders realized the true need for implementation. With COVID-19, the latter reason has clearly changed, and most stakeholders should see the urgent need to prepare for distance learning, be it for the consideration of social distancing or for reaching a wider audience. With a lack of education digitization, one misses ample opportunity for attracting future workforce across media-affine younger generations. Below, we describe the ongoing challenges for better distance learning and discuss pathways towards pandemic-resilient aviation education.

There exists plenty of research on the impact of COVID-19 on distance education, including the role in virtual class rooms (Alihat, 2020), e-learning (Soni, 2020), mobile learning (Naciri et al., 2020), offline learning (Anwar and Adnan, 2020), student perceptions (Biswas et al., 2020), student life (Aristovnik et al., 2020), and the role of teachers (Hosan et al., 2020). It is beyond the scope of this study to review all these impacts exhaustively. We focus on a few challenges which turned out to be most important from our perspective. First, the access of students to online material depends on the economic status of their families, and therefore is susceptible to inequality (Choudhury, 2020), due to limited devices as well as insufficient bandwidth in countries with less-developed communication infrastructure (Eltayeb and Sullivan, 2020). Second, the lack of physical interaction between students and their teachers are not well understood yet (Deví, 2020), and possibly leads to lack of motivation and reduced learning efficiency. Students need to be gradually advised and accompanied when facing the transitions to learn on their own, in an online format (Toquero, 2020). Finally, ensuring fair examination conditions to all students in online e-learning (Soni, 2020), mobile learning (Naciri et al., 2020), offline learning (Anwar and Adnan, 2020), student perceptions (Biswas et al., 2020), student life (Aristovnik et al., 2020), and the role of teachers (Hosan et al., 2020). It is beyond the scope of this study to review all these impacts exhaustively. We focus on a few challenges which turned out to be most important from our perspective. First, the access of students to online material depends on the economic status of their families, and therefore is susceptible to inequality (Choudhury, 2020), due to limited devices as well as insufficient bandwidth in countries with less-developed communication infrastructure (Eltayeb and Sullivan, 2020). Second, the lack of physical interaction between students and their teachers are not well understood yet (Deví, 2020), and possibly leads to lack of motivation and reduced learning efficiency. Students need to be gradually advised and accompanied when facing the transitions to learn on their own, in an online format (Toquero, 2020). Finally, ensuring fair examination conditions to all students in online
environments and avoiding students to fall to the temptation of cheating, requires the development of new techniques (Chen et al., 2020). Several course types cannot be transferred reasonably well, e.g., those involving mechanical interactions with aircraft parts which are not accessible remotely to the students. Given that future aviation jobs will presumably be involving less physical, routine, or repetitive tasks, a further shift towards more distance-learning parts can be anticipated (Zaharia et al., 2021b). To support the establishment of effective distance learning courses, new accreditation procedures are required, as traditional procedures turned out to be not as appropriate as expected; and a stronger focus on outcome-based training and evaluation is necessary (Scarpellini and Bowen, 2018).

Earlier research has shown that a blended learning strategy, which incorporates dual elements from face-to-face and human-computer interactions is the most promising distance learning method in aviation (Kears, 2016); in this setup, time for physical presence is reduced, but not fully eliminated. Given the strong need to create online content, aviation educators should prepare their teaching material specifically for the next generation of aviation professionals. Recent research on education has shown that nowadays and future students require a much higher level of engagement in teaching - which seems contradictory to the idea of lonely remote learning. In this context, the use of games as educational learning tools has been highlighted for several years now (Kapp, 2012; Miller, 2013; Gentry et al., 2019). The rationale is that such games often come with a remarkable motivational power; encourage people to engage without physical reward (Deterding et al., 2011). There are several reasons why such gamification has not revolutionized education yet. First, creating a highly-engaging instructional game is extremely time consuming and costly (Kapp, 2012). Considering that a single game often targets a small number of specific skills, the benefits are considered smaller than the costs (Dicheva et al., 2015). Second, the designers of the game need to be not only aviation experts, but also specialists in computer science and graphics skills, not to mention a background in human-computer interaction and psychology. Accordingly, in order to develop an effective game, a whole group of experts need to be united. Finally, it has been shown in the literature that technology turned out to be a major stumbling block in the process of creating distance learning content; or as Scarpellini and Bowen (2018) put it: Technology was a program’s greatest ally and most formidable foe when difficulties appeared.

The aviation education industry is not yet willing to invest the required human resources and money into gamification, except from a few lighthouse projects. For instance, the Federal Aviation Administration (FAA) has developed the airport design challenge, a five-week program targeted towards high-school students, with the goal to design a working airport in the game environment Minecraft; see Keim and Jarrard (2021) for further discussion on using Minecraft in higher education. To push the envelope for gamification in aviation education, there is a need for a better infrastructure to develop such distance learning content with gamification elements. In addition, we need better training of the aviation teachers. Given that the current mid-age teacher generation mainly grew up with digitized content and mobile devices, they have a much better prerequisite for preparing online content than the teacher generation 20 years ago. For the younger generations, such digital-relevant abilities are not considered extra skills, but rather part of everyday life (Miani et al., 2021).

3.3. Smarter careers

For the past decade, a major concern for aviation stakeholders was the recruiting of the future workforce; particularly, a shortage of pilots was anticipated as a major risk in aviation. With the emergence of COVID-19, the situation changed significantly within a few weeks of time, turning a lack of supply to an oversupply in pilots and crew members on the market. While the long-term effects are still uncertain, such career shocks (Akkermans et al., 2020; Miani et al., 2021) have a tremendous impact on career considerations and thought processes and might lead to shifts in interests and career choices. Accordingly, establishing a long-term, pandemic-resilient aviation system requires an integrated research agenda for tackling career challenges appearing on the horizon (Carnevale and Hatak, 2020).

During the early phase of the pandemic, the hardest hit group of aviation employees are those concerned with passenger handling and flight operations; the management workforce is less affected (Sobieralski, 2020). In the long run, this relationship might change. First, the long-term effect on pilots is presumably not as significant as for other aviation personnel. The reason is that pilot operations do not depend on the load factor, but on the number of aircraft movements. It has been shown in the literature, that the number of movements has seen a strong recovery in the past one year, mainly driven by domestic flights. The temporary, unexpected layoff of pilots might still cause reconsiderations among younger people, realizing that the choice of becoming pilot is less of a secure bet than imagined, but we conjecture that these effects are rather small. Second, for other aviation jobs, the threat is much larger, especially if their job profile offers sufficient potential for automation or savings.

The current aviation curriculums (in London, Australia, US, S Korea, and Hong Kong) seem to focus mainly on efficiency in the allocation of resources: operational efficiency for the industry and economic efficiency (the latter has implications for government policy making). Over the last two decades, environment/sustainability has become an important aspect, the so-called green aviation: e.g., emissions control; alternative energy for aircraft (e.g., bio-fuel). Then, COVID-19 has highlighted the potential of the pandemic-induced break for rethinking air transportation, hopefully orchestrating changes towards the construction of a more pandemic-resilient aviation operations and policies. It would be good to equip students with, for example, the knowledge (models, tools, operations, etc.) to deal with air traffic disruptions caused by global catastrophes such as COVID-19. It would be nice, in the future, to somehow incorporate the green and resilience, along with efficiency and technological innovations, into education of future aviation professionals.

Airlines should offer career and succession plans to personnel, specifically to flight attendants, to increase corporate identity (Ilkhanizadeh and Karatepe, 2017). Governmental support should be targeted towards the less-skilled workforce, as these are usually the hardest hit (Sobieralski, 2020). Another major issue for recruitment recently is related to graduates with multiple specializations, students who are experts in more than one domain. Examples for such dual domain experts are computer scientists with an aeronautical background, transportation engineers with an environmental background, or aviation experts with a law background. Given that future challenges in air transportation are largely multi-disciplinary, the lack of such adequate experts is not only concerning but yields pathways out of the crisis. Being an expert across multiple domains increases the resilience of workforce qualification, and more likely ensures an employability in various working places.

In addition, we are in a phase of life-long learning. Employers should support this transition by enabling the re-skilling of current employees on the job, e.g., through online courses, boot camps, or rotation programs (World Economic Forum, 2017). The short-term losses for such additional qualification rounds are easily outweighed by the long-term increase in productivity and increased systemic resilience of the workforce against shocks. This requires the identification of sweet spots between being competitive/profitable and protecting the workforce. In addition, there is a need for a better integration between academic career tracks and professional career tracks (Zaharia et al., 2021a). To sum up, while many stakeholders are talking about smarter airports and smarter aircraft, we advocate to aim towards smarter aviation education.

https://www.faa.gov/education/virtual_learning/airport_design/.
The latter will inevitably lead to the two formers.

4. Conclusions

Given the increased operational complexity, the vision of pandemic-resilient aviation requires the industry to gradually adopt new concepts, technologies, and educational patterns, some of which are not solely designed for aviation purposes. Below, we summarize the major insights of this study and provide recommendations for future work.

Most importantly, data is the key to the future. The appetite for data is growing among aviation stakeholders, given an increasing number of success stories from various aviation domains. Satisfying this appetite will require several major prerequisites. First, passengers need to be willing to share their data. Convincing the generations born towards the end of the 20th century will be essential for getting started, since their willingness to share data is inherently high, particularly once the benefits of sharing the data are clearly defined (World Economic Forum, 2017). Second, the aviation industry needs to be willing to share each other’s customer data. While there is an abstract consensus that such a pool of aviation data is beneficial to everyone, it will be highly challenging to get started, since airlines are reluctant to be the first participants. Regulators and governments should encourage the industry to create data-sharing platforms, based on advertising actual use cases and benefits. Third, the industry needs to be better prepared for the increasing threat of cyber attacks, and establish orchestrated strategies and implementations for resilient cyber security. Fourth, the industry and policy makers need to define standards for data interoperability; only if data can be accessed by all parties easily, the vision of hyper-personalization will become true. Finally, it should be noted that a successful implementation of the fully data-driven aviation requires a consistent implementation and interoperability across all domains. In terms of aviation education, it is critical to cultivate a data-driven culture for students (“Data drives decisions”) and develop their data skills. At the same time, we need to incorporate the green aviation, along with efficiency and technological innovations, into education of future aviation professionals.

Another critical element for pandemic-resilient aviation is the recognition of the importance of multi-stakeholder solutions. The COVID-19 pandemic has highlighted that a patchwork of uncoordinated country actions and region-specific regulations is only a driver for chaos and reduces the aviation industry’s ability to respond to shocks in an adequate manner. Accordingly, a multi-stakeholder approach needs to be developed and strengthened inside aviation. Here, stakeholders involve private, public, and civil-society organizations altogether, with the ultimate goal to develop policy frameworks and working implementations. There is a need for a better model of international collaboration, which exploits the ongoing digitization and efforts to disseminate and exploit information. There exist candidate programs which should receive more attention and more funding, e.g., the Collaborative Arrangement for the Prevention and Management of Public Health Events in Civil Aviation - CAPSCA,15 which was already established in the year 2006. The goal of CAPSCA is to improve preparedness planning and response to public health events that affect the aviation sector. However, CAPSCA’s visibility, flexibility, and authority throughout a pandemic should be further improved. Specifically, the performance of such organizations and programs should be analyzed in future research studies, together with recommendations on how to further improve them.

Education is another key element for leading us towards pandemic-resilient transportation. With the ongoing advances in automation, the ability to interact with machines and supervise their execution will become a critical asset for the next aviation generation. One potential threat here is that the digital natives are over-confident in using such novel technologies, given that they were raised up by interacting with all kinds of devices. Accordingly, we need to ensure that the new generation does receive appropriate formal training, and that they realize that this training is indeed meaningful, for reaching specific safety and security standards of aviation operations. Gamification is very likely one essential element for reaching these future aviation workers and making them learn by playing. Regarding the creation of digital learning content, there is a need for global cooperation, not only to create fancy lighthouse projects, but to invest into a broad aviation learning infrastructure, including shared codes for implementation, common visualization templates, etc.

The gap between innovation and regulation need to be narrowed. ICAO aims for a single universal aviation world of information (ICAO, 2020), it is on all aviation stakeholders to make orchestrated contribution, inducing sophisticated cooperation between governments, education institutions, industry representatives and regulators. Only if everybody is on board, we can turn the vision of pandemic-resilient aviation into reality.

Acknowledgement

Removed for double-blind review. This study is supported by the National Natural Science Foundation of China (Grant No. 71731001, No. 6186136005, and No. 6165101516).

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