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COVID-19 pandemic and air transportation: Summary of Recent Research, Policy Consideration and Future Research Directions

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ARTICLE INFO

Keywords:
COVID-19
Pandemics
Air transportation
Literature review

ABSTRACT

The COVID-19 pandemic can be considered an unparalleled disruption to the aviation industry in the last century. Starting with an at-that-time inconceivable reduction in the number of flights from March 2020 to May 2020, the aviation industry has been trying to navigate through and out of the crisis. This process is accompanied with a significant number of scientific studies, reporting on the direct and indirect impact of the COVID-19 pandemic on aviation and vice versa. This paper reviews the impacts in context of the recent literature. We have collected nearly 200 well-published papers on the subject in the years 2021/2022 and dissected them into a framework of eight categories, built around: airlines, airports, passengers, workforce, markets, contagion, sustainability, and economics. We highlight the essence of findings in the literature and derive a set of future research directions and policy considerations which we deem important on the way towards pandemic-resilient aviation.

Introduction

The impact of COVID-19 on aviation is devastating, as a few representative numbers for the year 2020 indicate (IATA, 2020): The number of air passengers reduced by 60.2% compared to 2019, leading to a system-wide load factor of 65.1%. International and domestic air travel demand dropped by 75.6% and 48.8%, respectively. Net losses of 126.4 billion USD, on revenue loss of 373 billion USD by airlines were observed in the year 2020. Direct aviation jobs (at airlines, airports, manufacturers, and air traffic management) decreased by approximately 43%, and aviation-supported jobs are estimated to have reduced by 52%.

While the aviation industry experienced a partial recovery throughout the year 2021, particularly in domestic markets, the industry is far from back to normality and needs to open up in a responsible manner (Dube et al., 2021; Tsvetkova et al., 2022; Calderon Peralvo and Cazorla Vanegas, 2022; Gao, 2022).

This study aims at dissecting and categorizing the aviation-related literature on COVID-19. As a baseline, we take our earlier study, entitled COVID-19 pandemic and air transportation: Successfully navigating the

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https://doi.org/10.1016/j.trip.2022.100718
Received 13 October 2022; Received in revised form 2 November 2022; Accepted 6 November 2022
Available online 8 November 2022
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paper hurricane (Sun et al., 2021d), which collected and summarized about 110 scientific papers published in the year 2020, describing the early impacts of COVID-19 on aviation. Since then, the paper hurricane has further pummeled the aviation literature. The reasons for the abundant number of studies on aviation and COVID-19 are manifold. First, it is frequently stated that aviation is probably among the hardest hit industries. Second, aviation plays a major role in epidemic spreading: While aviation is a victim of COVID-19 ramifications, our effective air transportation system enabled the spread of the virus to farthest places on our planet. The major rationale here is that the ability of our modern society to cross large distances in a short amount of time with notable seat capacities, reduces the geographical distance between distant communities significantly, following the notion of effective distance proposed for disease spreading analysis (Brockmann and Helbing, 2013). With a decreasingly effective distance between communities, the reaction time for the society to prevent an epidemic outbreak turning into a full pandemic is gradually smaller. In other words, the spread of COVID-19 is not due to specific aviation concepts, but rather supported and magnified by the efficiency of our transportation systems. With that in mind, an analysis of aviation under COVID-19 (not necessarily as a cause, but as a companion of the disease spreading) is a due task, and the increasing number of papers on that subject confirms this view in the literature. Another ramification of the paper hurricane is the fact that various academic outlets are relevant for publication of these studies, from aviation-specific conferences/journals, over transportation and health-related venues, towards economics and even law related venues - given the broad impact on all aspects of our life and aviation. To provide a comprehensive overview and guide the scientific process, we have collected a list of nearly 200 papers published in the year 2021/2022 on the subject of interest, following a diligent literature review mostly through Google Scholar and Web of Science, using relevant keywords, while also processing citations of earlier papers on COVID-19 and aviation.

The remainder of this study is structured as follows. Section 2 provides a formal categorization of research and discussion of the papers in this review. Section 3 aims to guide future efforts on the interaction between aviation and pandemics towards novel, interesting directions. This review is concluded with Section 4.

Framework for interactions between aviation and COVID-19

This section of our study surveys the literature on the impact of the COVID-19 pandemic on aviation, as published in 2021/2022 with COVID-19, with the baseline of Sun et al. (2021d), which reported the impact of the first year.

The existing literature on aviation and COVID-19 is highly disorganized, given the interactions of various causes: a timely, emerging topic meets a wide range of receptive venues, with concurrent submissions and heterogeneous article processing times. Moreover, given a clear lack of terminology and contributions from research groups trained with various backgrounds, the novelty of a paper can be hard to identify, let alone comprehend in context of the exiting literature. Finally, several papers have aimed to report the impact of COVID-19 on aviation, without identification of clear key messages. In order to bring structure into the existing literature, we have developed eight categories with central themes, as visualized in Fig. 2.

Airlines

Airlines are highly tuned for efficient operations and their main income is derived from operating aircraft. Accordingly, most airlines face tremendous difficulties during the COVID-19 pandemic (Mumbower, 2022). Many airlines needed to obtain government aid or secure investments from investors (e.g., Lufthansa and Air France), other simply disappeared from the market (e.g., Air Italy and Norwegian Air Shuttle). Early studies on airlines mainly focused on the network effects, which is often measured in the number of flights on selected markets. Another set of studies discussed the direct effects at the peak of flight reductions around March/April 2020, with the incurred operational challenges by airlines. The literature in the years 2021/2022 mostly reports indirect effects and long-term impacts of COVID-19 on airlines, as well as providing more financial-oriented analyses, given gradual availability of relevant data; see Table A1 in the Appendix for details.

One major problem for airlines, which became apparent throughout the last two years is the over-reliance on historical patterns/models together with the inability to make informed short-term modifications to their networks (Sun et al., 2021a). Accordingly, airlines should invest more into novel technologies, centered around data science and artificial intelligence, such that they are able to pick up trends more quickly (Garrow and Lurkin, 2021). The financial impact on airlines is extensive, raising the need to rethink business models in the long run (Kim and Sohn, 2022) and workforce restructuring (Kuno, 2022). Table 1 summarizes an airline response matrix, inspired by Kim and Sohn (2022), which proposes appropriate actions for airlines under different threat levels and durations. Several studies in the literature discuss specific airline examples, e.g., Allegiant Air (Zizka et al., 2021), American Airlines (Yu, 2021; Zuss, 2021), British Airways (Hamawandy et al., 2021), Garuda Indonesia (Haunan, 2021; Sebastian and Prijadi, 2021), LOT (Wasowska et al., 2021), Lufthansa (Kuno, 2021), and Singapore Airlines (Cheong et al., 2021). Other studies have taken a wider approach, by comparing a set of airlines, e.g., on Europe (Mrázová and Kazda, 2021; Nittmann et al., 2021; Schewiller and Zizka, 2021), Turkey (Deveci et al., 2022), or worldwide (Hruby, 2021; Thaichon, 2021; Singh et al., 2021). Finally, there are a few studies which discuss airline problems mostly in a generic way, without strong focus on specific examples (Amankwah-Amoah, 2021; Gole et al., 2021; Green, 2021).

Fig. 1. The unique impact of COVID-19 on aviation in context of earlier crises in terms of the number of transported passengers worldwide (data source: International Air Transport Association, IATA).
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were reviewed by Arora et al. (2021) and based on these insights a pandemic response matrix with four threat levels is proposed, whose essence is visualized.

In Table 2, touchless technology and appropriate ICT usage are estimated to be key elements, possibly through a revised terminal layout (Kumar et al., 2021; Stimac et al., 2021). In addition, frameworks and airport reference layouts have been proposed in the literature, which aim to support analysis and optimization, based on passenger flow models (Sanders et al., 2021; Schultz et al., 2021). Overall, there is a need for novel and effective airport strategies.

Based on data for Incheon International airport, Choi (2021) suggested that the commercial revenue perspective should be added to post-COVID-19 policies, emphasizing the open challenges for gate allocation and membership services when handling pandemic-aware passengers. A few other studies in the literature look at the effects specific to certain airports, e.g., Frankfurt Airport (Hansmeier and van Hulsen, 2021), selected airports in the United States (Raghavan and Yu, 2021), and selected Turkish airports (Karakus et al., 2021).

Airports

Studies on airports published during the first year with COVID-19, provided various reviews on the contribution of technology towards increasing passenger experience and compliance with social distancing rules, often without being specific to airports. In addition, earlier work had a strong emphasis on the process of aircraft boarding. Operators have presumably realized that the performance of boarding strategies is different in reality, compared to simulations on a computer, in terms of obtained social distancing as well as required boarding times. In addition, there is only limited number of (novel, yet effective) boarding methods conceivable. The literature in 2021/2022, however, focuses more on the evaluation of specific airports and the analysis of mitigation strategies, as summarized in Table A2 in the Appendix.

Since airports act as gateways between ground transportation and the connecting world of aviation, the potential of airports as virus-scaning facilities has been highlighted in the literature (Liu, 2021). It is envisioned that only passengers who passed all health checks successfully can enter a flight, with the ultimate goal of reducing the long-distance spreading. This idea, however, is likely to fail in practice, as there is no testing equipment available which reliably detects COVID-19 presence at all stages with a guarantee of 100 %. It should be noted as well that the criteria for testing and screening at airports worldwide are very heterogeneous regarding target audience, cost, and time period until test results are released (Alonso Tabares, 2021; Blistanova et al., 2021). Accordingly, there is a need for a uniform testing process as part of aviation - like the well-established security-driven ban on liquids in aircraft cabins. The potential responses of selected airports to COVID-19

Passengers

Passengers can be considered the complementary subject in aviation, who are directly or indirectly affected by flight bans, various control policies, and disease hot spots, which in turn changes their fears and behaviors. Few studies specifically targeted aviation passengers in the year 2020, presumably due to lack of data. In 2021/2022, a significant increase in the number of studies can be observed, as summarized in Table A3 in the Appendix. The dominant theme in this category is the change of passenger perceptions and behavior due to COVID-19. Particularly, the fear of disease spreading at destinations is an important driver to make decisions for travel allocation and membership services when handling pandemic-aware passengers. A few other studies in the literature look at the effects specific to certain airports, e.g., Frankfurt Airport (Hansmeier and van Hulsen, 2021), selected airports in the United States (Raghavan and Yu, 2021), and selected Turkish airports (Karakus et al., 2021).

Airports (Section 2.1)

- Revenue management
- Aircraft operations
- Customer relationship
- Competition effects

Airports (Section 2.2)

- Security / safety
- Testing strategies
- Social distancing
- Technologies

Passengers (Section 2.3)

- Choice modelling
- Perceptions
- Travel bookings
- Attitudes

Workforce (Section 2.4)

- Job insecurity
- Crew management
- Education and training
- Health

Markets (Section 2.5)

- Spatio-temporal resolution
- Time-series analysis
- Prediction
- Epidemiological correlation

Contagion (Section 2.6)

- Screening strategies
- Simulation
- Containment strategies
- Aircraft super-spreading

Sustainability (Section 2.7)

- Fuel consumption
- Emission
- Subsidies
- Greener aviation

Economics (Section 2.8)

- Financial health
- State aids
- Bailouts
- Legal complications

Fig. 2. Categorization of the scientific literature regarding the interactions between air transportation and the COVID-19 pandemic.

Table 1

| Level | Time | Example | Reaction |
|-------|------|---------|----------|
| Low   | Short| pre-COVID-19 | Normal operations |
| High  | Short| March-May 2020 | Ensure survival of airlines: Retrenchment for flight capacity, state aid packages, penalty fee waiver |
| High  | Long | June 2020-2021 | New markets and business models, continuous state aid packages, and security staff |
| Low   | Long | 2022 and beyond | Mitigate impacts, summarize lessons learned, and prepare for the disruption: Sustainable business models, more environment-friendly operations |

Table 2

| Level (spread type) | Reaction |
|--------------------|----------|
| Green (none)       | Normal operations |
| Yellow (potential) | Origin-based screening, protective equipment for screening and security staff |
| Orange (confirmed) | Origin-based screening and regular screening of airport staff, mandatory mask wearing in the terminal, light terminal zoning, social distancing at hotspots (restaurants, restrooms) |
| Red (uncontrolled) | Mandatory pre-departure screening, mandatory mask wearing and acrylic screens at counters, separated transit holding areas, non-essential shop closures |

McLeod, 2021; Suk and Kim, 2021).
across younger passengers (Kitinoja, 2021); see also Faiyetole (2022) for a discussion in the context of public transport. Accordingly, there is a need for aviation stakeholders to address these fears, e.g., through active travel interventions (Budd et al., 2021) or trust-building efforts, see Fig. 3 for the results of a survey across 2,096 aviation passengers. Particularly, the aviation industry must revise their passenger choice models include decisions regarding trust and preventive measures, aside from traditional choice attributes (Thepchalerm et al., 2021). In the age of big data, these decisions should be user-targeted and data-based more than ever (Zhang et al., 2021). Finally, it should be emphasized that the COVID-19 pandemic has highlighted the need to further strengthen the rights and legal instruments of passengers (Vasilj et al., 2021). This does not hold for the process of flying, but specifically the issue of booking cancellations and ticket refunds revealed necessities for improvement.

Workforce

A subject which has received recognizable attention in the last two years is related to education and human resources. Already before COVID-19 emerged, a fundamental shift in education was envisioned as necessary in order to address the challenges of future jobs in aviation. These challenges are mainly centered around the Fourth Industrial revolution, and involve techniques from information theory, computing, and other engineering subjects. However, the lack of short-term necessity for pushing the implementation of this envelope, often led to a reluctance in universities and other stakeholders to revise their curricula accordingly. With COVID-19, the momentum has changed significantly, not only in terms of challenges, but also regarding opportunities. In the years 2021/2022, a wide range of studies in the literature were concerned with the impact of COVID-19 on aviation education and the indirect effects on the aviation workforce. The studies are summarized in Table A4 in the Appendix. Please note that we discuss both subjects in one section, as it is often difficult to draw a clear line aviation between workforce impact and its inherent educational challenges.

Several studies analyze the effect of flight disruptions and induced temporary suspension of flight experience to the crew. It is found that the effect is not only measurable concerning increased stress levels (Alaminos-Torres et al., 2021; Sechko, 2021; Mack et al., 2021), depression (Cahill et al., 2021), fatigue (Drogoul and Cabon, 2021), and burnout (Ozturk, 2020), but also the negative impact on overall flight performance (Widodo et al., 2021; Olaganathan and Amihan, 2021; Jarry et al., 2021). According to Olaganathan and Amihan (2021), incident reports filed by pilots increased by 1000 % during the COVID-19 pandemic, requiring the development of appropriate mitigation measures. Given that aviation is highly safety-critical, it seems of tremendous importance to address these concerns in the near future. Better managerial strategies and communication can play a key role here (Linden, 2021; Wu and Shila, 2021), accompanied by more developed system-thinking in the aviation management (Welling et al., 2021). Another perspective on human resources and aviation concerns the large number of layoffs, and the corresponding challenges.

In aviation workforce education. It should be noted however, that the situation in the job market has gradually turned back into hiring-dominated one, where airlines are eager to replace earlier-laid-off workplace under the current signs of recovery. Some education-related studies focus on operational aspects, such as mask wearing (Dattel et al., 2021), while other concern a wider perspective such as teaching situational awareness (Dattel et al., 2021b). There is a necessity to focus on the development of non-technical skills across aviation students (Miani et al., 2021; Sun et al., 2021). Table 3 lists selected challenges for education in preparation of a pandemic resilient aviation system.

Markets

The most fundamental impact of COVID-19 on aviation is the tremendous reduction in the number of flights, which is a non-trivial interaction between two elements: a reduction in demand/supply, and a - maybe - surprising inability of airlines to match hidden demand with appropriate supply downstream the COVID-19 pandemic. In the year 2020, studies mainly provided quantitative descriptions of the reductions in supply, as measured by the number of flights for selected markets, often at an aggregated level. The new studies published in the years 2021/2022 are more concerned with seeking explanations and finding way out of the demand–supply inconsistency, as summarized in Table A5 in the Appendix. Several studies are concerned with the analysis of temporal indicators, particularly the number of passengers, throughout the COVID-19 pandemic; see Fig. 4 for the passenger counts between the years 2019 and 2022 for the 20 largest aviation markets in the world. Alternatively, proxy variables as the number of flights are used for analysis. Traditional time series analysis techniques are used to describe the impact of aviation on supply and/or demand (Andreae et al., 2021; Arora et al., 2021; Florido-Beñitez, 2021; Kuznetsova, 2021; Li et al., 2021; Warnock-Smith et al., 2021). Many of these studies report results at various aggregation levels, often finding that domestic

![Fig. 3. Preferred intervention measures by passengers to revive safe air transportation, collected from Budd et al. (2021).](image)
### Table A1
Airline-specific studies in the COVID-19 related aviation literature of the year 2021/2022.

| Study | Major results |
|-------|---------------|
| Aminwallah-Amoah (2021) | Innovation activities and responses of airlines are provided within the so-called CoviNovation framework. |
| Anderson (2022) | Description of the response by the federal government and the US airline industry towards COVID-19. |
| Cheong et al. (2021) | An aircraft allocation model based on different recovery scenarios highlights the importance of vaccination. |
| Deb (2021) | Internet search data leads to a flexible price volatility model for airline stocks under pandemic shocks. |
| Fontanet-Pérez et al. (2022) | Ultra-low-cost and low-cost airlines fared better than full-service network carriers did in terms of financial performance. |
| Garas and Hudsáková (2022) | Airline safety appeals reduce health risk perceptions and increase trust in the airline during COVID-19. |
| Garrow and Lurkin (2021) | Airline key themes are reported, including operational impact and the shift in revenue management. |
| Gole et al. (2021) | Break-even load factors are often above the maximum capacity with IATA-based social distancing. |
| Green (2021) | A decrease in premium cabin fare reduces the differential in revenue density, affecting economy-class service. |
| Hamawandy et al. (2021) | The business prospects of British Airways are described, including travel bans, passenger loss, and job cuts. |
| Haunan (2021) | Based on structured interviews, Garuda Indonesia’s most important goal is economic survival. |
| Hruba’ (2021) | Trend analysis and MCDM compare the financial impact for 12 airlines, most visible in airline profitability. |
| Kaffash and Khezrimoslah (2022) | The performance of US network and low-cost carriers in response to COVID-19 is compared. |
| Kim and Sohn (2021) | South Korean airlines show a need for reformation of cost and diversified business models. |
| Kirici et al. (2022) | Financial and operational factors are extremely important to ensure resilience for airlines during COVID-19. |
| Kuno (2021) | The effects of COVID-19 on Lufthansa airlines reveal significant financial losses and work reductions. |
| Li and Alexander (2021) | China Eastern Airlines revealed elements from planned strategy and emerging strategy under COVID-19. |
| Martins and Cró (2022) | Airline stock market reactions in line with COVID-19 evolution and key events is investigated. |
| McLeod (2021) | Cost-sharing between airlines during a crisis is modeled, with early data from COVID-19 as a use case. |
| Mrázová and Kazda (2021) | Full-service carrier and low-cost airlines comparison, with interactions between state, airline, and passengers. |
| Ng et al. (2021) | The Japanese domestic aviation market is analyzed, highlighting the need to lower LCC airline entry barriers. |
| Nittmann et al. (2021) | Crisis communication among four airlines compared; each airline focused on distinct aspects of the pandemic. |
| Sebastian and Prijadi (2021) | Garuda Airlines’ cost management should focus on a more dominant structure under crisis conditions. |
| Scheiwiller and Ziska (2021) | Communication and social media usage of 20 European airlines are compared using communication theory. |
| Singh et al. (2021) | The stock values of 52 airlines are compared, discussing regional differences and temporal evolutions. |
| Shin et al. (2021) | Airlines mostly assess vaccination passports positively, reducing perceived health risks significantly. |
| Sugishita et al. (2022) | The temporal networks of 17 US airlines are analyzed during COVID-19, reporting airline-specific findings. |
| Suk and Kim (2021) | Airline responses are categorized along time and magnitude, leading to four evolutionary crisis stages. |
| Sun et al. (2022b) | Load factors of European airlines throughout the COVID-19 pandemic are analyzed and potential drivers reported. |
| Thaichon (2021) | An overview on aviation crisis management covers various examples for the responses of individual airlines. |
| Thepchalerm and Ho (2021) | A meta review analyzes the impact on airlines from three perspectives (operational, market, and financial). |
| Wasowska et al. (2021) | LOT airlines is discussed, including temporal evolution of changes on LOT’s operations and onboard policies. |
| Yu (2021) | Deep learning methods analyze stock price time series from American Airlines; LSTM was best fit. |
| Zhang et al. (2021a) | Low-cost carrier networks increasingly overlap, leading to more competition during and post-COVID-19. |}

### Table A1 (continued)
Airport-specific studies in the COVID-19 related aviation literature of the year 2021/2022.

| Study | Major results |
|-------|---------------|
| Alonso Tabares (2021) | Location of screening, facilitation requirements, and responsibilities delegation are discussed. |
| Arora et al. (2021) | Several examples for specific airport responses are discussed, and matrix for pandemic response derived. |
| Aroskar et al. (2020) | Point of entry surveillance at Mumbai international airport for screening passengers is analyzed. |
| Blistanova et al. (2021) | Performance/safety measures for European airports are compared, finding highly volatile periods. |
| Choi (2021) | Procedures at Incheon International airport observed, commercial revenue generation should be considered. |
| Felix Greco et al. (2022) | The air traffic noise changes during the COVID-19 pandemic in the Hannover airport region is investigated. |
| Findley et al. (2021) | The possibility to track passenger flow during COVID-19 via mobile phone records and airport surveys was analyzed. |
| Goel et al. (2021) | A single arrival test on Toronto’s Pearson airport may identify-two-thirds of infected (by Day 14) individuals. |
| Hansmeier and van Hulsen (2021) | The technology and service level at Frankfurt Airport was evaluated as overly positive throughout the COVID-19 pandemic. |
| Hou et al. (2021) | Slot liberalization in China leads to a lower level of minimum subsidies for sustaining survival. |
| Hotle and Mumbower (2021) | Based on US data, large domestic airports and multi-airport cities are more affected than non-prime ones. |
| Hroncová and Tomová (2021) | The break-even point in terms of airport movements for selected European airports was identified. |
| Kantele et al. (2022) | The possibility of using scent dogs are airports for COVID-19 tracing is proposed and evaluated. |
| Karakus, et al. (2021) | With a focus on Turkish airports, the pandemic-induced changes in airport operations are identified. |
| Kleine-Kampmann et al. (2021) | The challenges for public health service at airports as point of entry towards Germany are reviewed. |
| Kumar et al. (2021) | Smart surveillance systems for monitoring and decision-making enforcing social distancing at airports. |
| Kuo et al. (2022) | The impact of COVID-19 on airport popularity in the US is compared, finding few significant changes. |
| Liu (2021) | Airports could act as virus scanning hubs, under usage of different policies, by passengers’ destinations. |
| Milne et al. (2021) | Boarding methods are compared regarding the effectiveness for enforcement of social distancing rules. |
| Raghavan and Yu (2021) | Six performance metrics are adapted to measure the financial performance of airports in the US. |
| Sanders et al. (2021) | Agent-based simulation for airport terminal operations with passenger handling and intervention strategies. |
| Schultz et al. (2021) | Airport terminal layout with passenger flow for the simulation of scenarios and mitigation strategies. |
| Štimac et al. (2021) | Technologies for touch-less terminal design require a trade-off between efficiency and safety. |
| Tidhar (2022) | The challenges and lessons learned for airport screening during the COVID-10 pandemic are reviewed. |

Aviation was less impacted by the COVID-19 pandemic than international aviation. Other studies proceed one step further to use the time series data to predict future demands based on extrapolation of machine learning techniques (Verhoeven et al., 2021).
Contagion

It is known that long-distance mobility through aviation can play a key role in the spread of infectious diseases (Budd et al., 2009; Monmousseau et al., 2020). During the past decades, we have seen several cases of so-called near misses (Velu and Iyer, 2021), where a combination of early identification, timely response, coordination, and possibly a matter of luck, led to an early containment of an epidemic outbreak; at least early enough, to avoid a pandemic as COVID-19. Examples for these near-misses include Ebola (Pigott et al., 2014), and SARS/MERS (Poletto et al., 2016; Wong et al., 2015). While such near-misses have supported the development of models and simulations tools to better understand the underlying dynamics of contagion spread in large-scale complex systems, we all know by now that the COVID-19 pandemic

Table A3
Passenger-related studies on aviation in the literature of the year 2021/2022.

| Study | Major results |
|-------|---------------|
| Afaq et al. (2021) | Passenger engagement with airline service providers on Twitter is analyzed, identifying largely positive sentiments of passengers. |
| Budd et al. (2021) | An online questionnaire from Norway showed that active travel interventions were favored over passive and technological ones. |
| Chan (2021) | Airfare analysis for the Philippines shows that advance purchasing and ticket cancellation are consistent with pre-COVID-19. |
| Diaconu (2021) | Traveling attitudes collected for passengers from Romania show that the importance of better understanding the willingness to fly. |
| Kitinoja (2021) | Millennials are rather unconcerned about getting infected on the next flight, especially with face masks and cabin crew vaccination. |
| Kitsou et al. (2022) | The international passenger traffic at Hellenic airports is reviewed and fore-casted mid-term. |
| Lamb et al. (2021) | Prevalence of trust concerns and emotional issues during the pandemic are revealed, particularly the fear of the unknown. |
| Lee and Leung (2022) | Passengers’ airline ratings throughout the pandemic have unique characteristics, focusing mainly on travel safety. |
| Leppavuori et al. (2022) | Quarantines and convenience of traveling were major concerns of passengers in Finland and Sweden. |
| Linden (2021) | Destination image is the largest pull factor under COVID-19 in Taiwan, self-realizations is the most important push factor. |
| Ma et al. (2022) | The impact of airport environment on Chinese passengers’ perceived safety is investigated in light of passenger satisfaction. |
| Manca et al. (2021) | The high impact of London passengers’ health concerns on their willingness to travel is confirmed. |
| Ouyang (2021) | Policy intervention, public risk perception, and available flight options change passenger behavior during COVID-19. |
| Pratt and Tolkach (2022) | Ethical decision making of passengers and airlines for so-called flights to nowhere during COVID-19 are assessed. |
| Samani et al. (2021) | Service quality requires mainly in-flight social distance/hygiene, information awareness, and infection alert procedures. |
| Schmaza et al. (2021) | The perception of corporate air passenger under COVID-19 indicates a continued relevance of air transportation. |
| Seo et al. (2021) | Technology-based self-service received a significant push in the eyes of passengers due to COVID-19. |
| Song and Choi (2021) | A high variation in the awareness of COVID-19-related factors and social perceptions are reported. |
| Thephalsallem et al. (2021) | Preventive measures have become an attribute of concern in Thailand; few traditional attributes remain important. |
| Vasi et al. (2021) | Air passenger rights and legal instruments under COVID-19 are discussed and exiting legislations reviewed. |
| Wild (2021) | Corporate social responsibility plays an important role in the mindset of passengers. |
| Wu et al. (2022) | The extent and operation of labor charter flights during the COVID-19 pandemic in China is investigated. |
| Zhang et al. (2021) | Passengers’ evolutionary changes in travel booking time, refunds, ticket changes, and passenger age are analyzed. |
| Zhang et al. (2022) | The impact of ‘Wild Your weekends’ promotions on passengers during COVID-19 is investigated. |

Table A4
Education-related and human resource-related studies in the literature of the year 2021/2022.

| Study | Major results |
|-------|---------------|
| Alaminos-Torres et al. (2021) | Spanish unemployed and furlough pilots experience high psychological distress during COVID-19. |
| Athanasiadou and Georgios (2021) | A model shows that corporate social responsibility leads to higher levels of organizational trust and pride among employees. |
| Byrnes et al. (2021) | Safety culture and safety climate of the flight training organization at Embry-Riddle Aeronautical University are analyzed. |
| Cahiil et al. (2021) | A survey reveals depression and anxiety across aviation workers, with weak help from organizations throughout COVID-19. |
| Dattel et al. (2021) | Aviation college females, non-pilots, and older respondents reported greater benefits of face masks. |
| Dattel et al. (2021b) | Situational awareness teaching in a virtual classroom of an aviation university was assessed, summarized as highly successful. |
| Drogoul and Cabon (2021) | Risk factors for air traffic controllers are discussed, especially fatigue needs to lose its negative connotation. |
| Gilad et al. (2021) | The potential long-term impacts on military aircrew are highlighted, including heart, lung and coagulation disorders. |
| Grout and Leggat (2021) | The international role of fitness-to-fly among crews is assessed, highlighting the need of better aeromedical evaluations. |
| Hong et al. (2022) | Airlines take steps to enhance their corporate risk management protocols since dealing with COVID-19. |
| Karaaslan and Erkmen (2021) | Crew resource management is assessed, highlighting the significant differences before and during COVID-19. |
| Karunakan and Babu (2022) | Human factors in aircraft accident mitigation and maintenance training needs in post-COVID-19 aviation are discussed. |
| Kwon (2021) | The efficacy and side effects of vaccines and the effect on pilots and air traffic controllers are investigated. |
| Linden (2021) | Aviation managers are recommended to develop a standard and shared strategy language, managing uncertainties proactively, and getting into a dialogue with all relevant stakeholders in to create long-term plans. |
| Miani et al. (2021) | An online survey across Australian undergraduate aviation students reveals the cognizance of oversupply during early COVID-19. |
| Olaganathan and Amihan (2021) | In context of pilot proficiency, it was found that incident reports filed by pilots increased by 1000 % during the COVID-19 pandemic, requiring the development of appropriate mitigation measures. |
| RRAFRC (2021) | The COVID-19 response of the Australian government in context of JobKeeper is reviewed, leading to a set of recommendations for future support, mainly helping aviation workers and increasing job security. |
| Sechko (2021) | The ongoing optimization of aviation and increased use of technology lead to much stress among aviation professionals. |
| Welling et al. (2021) | Structured interviews of five aviation middle managers and four employees highlight a lack of safety responsibility in the middle management, requiring a much stronger emphasis on system thinking in aviation. |
| Widodo et al. (2021) | A survey across 65 aviation engineering employees showed that job stress and pandemic-related stress contribute negatively to employee performance, the latter having more pronounced effects. |
| Wu and Shila (2021) | A survey among 200 student pilots shows the need for adapting aviation education throughout COVID-19, with an emphasis on communication, innovation, collaboration, and flexibility. |
| Yilmaz et al. (2021) | Remote working and active travel are best options for a pandemic future concerning airport ground access. |
simulation-based approaches proposed (Yu and Chen, 2021), connectivity indexes developed (Li et al., 2021b; Szabo, 2021), and regression models derived (Liu et al., 2021). The latter analyses reveal that a 1% decrease in flight frequency leads to about 0.9% decrease in the number of cases. Many of these studies highlight the need to perform balanced decisions, trading public safety with economic viability (Meng et al., 2021). In addition, the potential of in-flight transmission has been repetitively discussed in the literature. Among the general public, one can find connotations of aviation with contagion super-spreading events (Namlae et al., 2021). It has been shown in the literature that such fears are mostly unfounded, as the actual flight process is rather safe, given appropriate social distancing and mask usage (Bhuvan et al., 2021; Chen and Steffen, 2021; Holdik et al., 2021; Saretzki et al., 2021; Wang et al., 2021). This can also be partially explained by effective air filters installed on aircraft (Dietrich et al., 2021). Other streams of research on spreading concern comparisons with other transportation modes (Zhu and Guo, 2021; da Silva, 2021) and the potential ramifications and implications of using vaccination passports for air travel (Memish et al., 2021; Sun et al., 2021b).

### Sustainability

Societal long-term effects of aviation, particularly sustainability, have become an extremely important concept throughout the remaining decades. The major driver for this development is the increased awareness of the environmental impact mankind has on our planet, and the acknowledgment of potential contributions of climatically sustainable aviation (Gössling and Lyle, 2021). Earlier work in light of the COVID-19 pandemic did not contain very specific studies regarding sustainability. Several studies raised the general potential of using COVID-19 as an opportunity towards a better aviation system, addressing some of the inherent societal challenges. Beyond that, however, there were - to the best of our knowledge - no studies on such issues. In the years 2021/2022, this has changed significantly, given more available data and also more computational resources for performing experiments and simulations, as summarized in Table A7 in the Appendix.

The major stream of research in the sustainability literature concerns the degree of emission changes during COVID-19 and beyond. It is acknowledged that aviation, while being responsible for 3.5% of the anthropogenic climate forcing, needs to make a significant contribution to the societal goals, partially because of the omnipresent flight-shame debate around Fridays for Future (Ringbeck and Koenig, 2021), and possibly within wider initiatives such as responsible transport (Budd and Ison, 2020). Several studies confirm the overall positive impact of COVID-19 in terms of reduced emissions induced by aircraft (Arena and Aprea, 2021; Quaas et al., 2021; Xue et al., 2021), partially using aircraft fuel as a proxy indicator. Some studies cast a different perspective, by emphasizing that the passenger-emission has been increased significantly, mainly due to the reduced load factor (Bauranov et al., 2021; Vieira et al., 2021). Other studies are concerned with long-term impact of COVID-19 on emissions, taking into account different recovery scenarios. The major goal is to analyze how much COVID-19 could help to reach future environmental goals. For instance, (Gössling et al., 2021) shows that in combination with low-carbon transport options, phasing out fossil fuels can be accompanied by 26.5 Gt CO2 reductions until the year 2050. On the other hand, (Grewe et al., 2021) reports that simulations until the year 2100 reveals a high likelihood of missing Paris agreement goals, even when considering various technical expectable improvements; see also (Ringbeck and Koenig, 2021) for the results of a recent survey among 220 aviation experts and how to lead the goal towards climate-neutral aviation, under exploitation of COVID-19 ramifications. Another sustainability-related aspect discussed in the literature is resilience, i.e., the ability of a system to withstand external perturbations (Zhou et al., 2021; Guo et al., 2021). It could be argued, however, that COVID-19 is such a unique and impactful event, that

### Table A4 (continued)

| Study                        | Major results                                                                                                                                 |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| Yiiecke et al. (2022)        | The mediating role of aviation workforce well-being in context of COVID-19 anxiety is analyzed.                                               |
| Zaharia et al. (2021)        | Long-term communication, guidance and connection between education, training providers and employers are found to be critical for solving future in-pandemic challenges inherent to aviation education. |

### Table A5

Demand-focused studies of the year 2021/2022.

| Study                        | Major results                                                                                                                                 |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| Andreana et al. (2021)       | The outstanding impact of COVID-19 on demand is larger than in any earlier crisis witnessed by aviation.                                         |
| Arora et al. (2021)          | Effects on flight schedules are reported, broken down into regions.                                                                          |
| Busareddy (2021)             | The impact of COVID-19 of the United States aviation system is quantified, emphasizing short-term of domestic interest.                        |
| DeLaura et al. (2021)        | A pandemic-aware demand model is proposed, addressing the changed demand patterns throughout COVID-19.                                       |
| Florido-Beinitez (2021)      | The effect of COVID-19 on the Andalusian aviation sector is analyzed, reporting overall devastating impacts.                                   |
| Kozicki et al. (2021)        | The effect of COVID-19 on the German aviation industry is discussed based on a multidimensional comparative analysis.                       |
| Kuznetsova (2021)            | The impact on the aviation system of the Russian Federation is analyzed, highlighting the shift towards domestic travel.                       |
| Li et al. (2021a)            | Spatio-temporal variation of the worldwide air transportation networks by regions and time periods.                                           |
| Bao et al. (2021)            | The significant impacts on average distances between airport pairs and shifting centralities among airports are identified.                  |
| Marciszewska et al. (2021)   | Hidden goals of private tourism operators require governments and policy makers to rethink encouragements and incentives.                  |
| Purba et al. (2021)          | A relationship between Indonesian tourism and its economic growth is established, quantifying the loss due to the COVID-19.                 |
| Saus-Sanchez et al. (2021)   | Supply and demand datasets are analyzed, showing a reduced impact on domestic markets.                                                        |
| Tirha et al. (2022)          | Airline demand recovery considering three hypothetical scenarios of future COVID-19 transmission are discussed.                           |
| Warnock-Smith et al. (2021)  | The capacity, traffic and revenue changes in the domestic and international aviation markets involving China are analyzed, revealing significant heterogeneities in COVID-19 impact. |
| Wolle (2021)                 | The reduced passenger volume and the induced financial impact of COVID-19 on German aviation is analyzed, with Frankfurt and Munich as case studies, highlighting the role of international collaboration. |
deriving general resilience insights at a large scale seems rather difficult; and it is not clear how the results translate into a next pandemic or other external disruptions. Moreover, even if one was able to design a topologically more resilient system, the external actors will simply apply stronger bans on the system to disrupt it, if that is intended.

Economics and law

Many governments started to set up state-aid relief and support packages for the aviation industry. The European Union mainly responded to the COVID-19 pandemic by implementing a set of legislative additions and measures, which amend the common state aid EU legal regime (Trimarchi, 2021). Actual loans and aids were implemented by member countries, mostly to support their own (national) flagship carriers. The United States have released the Coronavirus Aid, Relief, and Economic Security Act (CARES) stimulus package (Mountain et al., 2020). Australia released several hundred million dollar-packages at various scales to support the aviation industry (Zhang and Zhang, 2021). The overall sentiment in the scientific literature is rather critical towards state aids, see Table A8 in the Appendix.

To sum up, most of the state aids come with public criticism, partially because they are given away without obligations towards the aviation industry (Bezemer, 2021) and also because these packages are often not reflecting the real need of aviation. As Tisdall and Zhang (2020) put it, waiving airways fees/charges are only useful in presence of actual flights, not when almost the whole fleet is grounded. Several studies focus on the European case, presumably because of the interesting setup, where individual member countries fight to support their own airlines within the European legal framework (Agnolucci, 2021; Furcăková and Tomová, 2021; Hobe, 2021; Pantazi, 2021; Trimarchi, 2021). Overall, it is found that the level of support is extremely heterogeneous across regions and magnitudes of support, as well as the actual type of support. The induced discriminatory activities are contrary to efforts in the last two decades to significantly increase (fair) competition among aviation stakeholders (Hobe, 2021). Agnolucci (2021) provides a detailed breakdown regarding the state aids of individual member countries, not only in terms of magnitude but also policy and sectoral distribution. Given that these support packages are given out arbitrarily; Ryanair, for instance, reportedly filed more than 15 lawsuits with authorities, to let the European Union investigate the degree of legality for state aids to national carriers (DeutscheWelle, 2021). Similar findings have been reported on India by Jha et al. (2021). Other studies highlight the importance to bind state aid towards the accomplishment of societal goals (Scheelhaase et al., 2021) and the potential in reducing investors’ fears (Corbet et al., 2022). In reality, however, the support decisions by member countries were largely fore-running the complex and slow decision making processes inside the European Union.

Guidelines for policy needs and future research

Based on our literature review summarized in the earlier section, we provide several recommendations and directions of future research, hoping that more research efforts could be targeted towards these topics. Each recommendation/direction of future work is described in an individual subsection. In general, throughout the past three years, many studies have analyzed the impacts of the COVID-19 pandemic on aviation, which was undoubtedly an unprecedented event in the early months. Parts of these impacts have gradually disappeared. For instance, initial middle seat blocking strategies were given up by airlines, for economic reasons. Grounded aircraft have mostly started to operate again, clearing up airport-wide parking places. Many temporary travel restrictions have been lifted or completely removed. Some airlines have paid back governmental subsidies. This raises the question of what impacts are left in aviation for the long run? One could argue the worst that could happen to aviation is a back-to-normal, without the lessons learned. Therefore, we believe that there is a need for studies which explore the long-term impacts, measures and effects which are likely to remain in aviation, induced by the COVID-19 pandemic. Some of such potential long-term effects are covered below, see Fig. 5 for an overview. Our discussion is complementary to other recent publications on COVID-19 takeaways/summaries, e.g., see Kim and Sohn (202) and Kim (2021, 2022).

The future role of evolving variants of concerns for aviation

With the recent revival of international air transportation and the increasing conviction that COVID-19 will become endemic eventually, the original contagion is seemingly losing its threat. In an endemic situation, one could imagine those emergent variants of concern could become the major driver for aviation restrictions. Recent responses to
Table A6
Studies on spreading and containment in the literature of the year 2021/2022.

| Study                      | Major results                                                                                                                                                                                                 |
|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Amoruso and Baldovin (2021) | Wastewater analysis for long-haul flights after deboarding can be used as passive health monitoring.                                                                                                         |
| Bhuvan et al. (2021)        | An review of historical confirmed cases for in-aircraft transmission is provided and it is argued that the risk for such events is extremely small, due to successful air-flow management implementations.                   |
| Botlikova et al. (2021)     | Time-series analysis for the European number of flights is performed, correlation analysis with the reported number of cases aggregated, and future development scenarios discussed briefly.                               |
| Chen et al. (2021)          | An overview of countermeasures for avoiding in-flight transmission are presented, highlighting the need for revisit once a sufficient degree of vaccination is achieved.                                           |
| Chen and Steffen (2021)     | A framework for safe air travel is discussed, emphasizing the low probability of in-flight transmission with masks.                                                                                         |
| Ding et al. (2021)          | A optimization-driven decision framework for air transportation lock-down/quarantine is proposed. Structured interviews across 18 international travelers revealed that travel anxiety is mainly driven by human errors in pandemic in-flight management, e.g., insufficient mask wearing and violating social distancing. |
| Holdik et al. (2021)        | Routine asymptomatic testing is found effective for reducing passenger risk during air travel.                                                                                                             |
| Li et al. (2021b)           | The international connectivity index, based on flight connectivity, is used to analyze the spreading behavior in air transportation under distinct containment policies, from a network robustness perspective. |
| Liu et al. (2021)           | The effect of travel bans on COVID-19 infections and fatalities is investigated with a regression model, finding that 1.5% decrease in flight frequency leads to about 0.9% decrease in the number of cases.                  |
| Memish et al. (2021)        | A brief discussion on vaccination passports concludes that there is a lack of scientific evidence for long-lasting immunization effects, which could put planned vaccination passport projects at jeopardy.               |
| Meng et al. (2021)          | A study on the USA, Singapore, and China compares the effects of different control policies and how they effect spreading, ad long-term economic impact, highlighting the need for balanced approaches.               |
| Namilae et al. (2021)       | The hypothetical case of in-flight-superspreading is discussed based on a passenger movement model, emphasizing the benefits of wearing different kinds of masks on board of the aircraft.                          |
| Rafiq and Ahmed (2022)      | The bi-directional relationship between human mobility and COVID-19 spread across US counties is investigated. While SARS-CoV-2 can be transmitted during aircraft travel, published data do not permit any conclusive assessment.                      |
| Rosca et al. (2021)         | The airflow in a small, 4-seat general aviation aircraft is analyzed, and it is reported that the risk of infection is small, if passengers should cough and sneeze towards the side wall of the cockpit.                                         |
| Saretzki et al. (2021)      | The development of COVID-19 in Africa is discussed in light of the international and domestic flight connections.                                                                                           |
| Sun et al. (2022a)          | The challenges inherent to the introduction of vaccination passports are discussed within a framework of five important aspects, highlighting not only the problems but also potential benefits of doing it right.                                           |
| Sun et al. (2021b)          | The emergence of new variants of concern is discussed through the global air transportation system, highlighting the importance of timely reactions for a successful containment.                      |
| Sun et al. (2021c)          | The rationale, use and materialized presence of travel bubbles in the global aviation system is discussed. A country-specific pandemic index is computed, which is used to decide whether or not air transportation should be used for specific markets; the approach is evaluated on the European Union member states. |
| Talaat et al. (2021)        | The aerosol transmission in a Boeing 737 cabin is compared with three scenarios: fully loaded, reduced capacity, and shield protections. The latter showing the best performance trade-off.                      |
| Wang et al. (2021)          | The aerosol transmission in a Boeing 777 cabin under different quanta generation rates and face masks was simulated, showing that face masks are critical for avoiding in-flight transmissions.                      |
| Yu and Chen (2021)          | Based on international flight data for Guangzhou, China, the effect of three control policies is compared, and it is found that double negative tests is the most effective one.                                      |
| Zhu and Guo (2021)          | The role of aviation and HSR for the spread of COVID-19 inside China is discussed, highlighting that HSR had a larger impact than aviation, which requires new transportation-related policies.   |

The future role of health/vaccine certificates

At the onset of COVID-19, a lack of health/vaccination certificates was considered a major hurdle for resumption of international travel. By now, standards have gradually been set up and several frameworks and implementations put into practice, e.g., the IATA Travel Pass app. However, new problems are emerging recently (Memish et al., 2021; Sun et al., 2021b). First of all, there are increasing challenges involving fraud of such documents, with unqualified passengers faking the presence of required health/vaccination status, especially on markets with loose controls. Given the global characteristic of aviation, it is essential to keep unified standards and ensure system-wide consistency. Second, since the degree of immunity is vanishing over time, the passports have to implement some kind of temporal validity measures, which can be validated at anytime and anywhere. Third, and most importantly, one could argue about the usefulness of such certificates with respect to containing the pandemic spread. The reason is that any certificate reflects temporal information of limited use to the contagion spread. Even if a passenger is fully vaccinated, he/she can still carry the virus towards the destination market. Again, it needs to be kept in mind that the major benefit of vaccinations is to avoid severe complications in case of an infection. Therefore, from a modeling and spreading perspective, vaccination is not a good prerequisite for containment. The usage of test certificates is subject to error; and, unfortunately, humans can be

1 https://www.iata.org/en/pressroom/2021-releases/2021-12-02-02/.
2 https://www.iata.org/en/programs/passenger/travel-pass/.
COVID-19 sustainability-related studies on aviation in the literature of the year 2021/2022.

| Study                                      | Major results                                                                 |
|--------------------------------------------|-------------------------------------------------------------------------------|
| Arena and Aprea (2021)                     | COVID-19 has a tremendous impact on the environment and there is a need to build a greener aviation system. |
| Bartle et al. (2021)                       | Air cargo sustainability should improve based on three distinct time horizons.|
| Bouranov et al. (2021)                     | Total emissions during COVID-19 were largely reduced, but the emissions per passengers increased significantly. |
| Vieira et al. (2021)                       | The lower load factor among Brazilian flights led to a doubled per capita emissions. |
| Calderon-Tellez and Herrera (2021)         | Modeling-based scenario analysis on the environmental impact of COVID-19 on three South American countries highlights the need to further reduce emissions and better coordinated policymaking. |
| da Silveira Pereira and de Mello (2021)    | Multicriteria Data Envelopment Analysis suggests a better mix of aircraft models for selected Brazilian airlines. |
| Dray and Schäfer (2021)                    | Cumulative aviation fuel use in recovery scenarios until the year 2050 is found to be up to 9% below that in scenarios not including the COVID-19 pandemic. The aviation sector needs revised growth patterns, otherwise it is very challenging to defossilize in a sustainable manner. |
| Franz et al. (2022)                        | COVID-19 recovery is modeled under consideration of low-carbon transport options until the year 2050. Phasing out fossil fuels can be accompanied by 26.5 Gt CO2 reductions in the time period. |
| Gouling et al. (2021)                      | Simulation for aviation emission evolution until 2100 shows a high likelihood of missing Paris agreement goals, with various technical improvements, under different COVID-19 recovery scenarios. |
| Guo et al. (2021)                          | A resilience index based on selected indicators, including passenger volume and aircraft movements, is proposed. |
| Hemmings et al. (2021)                     | Airport operation remain committed to decarbonisation, with climate change action remaining the key priority for airports despite the COVID-19 pandemic. |
| Jain et al. (2021)                         | The Fleet-Level Environmental Evaluation Tool is used to predict future emission based on six COVID-19 recovery scenarios, finding significant reductions due to reduced demand and better fleet mix. |
| Kalibekken and Sølen (2021)                | Public support for COVID-19 countermeasures and climate change policies are compared, finding that the former are more accepted because the more imminent threat and short-term nature of restrictions. |
| Liao et al. (2022)                         | Investigates the impacts of COVID-19 on the implementation of Carbon Offsetting and Reduction Scheme for international aviation. |
| Mai (2021)                                 | The challenges for reducing global aviation emissions, in context of ETS and CORSIA, are investigated, identifying several shortcomings in existing policy options. |
| Ovliensko et al. (2021)                    | Future CO2 emissions are predicted for Ukrainian aviation, showing that different types of carbon pricing and novel aircraft technologies are required for achieving significant reductions. |
| Quass et al. (2021)                        | Aircraft-induced cirrus is significantly reduced at times of COVID-19. |
| Ringbeck and Koenig (2021)                 | A survey among more than 220 aviation experts leads to pathways for climate-neutral aviation. |
| Santos and Delina (2021)                   | Governmental subsidies and promotions for sustainable aviation fuel should be provided through COVID-19. |
| Schumann et al. (2021)                     | A model study investigates the contrail changes over Europe induced by COVID-19, finding that overall 3% less contrails and highlighting the importance of fuel and engine efficiency. |
| Shaban et al. (2021)                       | A Cournot-style model shows that despite pandemic impacts, the profit of airlines can be increased by 25% using quantity discounts across underutilized and hot-selling routes. |

The future role of network, fleet, and pricing economics

The long-term changes in demand patterns, together with uncertainties regarding flight operations, presumably will force airlines to rethink their network choice and pricing strategies. Traditionally, most airlines price long distance point-to-point flights the highest, given the rationale that time-sensitive passengers are willing to pay more. With

| Study                                      | Major results                                                                 |
|--------------------------------------------|-------------------------------------------------------------------------------|
| Sobieralski and Mummower (2022)            | Reports that pandemic-induced private aviation boom has increased emissions by over 23%. |
| Soria Baledon et al. (2021)                | The politics behind greener aviation is discussed in context of global events, including COVID-19, emphasizing the role of different stakeholders in the policy-making process. |
| Xue et al. (2021)                          | Fuel consumption and emissions for four Chinese international airports throughout COVID-19 is reported. |
| Zhou et al. (2021)                         | An international robustness metric is proposed, based on weighted international efficiency. |
| Zhu et al. (2022)                          | Agent-based models and discrete event simulation should be used on the pathway towards sustainability. |

Economics-focused studies of the year 2021/2022.

| Study                                      | Major results                                                                 |
|--------------------------------------------|-------------------------------------------------------------------------------|
| Abeyratne (2021)                           | The relevant legal and regulatory implications for ICAO as well as salient economic fallout are discussed. |
| Adediran (2021)                            | The legal effects on aviation are discussed, highlighting synchronized regional and multilateral agreements. |
| Agnolucci (2021)                           | The role of European state aid measures on competition in aviation is investigated, highlighting significant differences by region, sector, and magnitude, leading to long-term distortions due to COVID-19. |
| Byrne and Adler (2021)                     | The European Union 2014 Guidelines on State aid to aviation are discussed in context of crisis handling. |
| Coret et al. (2022)                        | Investor response to state assistance concerning international aviation and tourism is investigated. |
| Furcakova and Tomova (2021)                | State aids to European airports are reported and discussed in the context of COVID-19 pandemic, categorized by number of aids, chronology, and the duration of decision making. |
| Hobe (2021)                                | State aids in the European Union leads to unfair competition and discriminatory effects, which is contrary to the overall strategic goals in the past 20 years. |
| Jha et al. (2021)                          | The financial health of the Indian aviation industry under COVID-19 is discussed, reporting the evolution of governmental response and discussing future scenarios for the Indian post-COVID-19 aviation sector. |
| Lee (2021)                                 | Multilateral, bilateral, and unilateral rule-based approaches for airline bailout are recommended for the post-COVID-19 era. |
| Pantazi (2021)                              | The effects of state aid under COVID-19 to European airlines is discussed, particularly in light of legal ramifications, and the need for long-term assessment emphasized. |
| Rappaport (2021)                           | Several legal complications in the United States airline industry are discussed, focusing on enforcement of existing rules and general inaction in the face of the crisis. |
| Scheelhaase et al. (2021)                  | State aids should be better distributed and bound to the accomplishment of societal goals. |
| Scheelhaase et al. (2022)                  | The economic recovery of aviation after COVID-19 is discussed, emphasizing the need for transparent and nondiscriminatory lending criteria of state loans. |
| Trimarchi (2021)                            | Financial aid to national airlines in Europe leads to evident asymmetry. |
| Varsamos (2021)                            | The European Commission should better trade-offs for airport state aid schemes. |
| Zhang and Zhang (2021)                     | Bailout decisions should be made careful, especially if an airline does not survive the COVID-19 pandemic. |

Reports that pandemic-induced private aviation boom has increased emissions by over 23%. The politics behind greener aviation is discussed in context of global events, including COVID-19, emphasizing the role of different stakeholders in the policy-making process. Fuel consumption and emissions for four Chinese international airports throughout COVID-19 is reported. An international robustness metric is proposed, based on weighted international efficiency. Agent-based models and discrete event simulation should be used on the pathway towards sustainability.
the potential absence of business passengers, which are the largest target group among time-sensitive passengers, the fraction of price-sensitive passengers is on the rise. Accordingly, the prices between non-stop and connecting flights might narrow down. Along similar thoughts, airlines might reconsider their fleets. COVID-19 has already swept across fleets for most airlines, leading to the retirement of older/fuel-inefficient aircraft. Future fleet changes might be induced by significant adjustments in flight frequencies. The absence of business travelers makes it harder to operate frequent connections at a high load factor; ultimately favoring larger aircraft operating at lower frequencies again, reversing recent trends towards the use of high-frequent narrow-body connections. Better modeling and understanding these effects are of outstanding importance to the aviation community.

The future role of regional disparities and asymmetry

While most countries have chosen accepting an endemic presence of the contagion, other countries are still trying to prevent endemic infections among their populations. One major example for the latter category of countries is China, whose dynamic zero-case policy has helped to largely keep the disease outside the country, with few regular flare-ups across border and seaport cities. It is uncertain how long China (and other countries) will commit to strict strategies (Normile, 2021). New Zealand is another interesting case: While they had partially capitulated from the delta variant, they are hesitating to finally open up their borders. Such disparities in pandemic intervention can lead to more challenges for aviation. Pre-COVID-19, the aviation flow between airports was highly symmetric, with the number of passengers on a market being in the same order of magnitude in either direction. With further regional disparities, one could imagine that the aviation world becomes asymmetric. New Zealand, again, is a good example here: While Australia accepts New Zealand’s population as incoming travelers, the inverse path towards New Zealand is still blocked. Since airlines are unwilling to perform half of the flights without passengers (so-called “backhaul problem” in transportation), the trans-Tasmanian aviation market is still under heavy pressure (Chan and Haines, 2021). In fact, the South-Asian market is presumably most affected in the end of 2021. One could perceive that similar issues arise elsewhere. The aviation sector needs to find answers for addressing this problem. In addition to hindering human mobility, regional disparities will also inevitably lead to greater deviations of airline performance in the future.

The future role of competition and fairness

Throughout the past two decades, the aviation industry has undergone significant efforts for facilitating the entry of new airlines as well as ensuring competition and innovation in the industry. Market structures have been changed through deregulation and liberalization efforts, allowing for more diverse interactions between stakeholders. COVID-19 has highlighted several remaining challenges regarding competition, which needs appropriate policy responses. For instance, the subsidies to mostly state-owned airlines have been perceived as unfair and skewing the competitiveness of the airline market. Similarly, repetitively waiving slot requirements at large hub airports, despite these airports operating well below capacity limits throughout most parts of the year 2021, raises concerns regarding the goal of ensuring competition in the airline industry. It is probably too late for the COVID-19 pandemic, but policy makers need to develop reasonable guidelines for dealing with future disruptions under the maintenance of competition.

The future role of micro-alliances/partnerships

For the past two decades, the airline industry has been mainly dis-integrated into three major alliances: Star Alliance, oneworld, and SkyTeam, with some airlines joining neither of the alliances, mostly low-cost carriers. Under these alliances, airlines combine efforts for marketing/operating flights; see Oum et al. (2000), Brueckner (2001) for a broad analysis of airline alliances. Such airline alliances have been rather stable, with minor changes over time. The need to offer a great variety of products to potential customers throughout the COVID-19 pandemic, has led to a new shape of alliance appearing in aviation: so-called micro-alliances (Garrow et al., 2021). Such temporal micro-alliances come with a great amount of agility, flexibility, and granularity; properties which are rather contrary to the image of traditional carriers in aviation. Here, these properties inherent to the startup culture (Sun et al., 2022c) are used to enforce contracts at the level of flights or even individual seats; compared to decade-long code-sharing agreements. Such an environment gradually further pushed the envelope on fluent supplier/retailer roles in aviation. Deriving formal models for such novel types of cooperation and describing the impacts on passengers and other aviation stakeholders might lead to an overall improved aviation system, independent of disease considerations.

The future role of cargo and freighters

During the early phase of the COVID-19 pandemic, air cargo has turned into a lifeline of many aviation stakeholders (Bouwer et al., 2021), given that cargo is not only essential for fighting COVID-19 (transportation of medicines, medical equipment), but also instrumental for keeping up global supply chains in high-value (and relatively small and light) goods. Some airlines had temporarily converted passenger aircraft to freighters, raising the question whether such hybrid operations could be a model for the future. Earlier experiences with hybrid passenger/cargo aircraft (so-called freighters) could teach a...
lesson here, highlighting the extreme safety concerns around hybrid operations. Accordingly, it seems unlikely that the aviation system will come back to such types of aircraft. Nevertheless, it will be interesting to see how the aviation industry will develop novel solutions for combining highly cyclical, volatile passenger transportation with rather stable cargo operations.

The future role of technology

One potential pathway towards a solution of several key challenges around the COVID-19 pandemic is the usage of modern technologies in aviation. Evolving technologies particularly include data science and artificial intelligence. With the informed usage of such technologies, airlines will be able to transform from simple model-driven operations to near real-time demand-driven operations. The aviation industry is rather conservative regarding the introduction of new technologies. The reasons are manifold, covering rather simplistic models, lack of competition, and safety/security concerns. There is a need for policy makers to enable transitions and incentivize technology adaptation. Such technology transitions should include sustainable development goals (Gossling, 2020).

The role of a sustainable recovery

It becomes increasingly clear that we need to change our attitude towards mobility and its implementation, given that the transportation sector is a leading producer of carbon emissions which ultimately lead to climate change and extreme weather disruptions and disasters; see Renne et al. (2022) for an excellent overview. Throughout the COVID-19 pandemic, various studies have highlighted the need to rethink aviation: This survey has an entire subsection on the subject of sustainability. There is a risk, however, that such studies remain purely academic without real policy implications and - particularly- significant changes in the mind of operators: Efficiency and cost minimization alone are not sustainable to ensure the life on this planet. In this context, we see a need for studies which provide implementable pathways (in context of the known resistances among stakeholders), possibly using game-theoretic models. Such models could be used to find phase transition points where operators are willing to commit towards a green aviation, beyond using it for green washing. The recovery from COVID-19 is an ultimate chance for doing so. Missing this opportunity now will likely inhibit future advances.

Evaluating the lessons learned

Even throughout the year 2022, there are still studies assessing the impact of COVID-19 on aviation in the very early phase, e.g., during the first half 2020. We conjecture, that further efforts in this direction will be a rocky road, given the extensive analysis in the literature. The universal process of contagion spreading in the air transportation system is well understood. In fact, it was rather understood before the outbreak of COVID-19, with various studies on earlier contagions. What we need to avoid is coming back to a business as usual as part of the recovery, without actually changing the underlying system. In this context, we see a room for various types of studies. First, one needs to understand the differences between the aviation system now (endemic) and the system before the outbreak (pre-COVID-19), answering the question: What has been learned and implemented? To the best of our knowledge, such studies are well published in the academic literature. Second, one needs to better understand how to prepare for the next pandemic outbreak - which is rather a matter of time - and identify the driving forces against significant changes in the system. Especially the latter is instrumental towards an aviation system with future.

Conclusions

The COVID-19 pandemic was anything but a near miss (Velu and Iyer, 2021); it was a full blow to our entire society. Aviation, by design, is prone to take huge, yet ambiguous roles in the evolution of pandemics, being one of the major casualties, but also enabling the effective spread of a contagion through a highly-efficient, global transportation system. Without changes to the way we live and travel, the COVID-19 pandemic will not be the last pandemic to hit our society (Chansuk et al., 2022; Tsvetkova et al., 2022; Rahman Fatmi et al., 2022). Using a categorization framework, this paper discussed the impact of COVID-19 on air transportation systems concerning various aspects. Such a comprehensive review of existing work is indispensable for the research not only to avoid reinventing the wheel by re-publishing known findings in various venues, but much more to extract the essence of scientific findings and derive a coordinated call for policy intervention and providing a clear set of recommendations for future work.

Funding

This study is supported by the National Natural Science Foundation of China (Grant No. 62250710166).

CRediT authorship contribution statement

Xiaoqian Sun: Conceptualization, Methodology, Writing – original draft. Sebastian Wandelt: Conceptualization, Software, Writing – review & editing. Anming Zhang: Conceptualization, Validation, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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