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How did COVID-19 impact air transportation? A first peek through the lens of complex networks

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ABSTRACT

The current outbreak of COVID-19 is an unprecedented event in air transportation. This is probably the first time that global aviation contributed to the planet-wide spread of a pandemic, with casualties in over two hundred countries. As of August 23rd, 2020, the number of infected cases has topped 23 million, reportedly relating to more than 800,000 deaths worldwide. However, there is also a second side of the pandemic: it has led to an unmatched singularity in the global air transportation system. In what could be considered a highly uncoordinated, almost chaotic manner, countries have closed their borders, and people are reluctant/unable to travel due to country-specific lock-down measures. Accordingly, aviation is one of the industries that has been suffering most due to the consequences of the pandemic outbreak, despite probably being one of its largest initial drivers. In this study, we investigate the impact of COVID-19 on global air transportation at different scales, ranging from worldwide airport networks where airports are nodes and links between airports exist when direct flights exist, to international country networks where countries are contracted as nodes, and to domestic airport networks for representative countries/regions. We focus on the spatial-temporal evolutionary dynamics of COVID-19 in air transportation networks. Our study provides a comprehensive empirical analysis on the impact of the COVID-19 pandemic on aviation from a complex system perspective using network science tools.

1. Introduction

The increased mobility enabled by aviation, owing to enhanced connectivity and efficiency (derived partly from agglomeration and traffic density effects), has become a two-edged sword. While air mobility has allowed more passengers to fly to more and remote destinations within a few hours at affordable prices (Janic, 2000; Lee et al., 2009; Diaconu, 2012), it has also significantly contributed to the risk of spreading diseases worldwide. It has been well known that air transportation plays a critical role in the spread of contagious diseases (Brockmann and Helbing, 2013; Likhacheva, 2006; Zaki et al., 2012; Bogoch and et al., 2015). While all these previous diseases have had terrible and harmful effects on their own, these consequences occurred more directly at the local level. Despite of heavy travel ban restrictions as well as quarantine policies enforced by governments, the COVID-19 outbreak, which is believed to have started around January 2020, quickly spread to almost all countries worldwide. The number of infected cases reached one million in April 2020, surpassed 5.8 million in late May, and reached 23 million in August 2020, with the disease being related to more than 800,000 deaths worldwide (as of August 23rd, 2020). Strict travel ban restrictions further amplified the substantial reduction of air passenger demand and resulted in a large number of flight cancellations. Although the total number of the COVID-19 infected cases is surging, a few countries seem to have achieved certain.

Successes in fighting COVID-19, such as China, where rebound activities have been undertaken in order to recover the economic development. The ambivalence of aviation, as the major driver of the COVID-19 outbreak internationally and one of the major (economic) casualties, turns this event into a singularity of historical dimension for aviation. Overall, ICAO estimated that the aviation industry would lose approximately up to USD 418 billion, and the air passenger traffic encountered an unprecedented decline ever since the WWII in 1945; much beyond that of disruptions caused by other effects in the literature, such as the volcanic ash of Eyjafjallajökull (Reichardt et al., 2019) or extreme weather (Merkert and Mangia, 2012). As of May 2020, most countries

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have active flight bans; accordingly, the mobility of air passengers is heavily constrained, particularly for international air travelers. For instance, initiated at the end of March 2020, China is continuing its *Five Ones* flight restriction policy, meaning that each country can only have one airline to and from China via one route, and one flight per week. When the Five Ones Policy will be lifted remains unclear.

Several recent studies investigate the following, important question: *How does air transportation (and other modes) contribute to the spread of COVID-19* (Christidis and Christodoulou, 2020; Gilbert and et al., 2020; Zhang et al., 2020)? In this study, we investigate a complementary question: What is the impact of the COVID-19 pandemic on global aviation from a complex system perspective? For this purpose, we analyze the aviation system in the period from January 2020 to May 2020. Our analysis is mostly based on operational indicators and complex network indicators, taking three distinct views: First, the global aviation system as an airport network, with nodes being airports and flights representing the direct connections between airports. Given the instrumental role of countries as decision makers, we also investigate the so-called country network, where nodes are countries and links denote the existence of direct flights between these countries. This aggregated network sheds light on the evolution of international connectivity during the COVID-19 outbreak. A complementary view of the country network is the domestic airport networks of countries. Overall, the focus of our study is on the spatial-temporal evolutionary dynamics of the COVID-19 pandemic on air transportation networks. This study, provides a comprehensive empirical analysis on the impact of the COVID-19 pandemic on aviation from a complex system perspective using network science tools.

2. Results

The data for this study was obtained from Flightradar24 and prepared by airline. In total, our dataset covers services of 150 airlines between 2751 airports. All flights were grouped by days into 24-h intervals; yielding one network per day induced by the flights taking place on that day. In total, we retrieved data for 152 days, from December 16th, 2019 to May 15th, 2020. The data about airports used in this study is from OurAirports (https://ourairports.com/data), including airport codes, location and time zone. Note that the flight data also contains cargo aircraft. While we have eliminated purely cargo airlines from the dataset, it was not possible for use to eliminate all aircraft use as cargo. Particularly, throughout the first half a year of 2020, some airlines have retooled their passenger aircraft for cargo-only transportation, with the aim to keep their aircraft flying. Accordingly, our results should be understood in presence of this limitation; cargo aircraft on their own are probably less likely to transmit the disease, than fully-loaded passenger aircraft.

2.1. The worldwide airport network during COVID-19

Fig. 1 visualizes the worldwide airport networks on two selected dates before and throughout COVID-19. These snapshots show the airport-level connectivity, with links representing direct flights between airports. We can observe that the Southern hemisphere is more affected than the Northern part; at least regarding the drop in connectivity. In the middle of May, the Southern region is almost flight-free, compared to earlier days. In fact, the worldwide airport network is largely unchanged for the first 2–3 months of the year 2020 (see below). This is rather striking, given that it is well-known that air transportation is the major catalyst for the wider spread of diseases; one would expect that drastic measures to reduce the connectivity on global air transportation would had taken place much earlier.

In order to further investigate the time of significant changes in the worldwide airport network, Fig. 2 reports the number of OD (origin-destination) pairs in the network as well as the number of active aircraft over time. Here, an aircraft is labeled as active if it had at least one recorded flight per day. Despite expected seasonal and weekly variations (Merkert and Webber, 2018), the airport network was rather stable until the middle of March. The slight trend of reduction in February is mainly caused by the lock-down in China and parts of Asia; however, most other countries had not yet introduced any travel restrictions. Starting from the middle of March, the number of served OD pairs dropped to about one-fourth (from 80,000 to around 20,000) within a period of about two weeks. Similarly, the number of active aircraft dropped with a delay of less than a week to around one-third of the original traffic (from more than 18,000 aircraft to about 6000 aircraft). Since the first half of April, the number of OD pairs and flights has been rather stable again, with some typical weekly variation. Towards the middle of May, it seems like there might be a re-start of an increasing trend. In summary, these analyses show that the aviation world has (measurably) reacted with a delay of about two months to the pandemic.

In our next analysis, the global airport network is investigated from a complex system perspective. We have computed the measure of four frequently-used network properties. Fig. 3 shows the temporal evolution of these four properties before and throughout the pandemic. The degree centrality of a node measures the fraction of other airports to which a node is connected. The degree centrality drops by around 50% throughout the pandemic; which means that each airport loses - on average - half of its destinations. In absolute numbers, the average degree of airports worldwide is reduced from six to three. There are some important airports, which still have significantly.

Higher degrees than the average; these airports will be analyzed individually below. The betweenness centrality of a node measures the fraction of shortest paths a node is located on. Intuitively, the larger the betweenness centrality, the more likely passengers will use an airport as a hub for transfer. It can be seen that the average betweenness centrality increases significantly throughout the pandemic. The major reason is that a few of the biggest transfer hubs have been virtually shut-down,

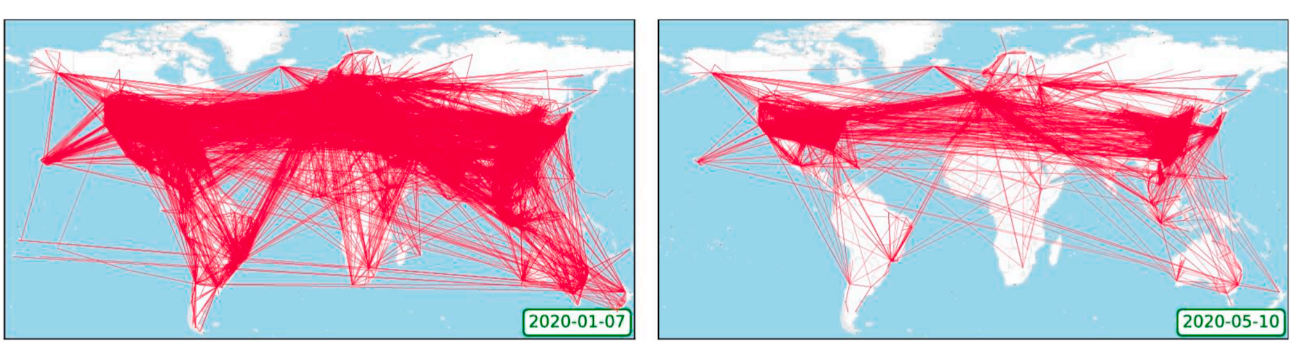

Fig. 1. Worldwide airport network on two selected dates before and during the COVID-19 pandemic. Nodes represent airports and links represent direct flight connections.

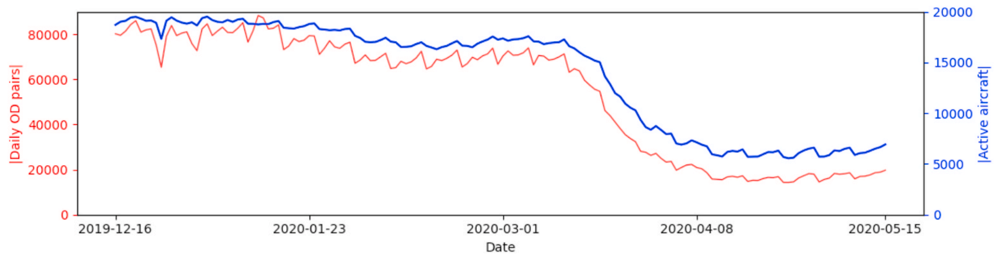

Fig. 2. Trend of the number of daily OD pairs (in red color) and the number of active aircraft (in blue color) per day. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

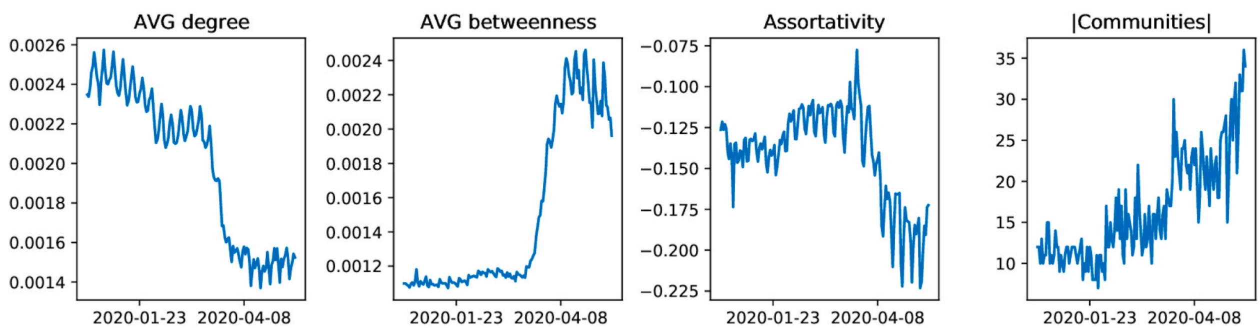

Fig. 3. Evolution of selected airport network properties over time of the pandemic from December 2019 to May 2020.

which increases the importance of other airports in the network; this effect will be analyzed further below as well. Assortativity, also referred to as assortative mixing, represents a node's preference to attach to others that are similar in some way. Here, we report the degree assortativity. A number of zero identifies non-assortative networks, while negative values imply that the network is completely disassortative. After a minor peak in the transition around middle of May, the assortativity of the network is reduced, meaning that we have less hub-hub connections, but rather more hub-spoke connections in the network. Finally, the number of communities is increasing significantly throughout the pandemic, from 10 at the beginning to more than 30 in the middle of May. This shows that the world increasingly creates virtual borders between groups of airports. Moreover, it is interesting to note that the number of communities is the earliest indicator to show perceivable changes to the worldwide airport network.

While the previous discussion focuses on the network level, we report further results on the node-level perspective, i.e., with a focus on individual airports. We selected two network metrics, degree and betweenness, given their importance for complex systems of all types.

Fig. 4 visualizes the temporal evolution of degree and betweenness for selected airports (color) and all other airports (grey). We selected eight airports by taking into account the total number of passengers in 2019 and considerations of spatial diversity. Regarding the degree centrality, we find that most of the larger airports face a significant drop in the number of destinations. This particularly holds true for the two major hub airports Istanbul Airport (IST) and Dubai International Airport (DXB) that both virtually dropped to a status of in-operativity. Being highly important for connecting Europe and Asia/Oceania, the discontinuation of these two airports makes sense, intuitively. Nevertheless, we can see that other airports maintain a high number of destinations. For instance, Hartsfield–Jackson Atlanta International Airport (ATL), which is a central hub for domestic transportation in the United States has been relatively unaffected by the pandemic so far. Finally, we can see that some airports are on the way to regain their original degree; for instance, Beijing Capital International Airport (PEK) has recovered about half of its originally-lost destinations (yet, at a much lower frequency). Regarding the betweenness centrality, two phases can be distinguished. Before the pandemic, the betweenness centrality of

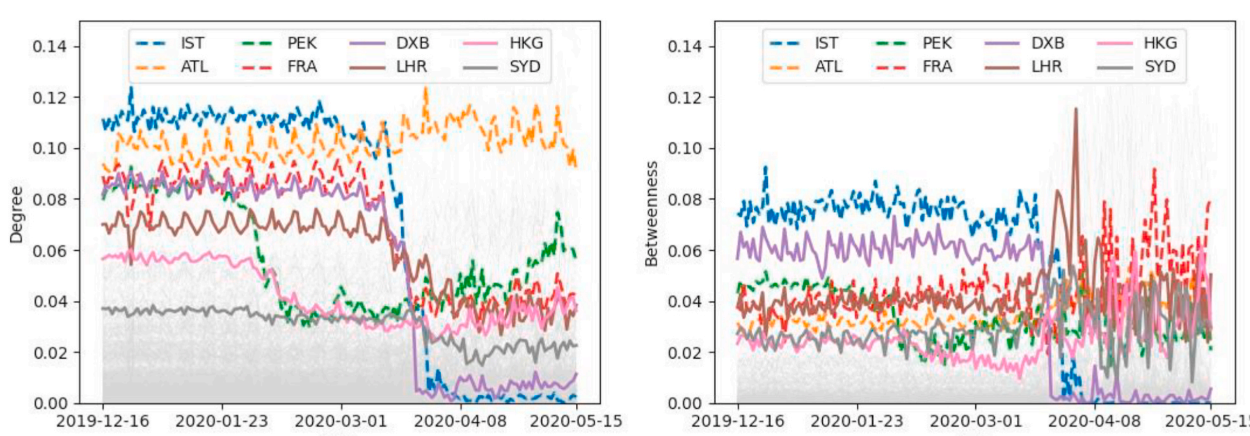

Fig. 4. Evolution of degree and betweenness for selected airports (colored) and all other airports in the network (grey).

airports was rather stable, with Istanbul Airport (IST) and Dubai International Airport (DXB) being the major components keeping the (intercontinental) system together. After the disruptions to the airport network, induced by countries' travel bans, the system has been in a highly fragile state, measured by the variance in the betweenness of nodes. For the whole period of April and May, there has been no single (long-term) outstanding node with high betweenness; on the contrary, the betweenness of nodes varies tremendously even within one week by up to one order of magnitude. Such changes in the importance can only be observed in systems with a high degree of chaos. Moreover, this fluctuation in node importance suggests that it is arduous for passengers right now to make informed choices on their travels, especially when involving more than one hop.

2.2. The international country network during COVID-19

We have analyzed the global air transportation system at airport level. Node aggregations often lead to additional insights regarding the system. Since the pandemic shows stronger impacts on international passenger traffic than domestic passenger traffic, we discuss the so-called country network (Wandelt and Sun, 2015) below, where nodes are countries and links represent direct flights between countries. The country network is created from the airport network by merging all airports that are located in the same country. Self-loops (induced by domestic connections) are removed. The number of flights between a pair of countries is computed as the sum of flights over all airport pairs for these two countries.

Fig. 5 depicts the international country network on two selected dates before and throughout COVID-19. In total, we have data for 213 countries within our study. These snapshots reveal the connectivity patterns of individual countries and how they evolved over time. Each country is represented by a node whose location in set to the median location of all airports in the country. We can see that some countries are still highly connected with other countries, e.g., the United States, Canada, and Mexico. Other countries have significantly reduced their connectivity, e.g., countries in Europe. As previously noted for the airport network, it is apparent that the countries in South America and Africa have dramatically reduced their connectivity to selected destination countries, compared to countries in North America.

In our next analysis, the international country network is investigated from a complex system perspective. We have computed the measure of four network properties; the results are shown in Fig. 6. It can be seen that most of the trends coincide with the airport network's statistics. Most transitions between before travel bans and after travel bans are more sudden, with less variation, compared to the airport network. One interesting difference is in the measure of assortativity. For the airport network, the assortativity was decreasing, which means that high-degree airports are increasingly connected to low-degree airports during the pandemic. For the country network, on the other hand, there is a trend that high-degree countries are more actively connected to other high-degree countries. This shows that there is a preference between countries to connect to other countries with more connections during the pandemic. There is, nevertheless, a strong variance in this pattern. Finally, the number of communities is increasing as well, which means that not only airport groups from communities have preferential connections, but so do countries.

Next, we shift the discussion from a network level to a node-level perspective, i.e., with a focus on individual countries. Fig. 7 reports the temporal evolution of two network metrics, degree and betweenness. Regarding the degree centrality, the changes in connectivity are not as extreme as in the airport network. Turkey (TR), Russia (RU) and France (FR) have experienced a significant reduction in destination countries; the other four selected countries have not been severely affected by the pandemic so far. Regarding the betweenness centrality, an interesting observation can be made for the United Stated (US). Despite widely-communicated travel bans, the country increased its importance in the country network throughout the pandemic. The high betweenness value of up to 0.4 is astonishing; this indicates that the US would be on up to 40% of all shortest paths through the country network. Therefore, from the complex-network perspective, the US has gone through the pandemic rather well so far. It is difficult to state a single reason for this observation; it might be related to the large number of US nationals spread around the world, who are still allowed to come back, despite active travel bans for larger parts of the external population. Either way, this phenomenon should be analyzed and explained further in future research.

2.3. Domestic airport networks during COVID-19

The international role of countries in the country network was one perspective of the air transportation system. Another perspective, which is taken in this section, is the role of air transportation in domestic transportation systems, i.e., within specific countries/regions. In the following, we discuss the domestic airport network (Wandelt et al., 2019), where nodes are airports within a specific country/region and links represent the direct flights between these airports. Analyzing these networks is of particular importance, given that the travel bans are mainly implemented at inter-country level. Therefore, it is interesting how air transportation has been affected by the pandemic within certain countries.

Fig. 8 shows the snapshots of three selected domestic networks before the pandemic and throughout the pandemic. We have selected China, Europe[1] and United States for comparison. The inclusion of Europe as a country/domestic flight region seems unusual at first. Our rationale is that Europe is comparable in size to the United Stated and China. If we had taken an individual European country instead, the sole number of domestic connections would have been orders of magnitude smaller. In addition, it should be noted that intra-European HSR services had ceased during the first weeks/months of the lock down as well. China had a visible, but not extensive reduction of air traffic in February,

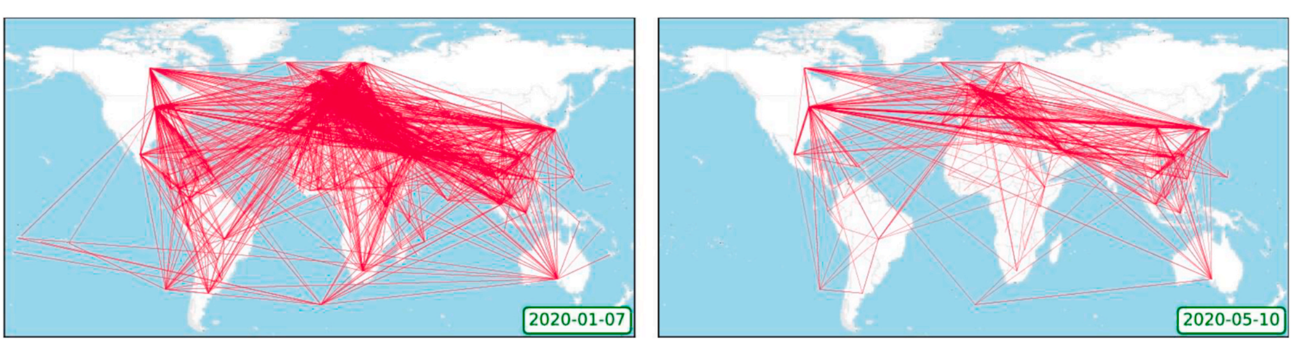

Fig. 5. International global country network on two selected dates before and during the COVID-19 pandemic. Nodes represent countries and links represent direct flight connections between countries. Self-loops (i.e., domestic flights) are not shown.

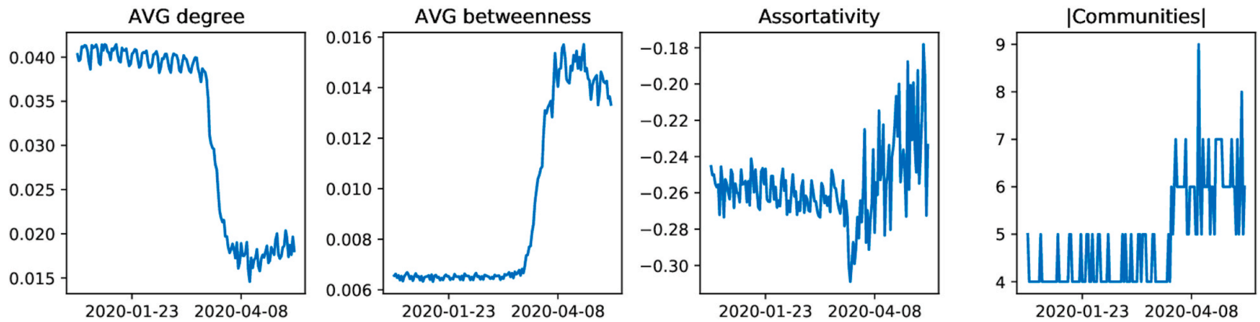

Fig. 6. Evolution of selected country network properties over time of the COVID-19 pandemic from January 2020 to May 2020.

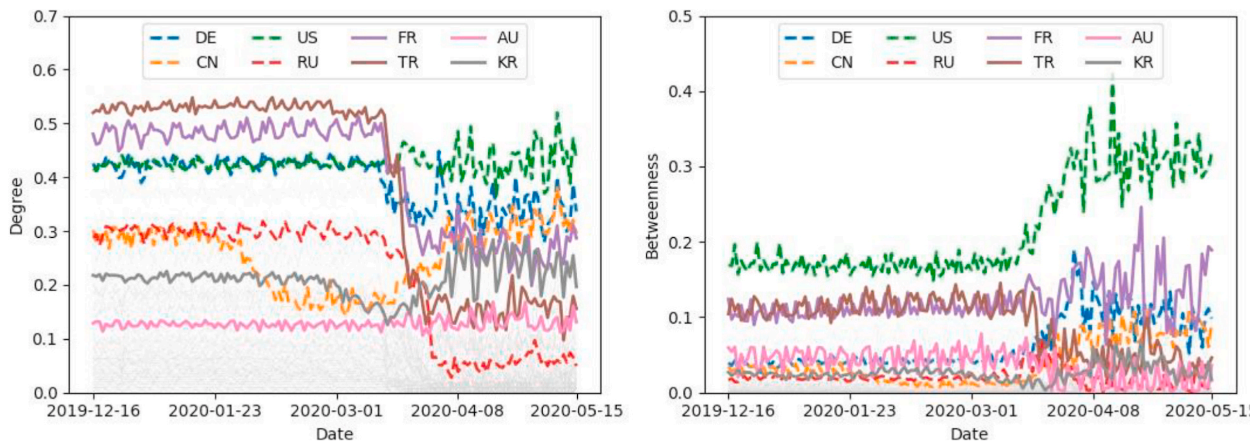

Fig. 7. Evolution of the degree centrality and betweenness centrality for selected countries (colored) and all other countries in the network (grey) in the international country network during the COVID-19 pandemic from December 2019 to May 2020.

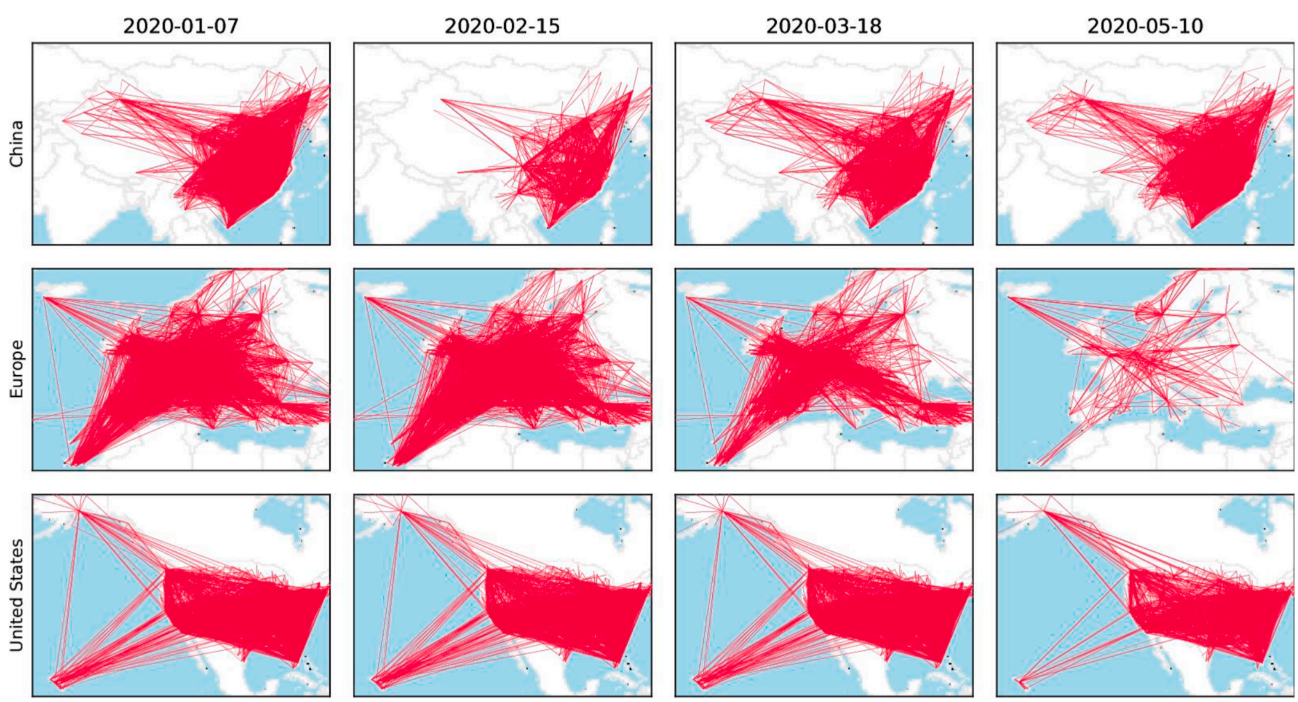

Fig. 8. Evolution of three domestic airport networks (China, Europe, and United States) during the COVID-19 pandemic from January 2020 to May 2020.

during the major part of its domestic lock-down. Since then, the airport network has largely re-covered to its original connectivity. Europe has probably undergone the most significant domestic changes of all four, with the latest network snapshot resembling a very sparse connectivity compared to the situation before the pandemic. Finally, the US has also undergone changes in the latest snapshot, but significantly less severe than has Europe. These snapshots reveal that the air transport lock-down in domestic networks happens to a different degree and is partially un-synchronized, with China having a head start (almost recovered by now) and the US locking-down relatively later. However, such analysis should take into account that the ground transportation systems in all three regions are significantly different. For instance, Europe and China have a well-established rail/high-speed rail system, which could possibly compensate for lock-down on air transportation. The US, on the other hand, has to rely on air transportation for long-distance travel.

3. Discussion and conclusions

Our study provides a comprehensive empirical analysis on the impact of the COVID-19 pandemic on air transportation systems, based on a multi-granularity network analysis, covering worldwide airport networks, international country networks, and domestic airport networks. The time scale ranges from January 2020 to May 2020 of the COVID-19 pandemic outbreak. We summarize the major findings of our study as below:

1. We observed from the worldwide airport network that the Southern hemisphere has been more affected than the Northern part; when considering connective alone. More strikingly, the worldwide airport network seemed to have been largely unchanged for the first 2–3 months of the year 2020. The evolution of the number of OD pairs and the number of aircraft in operation showed that the aviation industry has reacted to the pandemic with a delay of about two months, and the opportunity to avoid the COVID-19 from a local burst to a global pandemic was missed due to the postponement. Given existing research (Brockmann and Helbing, 2013) and the degree of knowledge about the disease in January 2020, one would have expected a much more coordinated and informed global response.

2. The slight reduction in the distance between OD pairs showed that flight restrictions were mainly imposed on long-distant international flights; accordingly, the impacts of the COVID-19 pandemic on international flights have been much stronger than on domestic flights. While this seems to be a natural move, the role of aviation for spreading the virus in domestic networks is probably underestimated. Taking the United States as an example, there exists no real alternatives to air transport when it comes to traveling from the East-coast to the West-coast. Accordingly, if the domestic airport network of the United States is still largely active, one needs to be aware that domestic flights are not immune to disease propagation.

1 The list of countries considered for Europe is as follows (using ISO-3 codes): AD, AL, AT, BA, BE, BG, BY, CH, CZ, DE, DK, EE, ES, FI, FO, FR, GB, GE, GG, GI, GR, HR, HU, IE, IM, IS, IT, JE, LI, LT, LU, LV, MC, MD, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR, UA, VA, and XK.

3. Four commonly-used complex network metrics in the worldwide airport network showed that each airport lost 50% of its connections on average, efficient network connectivity was further reduced, and the world increasingly created virtual borders between groups of airports throughout the pandemic. In particular, two major hubs connecting Europe and Asia/Oceania (IST and DXB) essentially dropped to the status of in-operativity; however, a central hub for the United States (ATL) has been largely unaffected throughout the pandemic. The fluctuation in node importance suggests that competition may still play an important, yet counter-productive role in the pandemic spreading.
4. Analysis of country networks focusing on the international passenger traffic of 213 countries in the world showed that connectivity patterns for individual countries are heterogeneous and fluctuate depending the COVID- 19 situation. While most of the evolution trends coincide with the worldwide airport network statistics, the difference in the assortativity metric showed that high-degree countries are more actively connected to high-degree countries, sharing a similar preferential attachment mechanism during the pandemic for the international country network; on the contrary high-degree airports are increasingly connected to low-degree airports in the worldwide airport network.
5. Nodal-level analysis of the international country network revealed that the importance of countries is changing significantly during the pandemic. Notably, the United States became one of the most critical countries in May 2020, if measured according to standard complex network indicators. These findings are somewhat contrary to the general belief that the United States administration locked all borders. Most of the other countries in the world experienced drastic reductions in their connectivity, due to the severe consequences of the pandemic.
6. The evolution of domestic airport networks focusing on the domestic passenger traffic for representative countries/regions showed different degrees of lock-down and partial un-synchronization: Europe has undergone probably the most significant changes regarding network connectivity, while the United States suffered less severely and China seems to be to have a head start towards recovery. Accordingly, the evolutionary dynamics of domestic airport networks are tightly correlated with the COVID-19 situation in specific countries.

Our study comes with a few limitations, which are summarized below. We did not possess actual passenger data or load factors for flights. Accordingly, some of these flights might just been empty or readjusted as cargo flights. Moreover, the network-centric analysis in this study neglects the number of flights, as it mostly focuses on connectivity measures. Such a limitation can be particular important for the United States, which kept with financial support the network active to a large degree, with flights taking place with a rather low load factor. Network analysis does not take these issues into consideration. With additional information on traffic and passenger flows, our results can be extended further.

CRediT authorship contribution statement

Xiaoqian Sun: Conceptualization, Validation, Writing - original draft, Funding acquisition. **Sebastian Wandelt:** Conceptualization, Software, Validation, Writing - original draft, Funding acquisition. **Anming Zhang:** Conceptualization, Validation, Writing - original draft.

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References

Bogoch, I., et al., 2015. Assessment of the potential for international dissemination of Ebola virus via commercial air travel during the 2014 west African outbreak. Lancet 385 (9962), 29–35.
Brockmann, D., Helbing, D., 2013. The hidden geometry of complex, network-driven contagion phenomena. Science 342 (6164), 1337–1342.
Christidis, P., Christodoulou, A., 2020. The predictive capacity of air travel patterns during the global spread of the COVID-19 pandemic: risk, uncertainty and randomness. Int. J. Environ. Res. Publ. Health 17, 3356.
Diaconu, L., 2012. The evolution of the European low-cost airlines business models. Ryanair case study. Procedia Soc. Behav. Sci. 62, 342–346.
Gilbert, M., et al., 2020. Preparedness and vulnerability of African countries against importations of COVID-19: a modelling study. Lancet 395 (10227), 871–877.
Janic, M., 2000. An assessment of risk and safety in civil aviation. J. Air Transport. Manag. 6 (1), 43–50.
Lee, D.S., Fahey, D.W., Forster, P.M., Newton, P.J., Wit, R.C., Lim, L.L., Owen, B., Sausen, R., 2009. Aviation and global climate change in the 21st century. Atmos. Environ. 43 (22–23), 3520–3537.
Likhacheva, A., 2006. SARS revisited. Am. Med. Assoc. J.Ethics 8 (4), 219–222.
Merkert, R., Mangia, L., 2012. Management of airports in extreme winter conditions—some lessons from analysing the efficiency of Norwegian airports. Res. Transp. Bus. Manag 4, 53–60. https://doi.org/10.1016/j.rtbm.2012.06.004. ISSN

2210-5395. http://www.sciencedirect.com/science/article/pii/S2210539512000132. Management of Transport in Remote Regions. URL.

Merkert, R., Webber, T., 2018. How to manage seasonality in service industries – the case of price and seat factor management in airlines. J. Air Transport. Manag. 72, 39–46. https://doi.org/10.1016/j.jairtraman.2018.07.005. ISSN 0969-6997. http://www.sciencedirect.com/science/article/pii/S0969699717302624. URL.

Reichardt, U., Ulfarsson, G.F., Petursdottir, G., 2019. Developing scenarios to explore impacts and weaknesses in aviation response exercises for volcanic ash eruptions in europe. J. Air Transport. Manag. 79, 101684. https://doi.org/10.1016/j.jairtraman.2019.101684. ISSN 0969-6997. http://www.sciencedirect.com/science/article/pii/S096969971730474X. URL.

Wandelt, S., Sun, X., 2015. Evolution of the international air transportation country network from 2002 to 2013. Transport. Res. E Logist. Transport. Rev. 82, 55–78.

Wandelt, S., Sun, X., Zhang, J., 2019. Evolution of domestic airport networks: a review and comparative analysis. Transport. Bus.: Transp. Dyn. 7 (1), 1–17. https://doi.org/10.1080/21680566.2017.1301274, 10.1080/21680566.2017.1301274. URL.

Zaki, A.M., van Boheemen, S., Bestebroer, T.M., Osterhaus, A.D., Fouchier, R.A., 2012. Isolation of a novel coronavirus from a man with pneumonia in Saudi Arabia. N. Engl. J. Med. 367 (19), 1814–1820. https://doi.org/10.1056/NEJMoa1211721, 10.1056/NEJMoa1211721. URL, PMID: 23075143.

Zhang, Y., Zhang, A., Wang, J., 2020. Exploring the roles of high-speed train, air and coach services in the spread of COVID-19 in China. Transport Pol. 94, 34–42. https://ssrn.com/abstract=3600619.