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COVID-19 pandemic and air transportation: Successfully navigating the paper hurricane

Xiaoqian Sun [a,b], Sebastian Wandelt [a,b,*], Changhong Zheng [a], Anming Zhang [c]

[a] National Key Laboratory of CNS/ATM, School of Electronic and Information Engineering, Beihang University, 100191, Beijing, China
[b] National Engineering Laboratory of Multi-Modal Transportation Big Data, 100191, Beijing, China
[c] Sauder School of Business, University of British Columbia, Vancouver, BC, Canada

A R T I C L E I N F O

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A B S T R A C T

This paper aims to analyze and understand the impact of the corona virus disease (COVID-19) on aviation and also the role aviation played in the spread of COVID-19, by reviewing the recent scientific literature. We have collected 110 papers on the subject published in the year 2020 and grouped them according to their major application domain, leading to the following categories: Analysis of the global air transportation system during COVID-19, the impacts on the passenger-centric flight experience, and the long-term impacts on broad aviation. Based on the aggregated reported findings in the literature, this paper concludes with a set of recommendations for future scientific directions; hopefully helping aviation to prepare for a post-COVID-19 world.

1. Introduction

Throughout the year 2020, COVID-19 has turned into a fully blown pandemic, which poses a global risk to our health and global economies. The disease was first observed in December 2019 around Wuhan and is caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) (Andersen et al., 2020). By March 11th, 2020, the World Health Organization (WHO) declared COVID-19 as a pandemic (World Health Organization, 2020). As of February 9th, 2021, there are 105.8 million confirmed cases and more than 2.3 million fatalities that were related to COVID-19. The long-term effects of COVID-19 are still unforeseeable, but the impact in the year 2020 alone is remarkable: The pandemic is estimated to have caused the largest global recession since the severe worldwide economic downturn in the 1930s (the Great Depression), with millions of people falling into extreme poverty (Sumner et al., 2020).

Across all industries, the aviation sector is probably among the hardest hit (Suau-Sanchez et al., 2020). The unprecedented decrease in passenger demand (together with country-wise flight bans), led to a halt of most airlines; many companies had to cease almost all their operations and grounded entire fleets (Sun et al., 2020a), many airports have closed their runways in order to free up space for aircraft parking (Adrienne et al., 2020) or just shutting down indefinitely, most companies in the aviation sector are working with minimum staffing on strict rotations (Iacus et al., 2020), and aircraft manufacturers and downstream industry have largely shut-down their production lines (Truxal, 2020). Overall, the impacts of COVID-19 are tremendous, as it can be seen by the number of reduced flights - with references to the previous year 2019 - visualized in Table 1. Nevertheless, the aviation industry has proven resilient to major setbacks in the past, including oil crises, financial crises, wars, and earlier diseases (Gudmundsson et al., 2020; Tanriverdi et al., 2020); and will likely find ways to overcome COVID-19, one way or another. Yet, it is often ignored that the aviation sector is not only a victim of COVID-19, but also known to play a key role in the spread of diseases, enabling the turn of a (local) epidemic into a (global) pandemic (Budd et al., 2009; Chinazzi et al., 2020; Yang et al., 2020), as it was observed already for several earlier diseases, such as, Ebola (Pigott et al., 2014), SARS/MERS (Poletto et al., 2016; Wong et al., 2015), seasonal influenza (Khan et al., 2009), and Malaria/Dengue fever (Semenza et al., 2014; Tatem et al., 2006), most of which were contained before turning into a full pandemic on the scale of COVID-19.

In addition to the outbreak of the pandemic, another singleton can be observed in the scientific literature: Given the outstanding role of COVID-19 and its impact on all domains of our lives, a substantial number of papers has been submitted and published on the role and impact of COVID-19. The main goals of our review are to give a guide to successfully navigate the paper hurricane on this important subject, and to suggest future research directions on the subject. Overall, we have

* Corresponding author. National Key Laboratory of CNS/ATM, School of Electronic and Information Engineering, Beihang University, 100191, Beijing, China.
E-mail addresses: sunxq@buaa.edu.cn (X. Sun), wandelt@buaa.edu.cn (S. Wandelt), zch28@buaa.edu.cn (C. Zheng), anming.zhang@sauder.ubc.ca (A. Zhang).

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identified more than 100 scientific papers on a wide range of aviation topics. These papers were identified using related keywords, such as, *COVID-19*, *air transportation*, and *pandemic*, and references found in these papers. The selected studies have appeared in a wide range of venues; the most frequent journals include Journal of Air Transport Management (20x), Journal of Travel Medicine (7x), and Travel Medicine and Infectious Disease (5x). A word cloud created over all these papers is shown in Fig. 1, generated by https://github.com/amueller/word_cloud. Collecting these papers and unifying them was a considerable effort, given that they appeared in various venues across different scientific domains. It should be noted that our review, therefore, mostly focuses on papers published after the outbreak; with only giving pointers to important earlier papers whenever strictly required for understanding the context. For a complementary review of air transportation literature right up to COVID-19 and how this literature might define and lead to a future of post-COVID-19 aviation, please see (Tanriverdi et al., 2020).

The remainder of this study is structured as follows. Section 2 provides an overview on the extant literature for air transportation as a system; with a focus on the contribution to spreading and how flight suspensions affected the global network. Section 3 turns to the passenger-centric experience of taking a flight, discussing the impact on airport processing, boarding, and in-flight activities. Section 4 reviews the literature that discusses the long-term impact of COVID-19 on aviation. Section 5 concludes our study and provides a set of recommendations for future work, based on the insights obtained from our literature review.

2. The global air transportation system during COVID-19

In this section, recent studies on the global air transportation system as a network in the presence of COVID-19 are reviewed. Fig. 2 shows worldwide airports based on their connectivity (measured degree), comparing April 2019 with April 2020. These identified (hub) airports are important for this analysis from two perspectives. On one hand, given the critical role of these airports in (efficient) long-distance transportation, they possibly make key contributions to the spread of pandemics, given that a large number of passengers passes through these airports. On the other hand, the larger airports are those which often experience the hardest impact of COVID-19, given an extraordinary reduction in the number of global passengers.

This section starts with a review on how air transportation contributed to the spread of COVID-19 from a network perspective (Section 2.1). Afterwards, we review literature on the temporal evolution of the global network throughout the pandemic in the early months of 2020 (Section 2.2). Overall, the goal of this section is to identify how network science tools have been used to analyze the global air transportation system in the face of COVID-19.

2.1. Air transportation as transmission medium for disease spreading

The increased international connectivity and ongoing globalization allow travel times that are much shorter than the incubation period of infectious diseases (Budd et al., 2009). The increase in connectivity as well as the short travel times are beneficial for passengers, but bad news form an epidemiological perspective. In general, it is known for at least a decade now, that air travel has the potential to be a significant driver in the spread of airborne diseases; as observed with Ebola (Pigott et al., 2014), SARS/MERS (Poletto et al., 2016; Wong et al., 2015), seasonal influenza (Khan et al., 2009), and Malaria/Dengue fever (Semenza et al., 2014; Tatem et al., 2006). This observation has led to a variety of research tools, e.g., the Global epidemic and mobility computational model (Balcan et al., 2010), the vector-borne disease airline importation risk model (Huang et al., 2012), or other Susceptible-Exposed-Infectious-Recovered-based models using airline data (Hwang et al., 2012), which help to identify the roles of airports/airlines in the spread of general vector-borne diseases. It appears, nevertheless, that many expectations about the ability to predict the spread of diseases were too high for COVID-19 or at least the earlier scientific results on other diseases were not used in the most beneficial way.

Table 2 summarizes the relevant literature on the spreading of COVID-19 via air transportation. These studies, in essence, use existing aviation datasets (usually concerning the number of flights or the number of passengers between airport pairs) to understand the spreading processes in the early months of 2020, where the major medium of disease transmission was still air travel (Lau et al., 2020; Nakamura and Managi, 2020). Compartmental meta-population models or data science techniques are used to obtain relationships between the number of cases and different regions in the world; leading to predictions about the time and extent of an arrival of COVID-19 in these places. Some studies take a rather global, network perspective (Coelho et al., 2020; Hossain et al., 2020; Zhang et al., 2020b), while others focus on specific regions, e.g., China (Li et al., 2020b; Zhang et al., 2020c), EU/US (Nikolaou and Dimitriou, 2020; Peirlinck et al., 2020), Iran (Tuite et al., 2020), Brazil (Ribeiro et al., 2020) or Columbia (Gomez-Rios et al., 2020). Overall, the findings in these studies are largely consistent, given the earlier work on disease spreading (pre-COVID-19). They find that the number of passengers is a rather reliable indicator of predicting when the disease arrives, given a fixed place of origin, a concept known as effective distance (Brockmann and Helbing, 2013) in the literature. Nevertheless, most early studies (had to) make assumptions which are independent of the specifics of COVID-19; and

Table 1
Global scheduled flights change year-over-year, January–November 2020.

Countries	January	February	March	April	May	June	July	August	September	October	November
Australia	−2.0%	−2.5%	−5.9%	−84.8%	−86.2%	−83.2%	−77.4%	−75.6%	−74.2%	−71.2%	−66.6%
China	5.1%	−54.2%	−38.7%	−42.3%	−27.9%	−19.6%	−17.2%	−10.1%	−5.1%	−0.4%	−2.6%
France	−0.8%	0.3%	−15.5%	−90.9%	−91.9%	−87.5%	−66.0%	−50.2%	−51.2%	−58.1%	−73.3%
Germany	−8.5%	−6.8%	−30.6%	−92.9%	−91.5%	−87.2%	−72.6%	−64.1%	−64.7%	−67.8%	−78.6%
India	3.2%	7.0%	8.5%	−82.3%	−59.5%	−65.6%	−52.7%	−60.0%	−55.7%	−46.7%	−43.9%
Italy	−3.2%	−4.1%	−48.0%	−85.6%	−83.3%	−88.0%	−66.7%	−52.1%	−55.3%	−60.5%	−72.6%
Japan	2.6%	−2.9%	−15.7%	−39.4%	−46.4%	−44.2%	−37.1%	−29.5%	−37.3%	−37.6%	−36.0%
Singapore	0.1%	−15.8%	−42.9%	−93.5%	−96.5%	−95.2%	−93.7%	−92.4%	−93.8%	−92.6%	−91.9%
South Korea	2.2%	−11.3%	−49.2%	−56.4%	−49.1%	−49.2%	−48.3%	−41.3%	−46.2%	−39.8%	−41.3%
Spain	−3.7%	−1.7%	−23.2%	−94.1%	−93.5%	−90.2%	−65.7%	−47.1%	−54.0%	−64.7%	−69.2%
Sweden	−9.0%	−5.4%	−22.9%	−87.9%	−89.7%	−85.0%	−75.7%	−72.2%	−72.1%	−70.0%	−71.3%
United Arab Emirates	−2.0%	−3.1%	−23.1%	−80.6%	−78.6%	−79.9%	−69.6%	−65.0%	−62.6%	−64.6%	−62.7%
United Kingdom	−3.7%	−3.2%	−22.7%	−92.6%	−93.6%	−90.2%	−80.2%	−66.8%	−64.9%	−68.0%	−81.8%
United States	2.7%	2.1%	−0.4%	−57.8%	−72.6%	−66.7%	−51.1%	−47.7%	−47.4%	−47.4%	−42.5%
TOTAL	1.5%	−7.8%	−14.5%	−65.9%	−68.9%	−64.1%	−53.8%	−48.3%	−47.5%	−46.4%	−46.0%

*Each month is compared with the equivalent month in 2019; negative values correspond to flight reductions. Cell colors are chosen according to the magnitude from white to dark red (Data source: https://www.oag.com/coronavirus-airline-schedules-data).

Fig. 1. Word cloud for all COVID-19-related papers reviewed in our study.

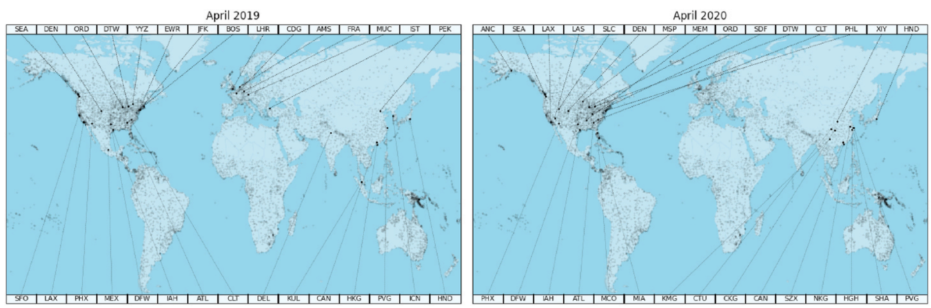

Fig. 2. Airports with the largest connectivity (in terms of degree) for April 2019 against April 2020.

accordingly, their findings have to be taken with caution when applying them to the spread of COVID-19.

2.2. Flight suspensions and their impact under COVID-19

Given the gradual public understanding that air transportation is instrumental as a medium for the spread of COVID-19, between March 2020 and May 2020, airlines began to implement a wide range of flight suspensions. Flight suspensions, initially, had a strong impact on the number of international flights and domestic flights equally, as it can be seen in Fig. 3. May 2020 can probably be considered the month with the least number of flights in the recent history of aviation. Afterwards, many airlines began to re-open domestic flights - mainly due to initial successes in fighting the first wave of the pandemic and also due to the starting summer (vacation) season in the Northern hemisphere. At a very extreme level, this effect can be observed for China and Russia, where the fraction of active domestic flights reaches about 90% of the original value (back in January 2020); see also (Czerny et al., 2021). Similar observations can be made for Japan, which relies on air transportation to enable movement between its islands. Fig. 4 compares the air transportation country network (Wandelt and Sun, 2015) for January 2020 and May 2020 where airports are aggregated into country nodes, highlighting the structural differences between the two (extreme) dates. Here, nodes are countries (consisting of all airports in that country) and links represent the existence of at least one international flight between two countries. The width of the link correlates with the average number of actual flights per day.

In the long run, the impact of COVID-19 on the global air transport system seems to be more profound on the international market (Sun et al., 2020b). Such a shift from international to domestic transportation brings challenges to airlines, particularly regarding aircraft usage, which can make the aircraft fleet a decisive factor for airline survival (Peoples et al., 2020; da Silveira Pereira and Soares de Mello, 2021). Other notable examples for reactions of countries are those of Germany and Great Britain, who apparently enforced the resumption of international flights, through their flagship carriers Lufthansa and British Airways. Notably, cargo flights were not affected significantly, given the need to transport medical equipment and the ambition to keep exchange of critical goods across borders alive (Nhamo et al., 2020; Nižetić, 2020; Li, 2020). This effect has been further analyzed by Bombelli (2020), who investigated the global networks of FedEx, UPS, and DHL, using network science tools; it was found that after short fluctuations in early stages, these integrators seem to have survived the pandemic rather unaffected.

Table 3 summarizes the findings in existing studies on flight suspensions during COVID-19. A major limitation of these studies is that they mostly rely on the number of flights. This number neglects the actual number of passengers on board of these aircraft (i.e., the load factor). In fact, it has been reported that some airlines were flying (essentially) empty aircraft, in order to not lose their slots at slot-constrained airports (Haanappel, 2020). The off-schedule flights for conducting take-home missions of people stranded in other international destinations often had a load factor close to 100%. Accordingly, the (network) analysis based on the number of flights alone has limited room for interpretation for fully understanding the effects of COVID-19 on air transportation as a system (Sun et al., 2020b). Similarly, most existing studies take into consideration passenger aircraft (or aircraft used by passenger airlines), which ignores that some airlines used the cabin area for 100% cargo transportation (without actual passengers) and also the indirect effects of flight reduction on non-passenger related issues, such as kidney transplantation, which heavily relies on commercial airlines for transport (Strauss et al., 2020).

Finally, it is important to understand that the flight suspensions modify the spreading process over the induced network away from the identified critical airports (super-spreaders). Accordingly, the results in Section 2.1, which mostly rely on pre-pandemic passenger/flight data, are unlikely to be valid for the air transportation network as it is active in present times. Therefore, one should understand the results from Section 2.1 and Section 2.2 as being complementary. Future research should always use recent data to make predictions about the (potential)

Table 2
Extant literature on COVID-19 pandemic spreading under air travel.

Study	Major finding
Christidis and Christodoulou (2020)	Aviation data about outbound flights from China are used to predict the countries with a high risk of infections; and a methodology for monitoring the evolution of the pandemic across countries is suggested.
Chu et al. (2020a)	It is shown that infection case-correlation analysis between countries and their induced network structures can be complementary to using aviation data for the detection of pandemic outbreaks.
Coelho et al. (2020)	Using a standard multiple regression model, it was found that the exponential growth rate of COVID-19 is explained mainly by population size and country's importance (airport connections).
Daon et al. (2020)	Scenario analysis shows that airports in East Asia have the highest risk of acting as sources for future outbreaks; complemented by airports in India, Brazil, and Africa.
Gomez-Rios et al. (2020)	Based on data for Colombia, it is argued that the initially scarce control of inbound air travelers and their non-compliance with procedures has significantly contributed to the spread to/inside the country.
Hossain et al. (2020)	A simplified SIR meta-population model is proposed, which allows to for the calculation of the arrival time, number of imported cases, and the potential for an outbreak, based on aviation data.
Lau et al. (2020)	The authors identified a strong linear relationship between domestic COVID-19 cases and the passenger volume inside China.
Musselwhite et al. (2020)	Reducing the hypermobility of transport networks and focusing more on local connectivity is perhaps a solution for creating novel post-pandemic mobility patterns for networks.
Li et al. (2020b)	Restrictions placed on air traffic in eleven megacities in China reduced these cities' COVID-19 cases, but the restrictions were only effective for a short time.
Nakamura and Managi (2020)	The overall relative risk of importation and exportation of COVID-19 from/to every airport was calculated and the necessity of air travel reduction is suggested.
Nikolaou and Dimitriou (2020)	A novel epidemiological model for Europe's airline network is developed, which is able to identify the critical airports for infectious disease outbreaks.
Peirlinck et al. (2020)	A SEIR meta-population model is developed, which is used to analyze the outbreak dynamics in China and US.
Ribeiro et al. (2020)	The expansion of COVID-19 is directly proportionally to the airport closeness centrality within the Brazililan air transportation network
Tuite et al. (2020)	The outbreak size in Iran is predicted based on air travel data between Iran and other countries, together with an estimation where the disease may spread next.
Zhang et al. (2020b)	Proposes a risk index which measures a country's imported case risk based on the number of international flights; and evaluates the evolution of index's values over time.
Zhang et al. (2020c)	The role of air travel in the spread of COVID-19 in China is compared to those of high-speed train and coach services, finding that the spread is a complex interaction and most likely to emerge in larger cities.

spreading paths during the ongoing pandemic and deciding which flights should be suspended.

3. Impact on passenger-centric flight experience

In this section, recent studies on the passenger-centric flight experience in presence of COVID-19 are reviewed. Specifically, this section starts with airport screening (Section 3.1), proceeds with aircraft boarding (Section 3.2), and then discusses the in-flight experience (Section 3.3).

3.1. Airport experience and screening

The airport processes have been largely affected by COVID-19: social distancing rules combined with screening requirements, have led to changes in passenger processing. Moreover, given that the pandemic does not seem to reach an end soon, we believe that ground handling processes will still require extreme cautiousness in the near future; therefore, provide a review of studies regarding airport experience and screening below. Traditionally, operating an airport successfully means to set an airport apart from its competitors; be it in terms of local competition (catchment area) or global competition (as a transfer hub) (De Neufville and Neufville, 1995; Rothkopf and Wald, 2011; Tuchen et al., 2020). The strength of an airport in competition depends on how good as substitutes travelers regard an airport to be (Forsyth and Dwyer, 2010). In recent decades, airports have developed towards multi-services business organizations and understanding passenger experience at the airport has become the crucial factor for airport management; it was recently shown that passenger expectations come with a concept of minimum tolerable service performance (Bezerra and Gomes, 2020). For instance, researchers found that for passengers at Taoyuan International Airport, a waiting time is unacceptable as soon as it exceeds 20 min (Chang et al., 2008). Accordingly, improving (or maintaining) passenger experience and waiting times are tremendously important for the successful management of airports. Here, the COVID-19 pandemic causes drastic changes to the passenger experience at airports, especially for operations which affect the safety and passenger waiting times and also reduced shopping experiences. Therefore, this leads to a conflict for airport managers, trading between safety and user experience: In the presence of the virus, social distancing is agreed to be one of the main successful measures, yet, affecting the capacity and throughput of an airport significantly (Dabachine et al., 2020).

A summary of literature on airport screening operations is provided in Table 4. There are controversial results in the literature regarding pandemic-safe passenger screening at airports: Although the screening equipment is costly, the effectiveness of detection is sometimes extremely limited. For instance, based on the data from 15 U.S. airports, it is found that passenger entry screening at airports is ineffective because of the non-specific clinical presentation of COVID-19 and asymptomatic cases (Dollard et al., 2020). Moreover, it is reported that screening of departing or arriving passengers can hardly intercept infected travelers (Normile, 2020). Similarly, a case study in Australia also reported that temperature screening has negligible value for the control of COVID-19 (Mitra et al., 2020). Sanitary risk management of airport facilities, such as security control lanes and check-in counters, has been discussed in the face of the pandemic. With the Wroclaw Airport, Poland, as an example, the impact of social distance on the performance of security control lanes was investigated (Kierzkowski and Kisiel, 2020); the authors found that different configurations of the security control lanes (Queue-based or Dedicated Stand-based) depend on whether the stakeholder has space to expand the system. With the Casablanca Mohammed V International Airport as an example, it was shown that it is possible to calculate the number of passengers to be processed in accordance with the available check-in counters, while considering sanitary measures (Dabachine et al., 2020). A few recent studies focused on equipment design of new equipment for the purpose of disinfection at airports, for instance, a walk-through-gate with different sensors (Hossain et al., 2020) and a tunnel system similar to the X-ray machines (Murthy, 2020). Furthermore, an on-site implementation of a 10:1 pooled test strategy for COVID-19 detection at Sanya airport, China, was recommended, in order to reduce costs and processing times (Li et al., 2020a).

Ideally, airports need to overcome ongoing challenges for maintaining passenger user experience while keeping prices low (Forsyth et al., 2020), in order to avoid repeating recovery-preventing counter--effects as in the global financial crisis for European airports (Wiltshire, 2018). In that line, Serrano and Kazda (2020) provided a comprehensive

Fig. 3. Evolution of the number of domestic and international flights for selected countries during COVID-19 pandemic (Data source: Flightradar24). Countries are labeled with their ISO-3 country codes. The blue color denotes domestic flights; and the green color denotes international flights. Note that passenger and cargo flights are not distinguished. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

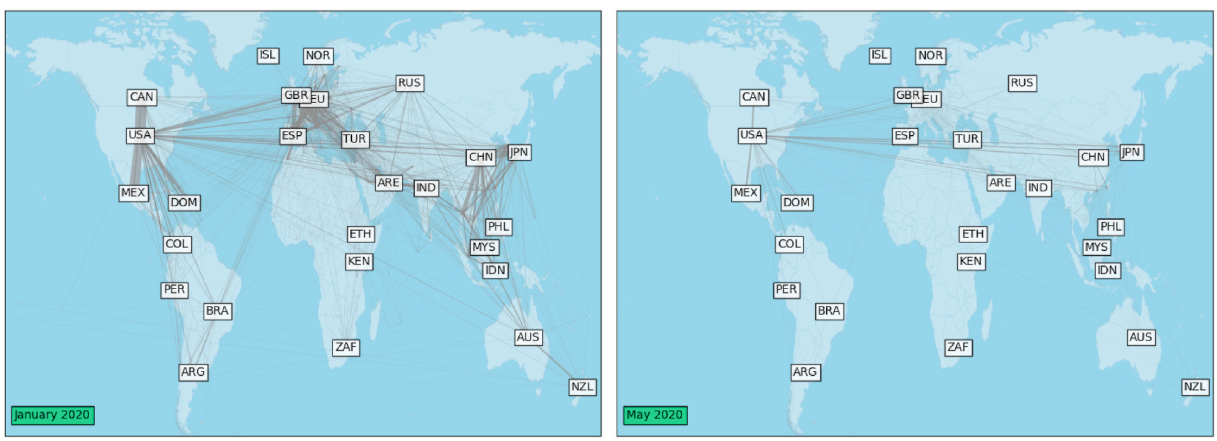

Fig. 4. Difference of the air transportation country network between January 2020 and May 2020, under the impact of COVID-19 (Data source: Flightradar24).

recommendation for airports, such as revenue generation sources and cost control strategies due to variable demand and capacity during and post-COVID-19.

3.2. Aircraft boarding

Literature on aircraft boarding pre-COVID-19 has mainly focused on efficiency, by answering the question: What is the *fastest* approach to get all passengers to their seats, mainly in an attempt to minimize the turnaround times of aircraft. The optimal choice for aircraft boarding depends on a wide range of interacting variables, including aircraft characteristics, load factor, patterns and limitations on passenger movements, size/presence of hand luggage, types of passenger inferences and disturbances, number of boarding groups, preservation of aisle symmetries, reliability of boarding time predictions and many more (Bazargan, 2007; Schultz, 2018; Tang et al., 2012; Zeineddine, 2017). In the literature, three most-frequently used boarding methods considered for aircraft boarding pre-COVID-19, while using the front and rear door are: Back-to-front, Outside-in (also called WilMA), and Reverse pyramid (Milne et al., 2020); other methods include by-seat-number (Steffen, 2008), random boarding, and zone boarding. See (Delcea et al., 2018) for an experimental comparison of more than 20 pre-COVID-19 boarding strategies. Notably, decisions about boarding strategies often come with a high degree of uncertainty, making it difficult to predict the actual boarding times (Schultz and Reitmann, 2019).

Throughout COVID-19, the question about how to board shifted towards: What is the *safest* approach to get all passengers to their seats, while not increasing the boarding time significantly. In other words, how does the seat layout and aircraft boarding need to be changed/exploited, in order to minimize the number of possible infections taking place during boarding/the flight. In general, the International Air Transport Association (IATA) recommends a distance of 1–2 m between passengers at any time, in an effort to ensure social distancing (IATA, 2020). Keeping this distance is difficult with most boarding/seating methods; in fact, a strict application of this rule would need to leave two rows empty between each passenger (Cotfas et al., 2020). In addition, social distancing during aircraft boarding does not only require a good boarding strategy, but also the passengers' self-willingness to perform social distancing (Salari et al., 2020); the latter one possibly having a dominating impact on the boarding result.

Since airlines are business entities, with the ultimate goal of making profit, they make individual decisions regarding the seating/boarding strategy; and these decisions are never purely driven by safety. Instead, profit-driven airlines have to make a trade-off between economic productivity and the resulting impact of various health risks (Cotfas et al., 2020). For instance, American Airlines announced to fill all seats as much as it can, which was not received well among epidemiologists and politicians (Barnett, 2020). Accordingly, the applied boarding strategies during COVID-19 vary across airlines (and time). Example reactions and boarding strategies of airlines are shown in Table 5. While several airlines adapted the back-to-front boarding procedure, it has been shown in

Table 3
Literature on flight suspensions in presence of COVID-19.

Study	Major finding
Adiga et al. (2020)	An index for measuring the effect of airline suspensions on delaying the spread is proposed; identifying mostly a few days difference only.
Albers and Rundshagen (2020)	Classification of airline reactions over time: Retrenchment, Persevering, Innovating, Exit, Resume, etc. based on aviation industry newsletter Aviation Week Network.
Bombelli (2020)	Analysis of the role of integrators/freight airlines during the pandemic; using complex network tools. Capacity reduction for cargo has taken place rather short-term only.
Budd et al. (2020)	The reactions of airlines towards the early stages of COVID-19, the possible drivers and explanations of decisions, and the possible mid-term impacts are discussed.
Iacus et al. (2020)	Scenario analysis based on air passenger data comparing normal projections with COVID-19 and discussing implications such as loss in revenue and jobs inside Europe.
Li (2020)	The air cargo sector in China has suffered a less severe depression compared to air passenger traffic.
Nhamo et al. (2020)	Effect of network changes on airport revenues are analyzed; During COVID-19, many airports converted into parking lots and ghost towns.
Nižetić (2020)	The impact of COVID-19 on the EU was analyzed, with hundreds of thousands of cancelled flights. Cargo flights were not severely affected.
da Silveira Pereira and Soares de Mello (2021)	Brazilian airlines are being analyzed; airlines with a better aircraft mix are more likely to survive many flight cancellations and its inherent challenges during a pandemic.
Sousa and Barata (2020)	Decisions on increasing and reducing mobility based on open data and machine learning are discussed on test cases for Hongkong and Wuhan.
Strauss et al. (2020)	Analyzing the impact of flight reductions on the kidney transplants transportation network on the US.
Sun et al. (2020a)	Complex network analysis tools are used to explore the impact of COVID-19 on air transportation, at different levels of fractality.
Sun et al. (2020b)	Countries' reactions in terms of flight reductions are compared to the number of COVID-19 cases; finding that largely heterogeneous responses led to a possibly too-late response.
Suzumura et al. (2020)	The number of flights during COVID-19 is analyzed as a time series; in addition, the number of workers in the tourism and airlines business are analyzed.

Table 4
Literature on airport screening operations in the presence of COVID-19.

Study	Major finding
Dabachine et al. (2020)	Modelling and processing algorithms for passenger processing under sanitary measures are discussed, with a use case on Casablanca Mohammed V International Airport.
Dollard et al. (2020)	Passenger entry screening at airports is ineffective because of the nonspecific clinical presentation of COVID-19 and asymptomatic cases.
Hussain et al. (2020)	A walk-through-gate with a wide range of sensors is proposed in order to better facilitate passenger screening at airports, if being placed at all entrances/exits.
Kierzkowski and Kisiel (2020)	Different configurations of the security control lanes (Queue-based or Dedicated Stand-based) depends on whether the stakeholder has space to expand the system.
Li et al. (2020a)	Pooling test strategies for infections could be successfully implemented on-site for COVID-19 detection at Sanya airport, yielding an increased test efficiency without loss of sensitivity.
Mitra et al., 2020	The role of temperature screening at airports for entry/exit scanning is questioned, because of having negligible value for the control of COVID-19.
Murthy (2020)	An automatic tunnel disinfection system is proposed, similar to the X-ray machines, which could handle passenger luggage at airports.
Normile (2020)	Screening of departing or arriving passengers can hardly intercept infected travelers, while screening programs being very costly.
Serrano and Kazda (2020)	Thermal screening, self-handling kiosks, wearing face masks, and increasing cleaning measures throughout the terminal area are recommended for near-term airport operations.
Tuchen et al. (2020)	A conceptual framework with a new perspective on airport user experience is proposed, aggregating the experience of all users under the impact of COVID-19.

Table 5
Aircraft boarding procedures for selected airlines during COVID-19.

Airline	Seating/boarding procedure
Alaska Airlines	Middle seat empty (Milne et al., 2020a)
Delta Air Lines	Middle seat empty; back-to-front by row (Cotfas et al., 2020)
Easyjet	Seat numbers (Milne et al., 2020a)
Go Air	Front-to-back from rear (Milne et al., 2020a)
Hainan Airlines	Random boarding
Southwest Airlines	In groups of ten passengers (Cotfas et al., 2020)
United Airlines	Back-to-front by row; business class last
Wizzair	Middle seat empty (Milne et al., 2020a)

the literature that this way of boarding is slow; and does not necessarily reduce social proximity. Passengers waiting for luggage storage led to clusters, with a significant impact on passenger contacts in context of Ebola and SARS (Namilae et al., 2017). The literature on boarding during COVID-19 and their main findings are summarized in Table 6.

The improvement of seating/boarding strategies in the face of COVID-19 requires making a wide range of assumptions, which leads to studies having difficulties in reflecting the real-world, without having fully understood all processes involved with COVID-19 (Barnett, 2020). Estimates in existing studies are divergent about their findings, as already observed in earlier literature (Barnett, 2020) on SARS/MERS aircraft boarding (Hertzberg and Weiss, 2016; Hertzberg et al., 2018). It is of paramount importance, to unify these existing results and derive consistent conclusions and concise recommendations for safer boarding strategies.

3.3. In-flight

Since passengers spend long periods of time in an enclosed aircraft cabin, there is a high (perceived) risk of transmitting the disease inside an aircraft during a flight. Evaluating the actual risk in a scientific way is tremendously hard, given the large number of variables in adequately-setup experiments, e.g., aerosol movement, virus kinetics, passenger health groups, effectiveness of face masks etc. Accordingly, there is a lack of formal understanding how likely a transmission in an aircraft cabin is during a flight (Bielecki et al., 2021). Table 7 summarizes the existing literature regarding in-flight operations in the presence of COVID-19.

It is believed that the primary way of in-flight transmission is face-to-face exposure during talking, coughing, and sneezing (Harries et al., 2020). Tracking the history of in-flight transmissions through questionnaires, surveys, and follow-up investigations is a tedious challenge; often complicated through transit passengers who cannot be traced further even with strong efforts (Khanh et al., 2020). It should be noted that - contrary to public perception - that there is no evidence for super-spreading events on aircraft so far. In fact, there is few studies in the literature which do convincingly (and without remaining doubt) prove that a transmission indeed occurred during the flight (Choi et al., 2020); is a notable exception for a virus-sequencing based confirmation of a transmission between passengers and flight attendants. In general, the proof of in-flight infections is an arduous endeavor, given that actual in-flight infections could only be identified as early as three days post-flight (Freedman and Wilder-Smith, 2020).

Table 6
Literature on aircraft boarding in presence of COVID-19.

Study	Major finding
Barnett (2020)	The probability of infection by a nearby passenger is; with middle-seat empty becomes.
Cotfas et al. (2020)	Back-to-front by row takes the longest time, but has the least infections. WiLMA and reverse pyramid by half zone perform best. Aisle distance increase in 0.5m led to an increase of 25% boarding time.
Islam et al. (2020)	Back-to-front doubles infection exposure, compared to random boarding. Authors suggest to fall back to earlier boarding strategies or use better random processes.
Milne et al. (2020)	Adapted reverse pyramid methods have best health metrics. The risk of infection spread to previously-seated passengers decreases when the aisle social distance increases from 1 m to 2 m.
Milne et al. (2020b)	Fewer luggage, reduced health risks. Increase aisle social distance. Make use of jet bridges as much as possible and force the change of face masks every 4 h.
Milne et al. (2020a)	An adapted reverse-pyramid boarding method provides faster boarding times with social distancing, if luggage volumes are high. Increasing the social distance from 1 m to 2 m further reduces infection risks.
Salari et al. (2020)	Assign passengers to seats metrics: passenger distance and aisle distance, leading to better solutions than simply blocking all middle seats.
Schultz and Soolaki (2020)	Group-building will significantly contribute to faster boarding and less transmission risk (reduced by approx. 85%). Following grouped pattern, pre-pandemic boarding times could be reached.
Schultz et al. (2020)	Physical distance rules extend boarding times significantly (more than doubled). Reduced load factor can lead to pre-pandemic boarding times could be reached.
Schultz and Fuchte (2020)	With random boarding, possible transmissions are reduced by approx. 75% when increasing the physical distance of passengers.
Schwarzbach et al. (2020)	Radio propagation simulation is used to assess the distance measuring for safer boarding in a three-dimensional aircraft model.

The decisions of how the in-flight procedures are adapted during quarantine are made by different authorities, leading to largely heterogeneous protocols (Bielecki et al., 2021); see Table 8 for an overview of selected examples. For instance, passengers must comply with measures considered important by the country of departure, the country of arrival, the airline, and, finally, other organizations such as IATA. Such an overlap of responsible authorities creates a jungle of rules, which are by no means consistent across the planet. There is a lack of unanimity and scientific evidence throughout the world with respect to the thresholds for necessity, effectiveness, duration, and implementation of in-flight measures. Particularly, airlines are struggling to be compliant with COVID-19 prevention guidelines, since they are profit-oriented: They are tempted to keep up flight services, in order to keep the demand of passengers high, despite possibly detrimental effects on safety and health (Bielecki et al., 2021). Ultimately, the new reality induced by COVID-19 may lead to new international conventions on air transport (Naboush and Alnimer, 2020).

4. Long-term impact on aviation

The following section discusses the long-term impact on aviation. Section 4.1 discusses studies related to the issue of airline finances and how governmental aids have the potential to shift the aviation landscape for years ahead. Section 4.2 reviews the literature on passenger demand estimation for a post-COVID-19 world. Section 4.3 completes this section with a list of challenges and trends in the long term.

4.1. Airline financing

It is known that airlines have a particularly high capital cost, e.g., the typical airline has cash to cover only around two months of revenue loss

Table 7
Literature on in-flight operations in the presence of COVID-19.

Study	Major finding
(Ahmed et al., 2020)	An important source of information for onboard surveillance of passengers is wastewater epidemiology, based on data from several Australian-bound flights.
Albastaki et al. (2020)	It was found that wastewater samples are very cost-effective techniques, which can help decision makers to determine the level of precautionary measures an airport should take for arriving flights.
Bielecki et al. (2021)	In-flight infection probability is approx. 1 per 27 million passengers. In-flight protocols should include: highly-efficient filtering, rapid testing, sniffer dogs, regular disinfection, and traffic-light system.
Chen et al. (2020a)	Based on data for a flight from Singapore to Hangzhou with 335 passengers, the major driver for infections could not be attributed to in-flight transmission, but rather pre-flight exposure to the virus.
Chen et al. (2020d)	In-flight protocols should include: QR-code scanning, better diet preparation, eating peak time reduction, stricter enforcement of lavatory-seat assignment, avoidance of tissue/material sharing among passengers.
Choi et al. (2020)	Based on data for a flight from Boston to Hongkong, it is verified by virus sequencing that the infections spread from a married couple to two business class flight attendants during a flight.
Eldin et al. (2020)	Based on data for a flight from Bangui to Paris, it is argued that a transmission of a virus might have taken place, excluding other options based on interviews and investigations.
Freedman and Wilder-Smith (2020)	Strict use of masks appears to be protective. Lack of data availability prevents structured studies leading to scientific evidence of mask vs mask-free transmissions.
Harries et al. (2020)	Major risk factors include the proximity to index patients and being seated in the middle seat. Avoid queuing for wash-rooms and possibly change seats given on-flight events, such as, coughing passengers.
Khanh et al. (2020)	On a 10-h commercial flight from London to Hanoi, a single passenger caused an outbreak with 16 persons in the business class; seating proximity was strongly associated with infection risk.
Naboush and Alnimer (2020)	The legal implications of in-flight transmissions are discussed, leading to the question whether an in-flight infection could be considered an *accident* or not.
Nir-Paz et al. (2020)	On a repatriation flight from Japan to Israel with eleven passengers, two were infected upon arrival; despite close proximity and partially being unmasked during the flight.
Parker and Mahomed (2020)	The role of hypoxia and thrombosis is underestimated during COVID-19; regular oximetry scanning should be implemented.
Pavli et al. (2020)	Based on 18 international flights bound to Greece, revealed five cases of probable in-flight transmission among 2,224 passengers.
Schwartz et al. (2020)	Based on a lack of infection on a flight from Guangzhou to Toronto, it is concluded that in-flight transmissions are rare; especially in the presence of face masks and milder symptoms.
Zhang et al. (2020a)	Based on international flights to Beijing, with questionnaires covering a total of 4,492 passengers, 161 passengers were found to be infected; two of whom are likely to have been infected on the aircraft.
Zhang (2020)	It might be necessary for passengers to share their health information before and during flights.

(International Air Transport Association, 2020; Zhang and Zhang, 2018); accordingly, it is clear that airlines are at high risk regarding survival of COVID-19. For governments there are two major reasons for making an airline survive: the preservation of essential connectivity (Merkert and Williams, 2013; Tchouamou Njoya et al., 2018) and protecting millions of jobs in directly and indirectly affected industries (Goessling et al., 2017). This kind of support is primarily given to selected national operators in each country, which often enjoyed preferential treatment before COVID-19. While these motivations seem reasonable for each individual government, given that aviation is seen as

Table 8
In-flight measures for selected airlines during COVID-19.

Airline	Mask	Eating	Drinking	HEPA	Sanitary disinfection
Aeroflot	x	x (limited)	x	x	x
Air Canada	x	x (prepacked)	x (limited)	x	x
Air China	x	x (prepacked)	x (limited)	x	x (hourly)
Air France	x	x	x (limited)	x	–
Alaska Airlines	x	x (limited)	x	x	x
British Airways	x	x	x	x	–
Delta Air Lines	x	(own food ok)	–	x	x
Emirates	x	x (limited)	x (limited)	x	x
Lufthansa	x	x	x	x	–
Ryanair	x	x (limited)	x	x	–
Southwest Airlines	x	x (limited)	x	x	–
Swiss Airlines	x	x	x	x	–
United Airlines	x	x (limited)	x	x	–

Source: Mostly adapted from (Bielecki et al., 2021).

a key strategic sector (Zhang and Graham, 2020), they lead to trouble in the global context: The magnitude, skewed distribution, and different types of financial aid, lead to concerns regarding the competition between airlines; which will have (unexpected) long-term effects on the international air transportation market in the future.

Therefore, several recent studies analyze the impact of COVID-19 and government subsidies on airlines; see Table 9 for a summary. Generally speaking, the goal is to find a trade-off between ensuring connectivity and maintaining competition with several economic and political dimensions (Abate et al., 2020). Particularly, it is questionable whether ongoing re-orientation of public policies helps to reach previously-set sustainability criteria (e.g., regarding climate change and environment), unless airlines are specifically bound to such conditional help (Goessling et al., 2020). Given that airlines hesitate to bargain with governments during COVID-19 (Akbar and Kisilowski, 2020), an enforcement of actual goals, compared to unconditional financial aid, might help to reach long-term goals despite the ongoing pandemic; possibly even faster. The airline industry is always fast to request a bailout, these bailouts are rarely appropriate; some studies suggest that letting airlines go through bankruptcy is a better option (de Rugy and Leff, 2020); an option which, for instance, American Airlines, Delta Air Lines and United Airlines all have taken - in the past. In pre-COVID-19 times, airlines might have secured financial aids from the private sectors (banks or investors); yet, throughout COVID-19, these private investors have become extremely cautious, due to the uncertainty of the economic future of aviation (Truxal, 2020). Accordingly, grants offered by governments (direct wage subsidies, tax relief, loans, etc.) might be the only option for airlines to take. Therefore, governmental interventions will create winners and losers among airlines - clearly reshaping the competitive landscape for years ahead and affecting travelers and regional residents (Akbar and Kisilowski, 2020). Related to airline finances, the impact of COVID-19 press releases on airline stock prices has been investigated by Maneenop and Kotcharin (2020), finding examples for underreaction and overreaction.

Table 9
Literature on airline finances impact of COVID-19.

Study	Major finding
Abate et al. (2020)	Most governments give a high priority to support national operators in each country in order to maintain air transport connectivity.
Agrawal (2020)	The impact of COVID-19 on Indian airlines was analyzed, covering suspended operations, drying cash reserves, and deteriorating solvency.
Akbar and Kisilowski (2020)	Airlines' nonmarket responses to COVID-19 governmental policy measures were analyzed, including non-/bargaining, compliance/partnership or selective avoidance/conflictual.
Chen et al. (2020c)	The impact of government responses to COVID-19 on stock returns of travel and leisure companies in the U.S. was examined. The airline sector suffers most of the negative impact of restrictions.
Goessling et al. (2020)	Bailing out airlines could be bound to conditions, such as emission reductions, carbon pricing or levies on frequent flying; as suggested by climate campaigners.
de Rugy and Leff (2020)	Bailing out airlines is not an inefficient way to protect airline industry.
Truxal (2020)	The extent to which and on what conditions state aid measures are applied to air transport in EU were investigated, the boundaries of state aid regime are set for a liberal market economy.
Vinod (2020)	An approach which monetizes seat inventory so that corporations can prepay for travel and receive a discount was recommended, in order to generate cash-flow for airlines to continue daily operations.

4.2. Passenger demand prediction

Given that passenger demand was the major driver for the extensive growth of the aviation sector for several decades, a major challenge for post-COVID-19 is to predict the future demand. Obviously, there is no silver bullet-like demand prediction, let alone recovery plan, showing demand rebound across all regions, given the variance in pandemic status, scale of aviation, and highly-distinct development levels (Akinola, 2020). Nevertheless, first studies have appeared in the literature in an attempt to make rough estimations of the demand recovery shape. Table 10 provides an overview on these studies. The typical question in these studies is whether the recovery is rather L-shaped (meaning a longer valley of reduced demand) or U-shaped (meaning a timely recovery to earlier passenger demand) (Gallego and Font, 2020). In general, it seems to be agreed that the recovery phase will take at least 2–4 years (Gudmundsson et al., 2020; Oxford Analytica, 2020), with the Asian regions, and here specifically China, recovering much faster than, e.g., Europe and the Middle East. When identifying the passengers' willingness to fly, a set of four major criteria have been reported in the recent literature: perceived threat of COVID-19, agreeableness, affect, and fear (Lamb et al., 2020). The difficulty in obtaining objective and comparable assessments of these four indicators make it clear that predictions into the future - at the current stage - come with large uncertainties. In addition, complex network-based analysis has revealed that a return of demand is unlikely to be same among different players/airlines, depending on the type of competitive advantage (Ye et al.,

Table 10
Literature on long-term passenger demand changes in the face of COVID-19.

Study	Major finding
Abate et al. (2020)	A decrease in passenger demand for tourism and for business travel is expected until at least the end of 2021.
Gallego and Font (2020)	The changes in air passenger demand due to the COVID-19 were investigated, a flat-line L shape rather than a U shape recovery was suggested.
Gudmundsson et al. (2020)	The recovery periods for passengers and freight were estimated. It was shown that the recovery would take on average 2.4 and 2.2 years for passenger and freight demand.
Lamb et al. (2020)	Based on a survey with 632 participants, passengers' willingness to fly during and after the COVID-19 was studied. Four predictors were identified: perceived threat of COVID-19, agreeableness, affect (emotional predictors), and fear.
Oxford Analytica (2020)	The airline industry will not see traffic return to 2019 levels until 2024 or later.

2020). The aforementioned studies discuss the demand changes for passenger transportation. The demand in air cargo transportation has been rather stable throughout COVID-19 so far (Choi and Park, 2020; Kim et al., 2020; Li, 2020).

4.3. Future trends and challenges on aviation

Except from the recovery to earlier demand levels, there are many future challenges for all air transportation stakeholders. We summarize the studies on this subject in Table 11. The new era of post-COVID-19 aviation (or tourism in general), will lead to the opportunity to push the envelope for new business concepts and technologies, e.g., the emergence of super long-haul flights, reducing hub operations (Bauer et al., 2020) or the design of a world-wide immunity license, which can increase not only the safety of passengers and airlines, but also the trust of destinations (Chen et al., 2020b). Other researchers suggest that the weakness of aviation should rather lead to a stronger emphasis on a backbone railway network, including high-speed railways (Tardivo et al., 2020); nevertheless, this needs to take into account that rail operation by itself is not necessarily safer than air transportation (Zhang et al., 2020c). On the contrary: for most countries, air passengers receive much more security/safety considerations than rail passengers. There are also societal challenges, which will impact aviation in the long run, e.g., stay-at-home telecommunication vs. personal travel, crowd-reduction in public (and transportation systems), and the development of connected and automated vehicles (Hendrickson and Rilett, 2020). Similarly, it can be anticipated that the customer protection rules will be adapted, given the experiences with airlines during COVID-19 (Truxal, 2020; Peoples et al., 2020). Another major challenge with very high potential is to design a sustainable aviation future (Amankwah-Amoah, 2020; Ioannides and Gyimothy, 2020; Niewiadomski, 2020); for instance, aiming for greener, environment-friendly transportation. With the given high economical pressure to airlines, this development is possibly at risk. Governments, however, can and should use their bailouts and credits, binding them to the enforcement of long-term changes to the air transportation as a system. Similarly, governments and airlines should use the momentum of the crisis to aim for a system design which is more resilient towards global health risks (Romagosa, 2020). Furthermore, the impact of COVID-19 on air traffic management should be better understood as large system, where reduced traffic also leads to less controller workloads and, thus, presumably to less infections. Finally, the general aviation sector has encountered the challenges of COVID-19 and, as an under-researched industry sector, deserves more attention, especially its long-term resilience (Tisdall et al., 2020).

Table 11
Literature on future challenges in the face of COVID-19.

Study	Major finding
Bauer et al. (2020)	Ultra long haul operations can give a competitive advantage in terms of health facing COVID-19.
Chen et al. (2020b)	The possibility of implementing "immunity certificate/ passport/license" for safe re-opening of travel was discussed.
Hendrickson and Rilett (2020)	Uncertain long-term impacts of COVID-19 were discussed, such as stay-at-home telecommunication vs. personal travel, and crowd-reduction in transportation systems.
Macilree and Duval (2020)	Several aero-political issues impacting the aviation section post-COVID-19 were reviewed, covering the role of ICAO, airline bailouts, and ownership.
Suau-Sanchez et al. (2020)	Based on a survey with 16 senior aviation executives, structural changes of the aviation industry due to COVID-19 incorporating supply, demand, regulation and business ethics, were investigated.
Tardivo et al. (2020)	The impact of COVID-19 on transport sector was analyzed. The establishment of rail as the backbone of the European sustainable mobility is recommended.
Wilson and Chen (2020)	Preparation of reopening should incorporate the risk assessment of COVID-19, such as traveller's personal risk stratification, trip-based determinants, and policies including health in-assurance.

5. Conclusions and future work

Based on the rich existing literature regarding COVID-19 and air transportation, summarized in the earlier sections, we discuss several directions of future research below, hoping that more research efforts could be focused on these topics. Each direction of future work is described in an individual subsection.

5.1. Making richer datasets available to the community

Several studies on air transportation impact and spreading use the prevalent data sources on aircraft movements emerged over the last few years, driven by advances in ADS-B penetration, most notably Flightradar24; see Table 12 for a summary of these and similar datasets. Nevertheless, even if ADS-B-based data from these websites can be bought or obtained by scraping, crucial information (in terms of COVID-19) is missing from these: information on the number of passengers and their individual routes. Naturally, such data is extremely precious - if not a business secret - for many airlines. Nevertheless, in order to fully understand the role of air transportation in spreading, there is a need to have richer data available to a wider research community. Similarly, any disease spreading models, such as GLEAM (Balcan et al., 2010), come with a whole range of parameters describing mobility, for instance, including regional migration coefficients. Obtaining such data at a large scale, i.e., for many countries, requires tremendous efforts. Similarly, many studies on in-flight transmissions are reported by local authorities or hospitals. They do not make data available for political/-economic/other reasons. Widely available, robust data for whether there are really transmissions with proper masking, would yield more valuable insights. Such detailed activity logs/records do come with privacy concerns; and researchers need to find ways to address these.

Overall, it should be understood that data (availability) is the key for understanding the pandemic; especially if researchers want to use recent tools developed in data science or artificial intelligence. There are a few noteworthy examples for special-purpose data repositories, mostly disease-related, which should be exploited by researchers, made available by the WHO,[1] John Hopkins of Medicine,[2] European Union,[3] United States Centers for Disease Control and Prevention,[4] and Our World in Data.[5] These websites are a good start for understanding the disease distribution; but there needs to be more and better, specifically in the context of air transportation, in order to better understand the mid-term and long-term impacts of COVID-19. In addition, with further dissemination of (free) available data for research, we will need further (open-

Table 12
An overview of the data sources for air transport.

Organizations	Links
Airport Council International	http://www.airports.org
Flightradar24	https://www.flightradar24.com
Flightaware	https://www.flightaware.com
Innovata Flight Schedules	http://www.innovata-llc.com
OAG (Official Airline Guide)	http://www.oag.com
Open Flights	http://openflights.org
Sabre Airport Data Intelligence	http://www.sabreairlinesolutions.com

[1] https://covid19.who.int/.
[2] https://coronavirus.jhu.edu/.
[3] https://data.europa.eu/euodp/de/data/dataset/covid-19-coronavirus-data.
[4] https://covid.cdc.gov/covid-data-tracker/.
[5] https://ourworldindata.org/coronavirus.

source) tools for simulation at different scales and granularities, from micro-scale to macro-scale. To sum up, data and methods/implementations should not be hidden behind paywalls, but the ultimate goal should be to make them accessible and reproducible to all research teams, independent of the available funding. This will spur synergies among research groups worldwide.

5.2. Further disease-specific adaption of models

Many early studies are direct extensions of previous works on disease spreading, making COVID-19-independent simplified assumptions, e.g., introduce a simplified proximity measure/detector during aircraft boarding. A tighter integration of COVID-19-specific disease models with these optimization problems, by taking into account more disease-specific parameters which gradually appear in the (medical) literature, will be beneficial for better understanding the effects of COVID-19 on air transportation. Specifically, it would be very interesting, yet challenging to further identify the role masks play during all activities involved; and how their usage changes over time; the results in (Chu et al., 2020b; Mitze et al., 2020) could be used as input. Similarly, simulations should better understand the role of passenger/passenger and crew/passenger directly facing each other during boarding. Here it could help to also exploit results of earlier studies on SARS/MERS, e.g. (Hertzberg and Weiss, 2016; Hertzberg et al., 2018), which analyzed the probability of viral infection in an aircraft as a function of distance. Finally, studies should not only look at aerosol transmissions; high-efficiency particulate air filters in aircraft ventilation systems are known to be highly effective (Sandle, 2020). Accordingly, the contaminated surfaces or the direct contact with infected persons could be possibly a high, underestimated risk for in-flight transmissions.

5.3. Verification of results in real air transportation environments

Many studies that have appeared regarding COVID-19 are based on simulations; this particularly holds for those results reported in Section 3, including airport screening, aircraft boarding, and risk of in-flight infections. Future studies should aim to reproduce, validate, and extend these results in real-world environments, i.e., based on real operations at airports and in real aircraft. Inconclusive results, between simulation outcomes and real-world observations, are probably caused by underlying study setups (Bielecki et al., 2021). Particularly, future work needs to take into account real human behavior during simulations. Having mannequins sitting for hours in a ventilated cabin is a start, beyond simple computer simulations. However, a real problem is that all models ignore passengers' self-willingness for distancing; psychologically studies could lead to novel insights, which in turn help to improve the simulations. Similarly, the role of seatbacks as shield from virus cells is not well understood in the literature (Barnett, 2020). Moreover, distinct flight types have rather different behavior profiles as well, e.g., it is known that long international flights involve many more passenger movements and interactions, compared to short-haul flights (Harries et al., 2020).

5.4. Tolerable service performance of passengers under COVID-19

While existing studies have found that passengers are sensitive to exceeding maximum waiting times, one emerging challenging research question is: How does this threshold change during COVID-19 and how does this finally affect user experience? Many passengers are probably aware of the trade-off between efficiency and safety in air transportation operations (or any other operations for that matter). In addition, with an ongoing pandemic, passengers are more likely to avert from crowded public places. Accordingly, one could ask how much the awareness and preparedness of passengers shifts their tolerable service performance during a pandemic? This does not only include rather obvious services such as security screening, boarding, or on-board service; it also includes services such as short-term flight cancellations, which became very common for some airlines during the summer 2020, when airlines seemed to have used flight offers just to test the market, cancelling sold flight tickets a few days/weeks before the flight. These processes, and their long-term impact on passengers, e.g., the question whether a passenger will fly again with the airline after such short-noticed cancellation experience, deserves research attention. Finally, future studies could put these results into the context of competition, to see how the (in-)tolerance to service performance has the potential to change the market landscape in the long run.

5.5. The role of (lack of) international collaboration

It has been observed in the literature that border closures came rather too late and turned out ineffective for controlling the spread. One reason for the late reaction could be seen in an ineffective coordination and communication between the relevant stakeholders; particularly during the first one or two months of the pandemic. When the first hundreds of cases were discovered in Wuhan, in late January 2020, several well-known epidemiologists and physicists recommended to control the long-distance flow of passengers; and introduce checks before it is too late. At that time, however, passengers were still allowed to fly arbitrarily around the planet, without wearing any masks, without checking/tracking of passengers at arrival, and so on. Arguably, the international communication and alignment of strategies handling COVID-19 could be one reason for the lack of implementing effective containment strategies. Future research could investigate the role of the observed non-optimal cooperation patterns and what incentives/motivations could lead to better cooperation between countries, governments, and other entities in the future.

5.6. Planning the future of travel bubbles?

Travel bubbles are discussed as a possible future for aviation (Hudson, 2020; Sharun et al., 2020). For instance, Japan has announced plans to create a travel bubble with five other Asian countries/regions (Cambodia, Laos, Malaysia, Myanmar, and Taiwan) in September 2020 (Furutani, 2020). In addition to these travel bubbles, other new operation modes might emerge in air transportation, such as, preference for ultra-long-haul point-to-point connections, which avoids passenger switching at hubs (Bauer et al., 2020), and the introduction of immunity passports for traveling (Chen et al., 2020b). Researchers should further anticipate these changes in the scientific literature, in order to build a well-analyzed foundation for putting such concepts into practice.

5.7. Cargo-focus as a mid-term solution?

Air cargo business has been rather resilient against COVID-19 (Choi and Park, 2020; Kim et al., 2020; Li, 2020). Accordingly, cargo transportation can possibly be seen as a new opportunity for the aviation industry. There is a potential for future studies to explore replacing former passenger transportation with more cargo flights, particularly in presence of increasing online deliveries during the pandemic. In addition, given that some parts of the cabin have to be left free due to social distancing, airlines could explore using the free space for additional cargo; future studies could investigate the potential of such mixed operations and also estimate the passengers' acceptance.

5.8. Understanding the long-term impact and chances for de-globalization and environment

The pandemic provides an unprecedented chance for rethinking global transportation and consider the opportunity of a reboot. Accordingly, there are plenty of opportunities for building future transportation and mobility concepts, which are not only pandemic-safe, but also sustainable and possibly farther away from globalization sideeffects, such as, environmental degradation, economic over-exploration, and over-crowding (Ioannides and Gyimothy, 2020; Niewiadomski, 2020). Researchers are encouraged to think, design, and disseminate such novel considerations of sustainable mobility; COVID-19 is a unique chance in that regard. Along the same lines, it would be interesting to further investigate the long-term impact of COVID-19-induced air transportation changes on the environment; initial studies report significant reductions in CO over the year 2020 (Huang et al., 2020).

5.9. Long-term impact and alternatives to government support on competition

Government support can include measures such as subsidies, credits, and all kinds of guarantees. It should be investigated how these (usually nationally-distinct) support decisions affect the competition in the global aviation sector. Moreover, policies should preferably support all levels of industry rather than being too airline-specific (Tisdall et al., 2020). In face of increased online shopping and reduced travel demand, it might be beneficial for some airlines to further convert some aircraft into cargo-only operations.

5.10. Holistic approaches for reducing the impact of future pandemics

Finally, there is (already) a strong need to prepare for future pandemics. The worst that could happen is that the paper hurricane on COVID-19 leaves a landmark of highly-specialized studies, without leading to well-analyzed and well-understood approaches for avoiding (or at least mitigating) the effects of future pandemics. It should be kept in mind: unless significant changes occur to our behavior, our globalized world will face another pandemic spread rather sooner than later.

Author statement

Xiaoqian Sun: Conceptualization, Methodology, Writing - Original draft preparation. **Sebastian Wandelt**: Data curation, Software, Visualization, Writing - Original draft preparation, Writing - Reviewing & Editing. **Changhong Zheng**: Writing - Original draft preparation. **Anming Zhang**: Conceptualization, Validation, Writing - Reviewing and Editing.

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