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The Impact of COVID-19 on Air Transportation Network in the United States, Europe, and China

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Abstract: The air transportation industry has undergone unprecedented changes throughout the COVID-19 pandemic, as measured in terms of flight cancellations, aircraft retirements, airline bailouts, and disconnection of worldwide communities. In this study, we performed a cross-comparison of the impact COVID-19 had on three aviation centers of the world—the United States, Europe, and China. Methodologically, we analyzed the air transportation system as complex networks and by using time series analysis. We discovered that the peak of COVID-19 impact was around April/May 2020, followed by a strong recovery mostly in domestic subsystems. We found a homogeneous impact on the United States, a strong heterogeneous impact on Europe, and a rather short-term impact on China. Domestic flight connectivity recovered much faster than international flight connectivity, particularly for the Chinese air transportation system. Our study provided a comprehensive, data-driven analysis of the COVID-19 impact on air transportation for these three major regions, augmented by references to the rich scientific literature on this subject. We hope that our work opens up pathways to a better understanding and a higher degree of preparedness for future pandemics.

Keywords: COVID-19; air transportation; complex networks

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1. Introduction

Aviation stakeholders have, despite temporary setbacks, seen decades of growth, spurred by the increasing desire for mobility and rising economic wealth. The growth in terms of connectivity and connection frequency leads to various challenges. One of these challenges was anticipated for a while by some researchers but almost entirely neglected by the public and responsible policymakers: Air transportation with its unprecedented connectivity creates an environment where small epidemic outbreaks may quickly turn into full-blown pandemics. We have witnessed exactly this singularity at a large scale with the emergence of COVID-19 throughout the year 2020. Notably, the universal patterns underlying the spread of diseases have actually been understood well by epidemiologists for several decades, based on historical events. For instance, in 2003, the severe acute respiratory syndrome (SARS) was able to spread to 25 countries within a period of four months after the suspected outbreak, making SARS the first easily transmissible infectious disease of the 21st century [1,2]. In 2012, the Middle East respiratory syndrome coronavirus (MERS-Cov) started to spread mainly via air transportation, reaching 26 countries [3,4]. In 2014, an Ebola outbreak quickly spread to three West African countries [5,6]. These earlier diseases had a rather local impact, at the scale of what could be called an epidemic. These did not grow into a pandemics (i.e., an outbreak with worldwide impact), because, presumably, relevant policymakers were quick enough to make the right decisions, leading to an early cut of transmission chains.

For COVID-19, however, the outcome was rather different. The initial time window for keeping the outbreaks local was largely missed, mainly caused by a lack of international communication, leadership, and counter-measure implementation [7–9]. The underlying virus, SARS-CoV-2, was first identified in Wuhan, China, at the end of 2019. Toward the end of January, the disease had already spread to a number of Chinese cities, mainly following air transportation [10]. It is not absolutely clear how much COVID-19 was spread locally at that time; some studies report that the virus was present in at least 18 countries worldwide, but the media for virus spreading was predominantly air transportation [11]. On 11 March 2020, the World Health Organization finally declared COVID-19 as a pandemic [12]. As of 11 April 2021, a total of 134 million cases has been confirmed and 2.9 million fatalities reported. According to its impact, COVID-19 can be ranked among the most impactful pandemics in recent history, not only specifically on air transportation but other modes as well [13]. An investigation of the correlation between positive COVID-19 cases and transport accessibility in Italy showed that accessibility becomes the worst enemy during a pandemic [14].

The air transportation system has an ambivalent role with regard to COVID-19. On the one hand, it was one of its major drivers, making the quick spread of the disease to distant regions ultimately possible. On the other hand, it was among the hardest-hit industries [15]. The major reason for the huge impact on aviation is the unprecedented reduction in the number of flights around the world, caused by a variety of factors, including border control measures, shifts in travel demands, and vulnerabilities of the highly profit-oriented aviation industry. Several researchers conclude that the whole aviation sector is in danger because of COVID-19 [16,17]. It should, however, be noted that COVID-19 also had positive impacts on aviation, most importantly a significant reduction in emissions from aircraft [18–21]. These reductions are mainly caused by flight suspensions and early retirement of the old aircraft fleet. For a comprehensive survey, please refer to [11].

This study reports on a cross-comparison of the impact of COVID-19 on the three aviation centers of the world: the United States, Europe-27 (referring to 27 European Union countries after the United Kingdom left the European Union), and China. These systems were not selected arbitrarily; they represent the three largest aviation subsystems worldwide. Particularly, the United States has the largest domestic aviation network and the largest number of airports. China is one of the fastest-growing aviation markets in recent decades. Furthermore, the European markets consist of several key players in the global aviation system, including France, Germany, and The Netherlands. Altogether, we believe that the selected networks are most suitable to study COVID-19 impacts on the aviation sector on a global scale. In addition, it is extremely instructive to see the distinct and rather heterogeneous response to this disruptive event of these three subsystems. Figure 1 provides an overview of the airports of three selected regions. Given worldwide flight data, we analyzed the air transportation system as complex networks. In order to derive meaningful insights, we did not limit our report data to the year 2020 but present them in light of the normal year 2019 (in terms of the number of flights). Figure 2 provides a preliminary overview of the impact of COVID-19 on the three regions of this study. China was the first to have a significant number of reported cases in February 2020; a very restrictive lockdown, followed by extensive usage of face masks and contact tracing, virtually led to single-digit, mostly imported infections. Accordingly, the total number of flights in and from China reduced rather early, in the end of January. Throughout the year 2020, the number of flights gradually recovered, almost reaching pre-COVID-19 peaks. The number of infections in Europe-27 and the United States grew significantly, with a delay of about two months. Since that time, both regions have undergone a series of waves, which have become increasingly extensive. The number of flights in the United States and Europe was reduced at about the same time, in March/April 2020, and both regions showed a recovery toward summer 2020. While Europe returned from the peak after summer 2020, the number of flights in the United States was still slowly increasing. Note that Figure 2 reports only the total number of flights. As we will report below, there are rather strong spatial deviations in the recovery, particularly regarding the distinction between international and domestic flights. We conjecture that a better understanding of the system responses will ultimately lead to better-orchestrated solutions. Our study contributes the first step toward a better and more pandemic-resilient aviation system.

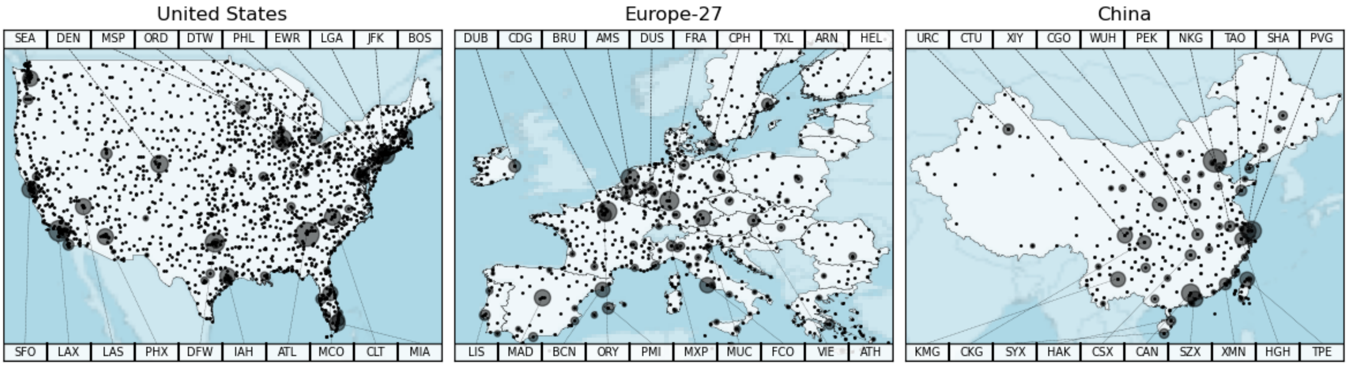

Figure 1. Overview of airports in the three regions. Each circle represents one airport; the size of a circle correlates with the total number of flights in the year 2019. Top 20 airports according to the number of flights are highlighted by the IATA code. (Data source: Flightradar24).

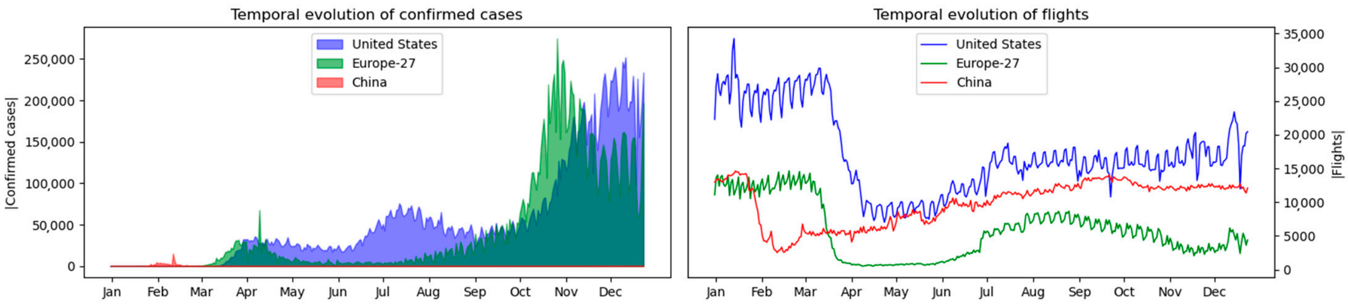

Figure 2. Comparison of the three regions according to evolution of the number of reported COVID-19 cases (**left**) and the total number of flights, subsuming departures and arrivals, year 2020 (**right**). (Data source: Our World in Data and Flightradar24).

The remainder of this study is organized as follows: Section 2 reports the evolution of international connectivity with a focus on the three regions under consideration. Section 3 investigates the specifics of the intracontinental networks. Section 4 analyzes the impact of COVID-19 on specific airports of the three regions. Section 5 concludes this study and discusses several directions for future work.

2. International Flights

Next, we analyzed the impact of COVID-19 on international flights in detail. Figure 3 reports the temporal evolution of international flights for 30 countries. These countries were chosen by ranking the total number of international departures for all countries worldwide in descending order and selecting the Top 30. Countries from the three selected regions are highlighted by color, respectively. China is among the countries with the strictest lockdown on international flights: Since February 2020, immigration to China has been highly constrained, also giving restrictions on permitted travelers, leading to a reduction by approximately 90%. The United States implemented a similarly strict lockdown as China, with a delay of about two months (in March/April 2020), but has since then gradually increased the number of international flights back to approximately 50%. European countries, in contrast, show a significant short-term recovery in summer 2020, followed by another lockdown wave toward the end of 2020. This observation is consistent among all countries in Europe-27. Comparisons with the remaining countries show that there three types of evolutions, i.e., permanent lockdown, gradual recovery, and second-wave lockdown, are typical for the policies implemented in other countries as well.

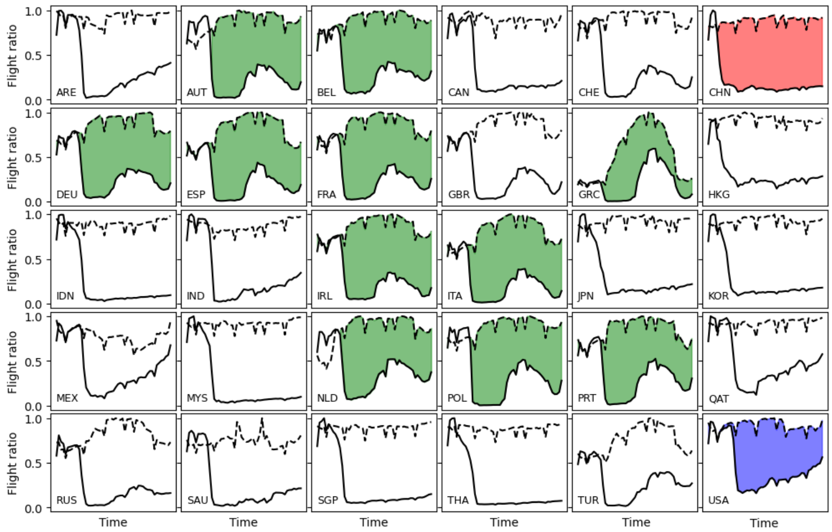

Figure 3. Evolution of the total number of international flights for the top-ranked 30 countries worldwide. The dashed line represents data for the years 2019, and the solid line is the evolution for the year 2020. Data are 01-normalized with respect to the maximum number of flights for any week in the year 2019 and 2020. Countries are colored as the United States (blue), Europe-27 (green), China (red), and others (white). (Data source: Flightradar24).

An interesting question is whether flight restrictions and recovery are occurring equally among specific destinations. In order to answer this question, we computed the temporal evolution of the number of intercontinental destinations for each of the three origin regions. The results are shown in Figure 4 for the United States, Figure 5 for Europe-27, and Figure 6 for China. In each figure, the origin region is highlighted by color in the map, and the corresponding destination continents have a subplot with the temporal evolution visualized on top, distinguishing the min–max-normalized number of flights for the years 2019 and 2020.

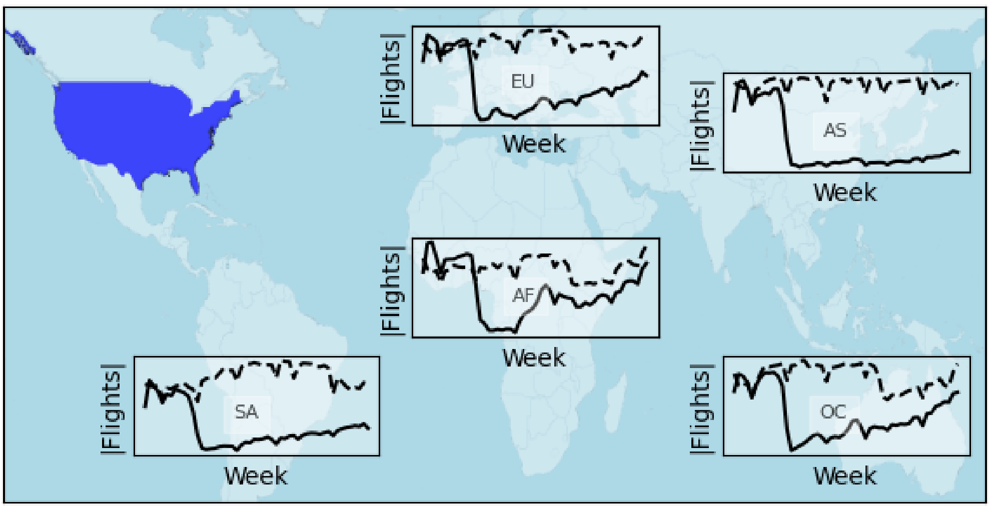

Figure 4. Continental connectivity for the United States to five other continents (dashed line = 2019, solid line = 2020). (Data source: Flightradar24).

The results for the United States (Figure 4) are discussed first. The evolutionary patterns are rather diverse among the five destination continents. Particularly, we found a much stronger recovery in connections to Africa and Oceania, compared to Asia. The weak recovery in connections to the latter is partially due to the missing recovery of flights between the United States and China. Flights to Europe (notably the whole continent, not only Europe-27), and South America have been gradually recovering throughout 2020. This observation is quite interesting and leads to an important insight: Despite the existence of second and third waves in Europe (July to August 2020, November to December 2020), the connectivity has been essentially recovered monotonically. Presumably, from an epidemiological point of view, this opening allowed the virus to spread further, and particularly, opened the doors wide for the potential spread of virus mutations. From an economic point of view, on the other hand, it seems reasonable to reignite the economic ties. This ambivalence is at the heart of many decisions and outcomes experienced throughout the year 2020, when handling COVID-19.

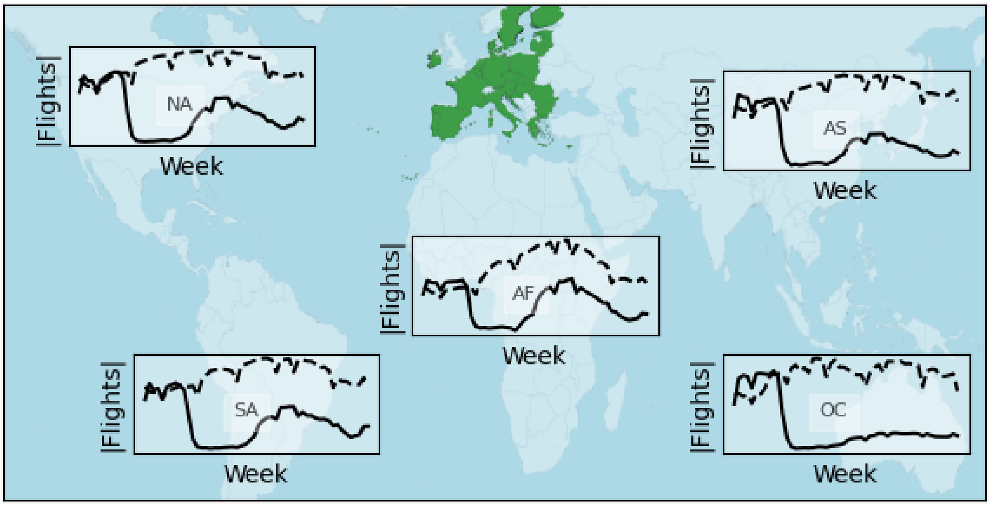

Figure 5. Continental connectivity for Europe-27 to five other continents (dashed line = 2019, solid line = 2020). (Data source: Flightradar24).

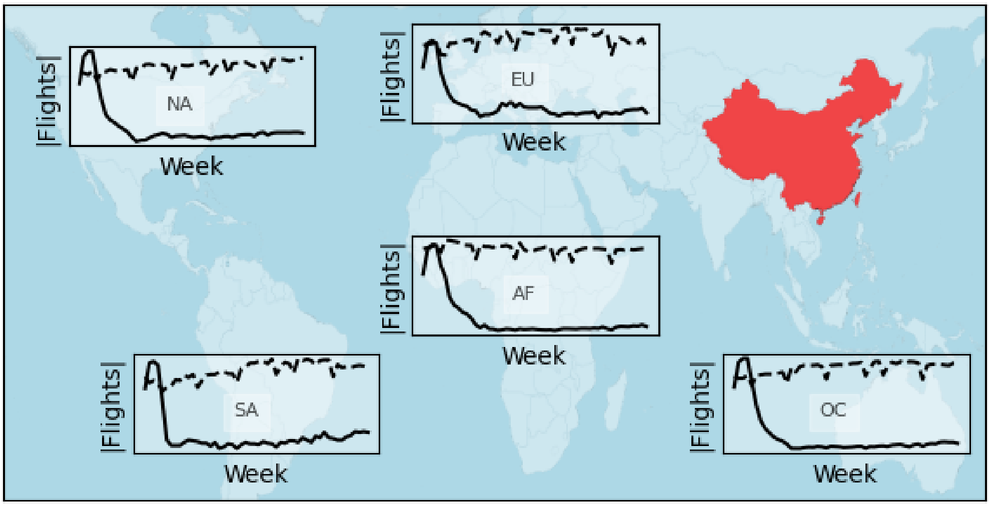

Figure 6. Continental connectivity for China to five other continents (dashed line = 2019, solid line = 2020). (Data source: Flightradar24).

The results for Europe-27 (Figure 5) show a temporal strong recovery to four continental regions: Africa, Asia, North America, and South America. Presumably, these evolutions are purely driven by European policies. Only flights to Oceania were below 10% of the pre-COVID-19 traffic throughout the full year 2020, likely induced by strict migration policies of Australia in the whole year 2020.

Finally, the results for China (Figure 6) show that the strict flight bans equally affected all regions of the world, with a very slight, temporary recovery in mid-2020. Toward the end of 2020, the connections to South America recovered slightly more, compared to other regions.

In the next experiment, we compared the evolution of selected node centralities of countries in the international country network, as defined in [22]. Here, flight edges between country pairs exist, if there is at least one airport pair connecting the two countries. Such a representation provides an aggregated view of international air transportation. The importance of a country is computed by combining a local and a global node importance metric. The degree of a node measures the local connectivity in terms of the directly connected neighbor countries and, accordingly, a high degree is indicating a larger local influence. The betweenness of a node, on the other hand, measures the number of times the node appears on all-pairs shortest paths in the network (in terms of the number of hops). Since the shortest path considers the whole network, betweenness is considered a global node importance measure. From a passenger perspective, countries with high betweenness are excellent transit countries between origin and destination, if the two are not connected directly, highlighting the importance of the indirect spreading of disease. It is known that the importance of air transportation necessitates the consideration of both properties [23]; accordingly, we computed the product of degree and normalized betweenness for each country in the network over time. Figure 7 reports the node importance for the top 10 ranked countries. The United States is the most important country in the worldwide air transportation system, regarding our complex network-based importance measure. It is followed by several European countries and China. Notably, the network underwent severe disruptions between March 2020 and August 2020, as can be seen by the change in importance. During that period, the importance of the United States became almost twice as strong as before. It is interesting to note that the second wave in the United States (starting around June 2020) was triggered shortly after reaching the peak in node importance (May 2020). While we cannot prove a causality relationship here, it at least suggests that there could be a hidden, additional explanation.

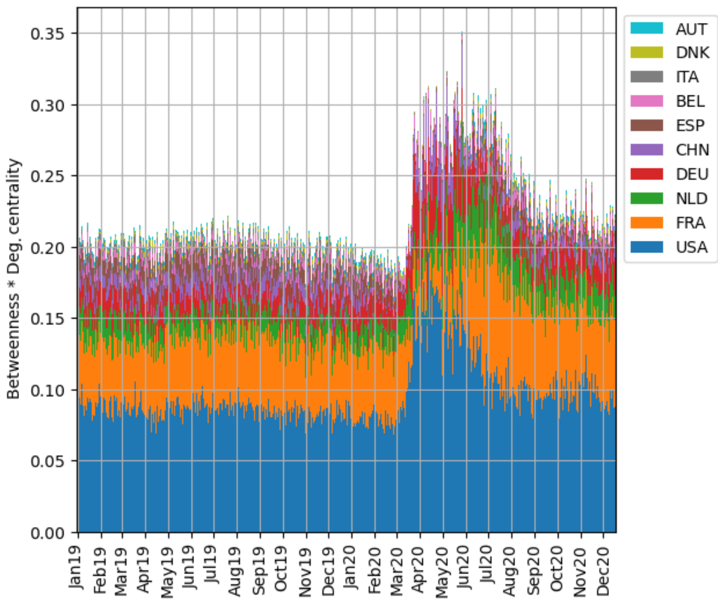

Figure 7. Evolution of node importance for selected countries in the worldwide country network. (Data source: Flightradar24).

3. Domestic Flights

Next, we analyzed the evolution of domestic flights (in fact, intraregional flights) in the three regions under consideration. Figure 8 reports the evolution of the Top 30 domestic networks, according to the total number of flights in the year 2020. Countries from the three selected regions are highlighted by color, respectively. Contrary to international flights, restrictions to domestic flights have been less severe and of a rather short-term nature. Interestingly, this holds for many countries in this study, independent of the region. Only for a few countries extreme domestic flight restrictions still remained at the end of 2020, including Germany (DEU) and France (FRA), and several Asian countries. Moreover, some countries, such as the United States, never completely locked down their flights. Possibe explanations include the high dependency of the United States on air transportation between cities, compared to other European countries or China, which often have a well-established high-speed railway system as the alternative. We further analyzed the interactions between flight restrictions intensity and duration in Figure 9. For each country, we plotted the minimum ratio of domestic flights between the year 2020 and the year 2019 (y-axis) against the normalized area between the two curves (x-axis). European-27 countries are marked as green circles, the United States and China by name. We can observe that the role of the latter two countries stands out, in terms of fewer domestic flight reductions; in fact, only South Korea had an even smaller reduction in domestic flights. For the countries from Europe-27, a wide range of normalized areas between the curve can be observed, indicating a heterogeneous distribution of flight reduction temporal extensions.

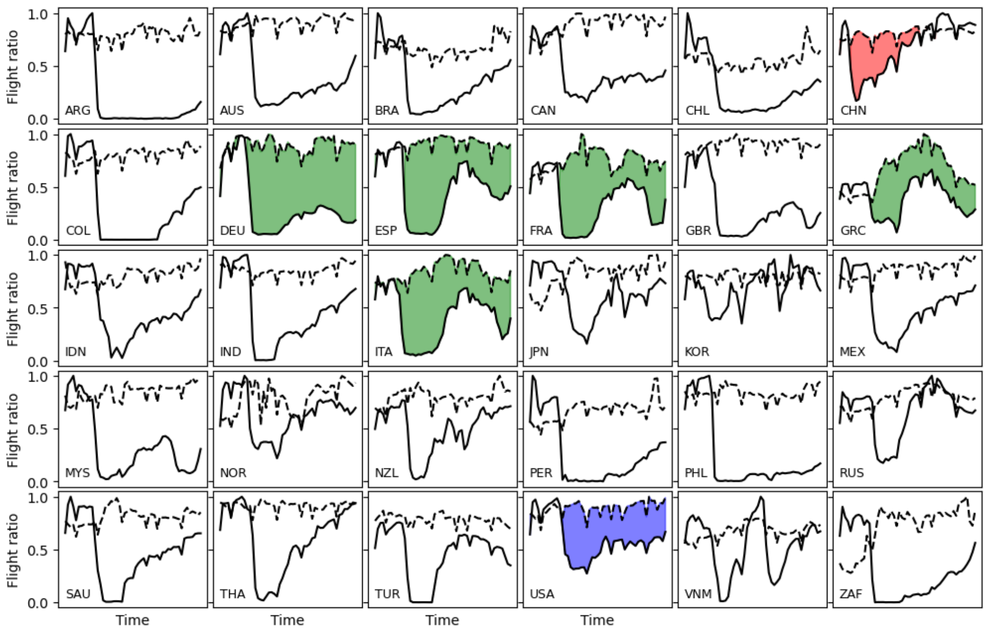

Figure 8. Evolution of the total number of domestic flights inside the top-ranked 30 countries worldwide. The dashed line represents data for the year 2019, and the solid line is the evolution for the year 2020. Data are normalized with respect to the maximum number of flights for any week in the years 2019 and 2020. Countries are colored as the United States (blue), Europe-27 (green), China (red), and others (white). (Data source: Flightradar24).

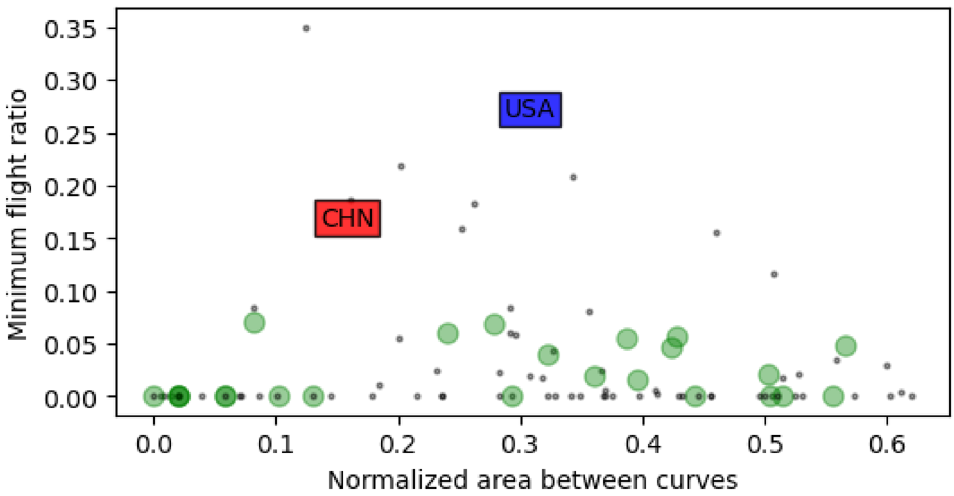

Figure 9. Correlation between magnitude and duration of COVID-19 impact on domestic air transportation. (Data source: Flightradar24).

4. Airports

In a final set of experiments, we investigated the impact of COVID-19 on airports in the three regions of interest. For each airport, we computed the area between the curve for the total number of weekly flights in 2019 and 2020. A larger area between the curves indicates a stronger reduction. The area is normalized and plotted in Figure 10 for the United States, Figure 11 for Europe-27, and Figure 12 for China. Each airport is represented by a circle, whose size correlates to the total number of flights in 2019, using a color scheme ranging from 0 (dark blue, maximum reduction) to 1 (light green, negligible reduction).

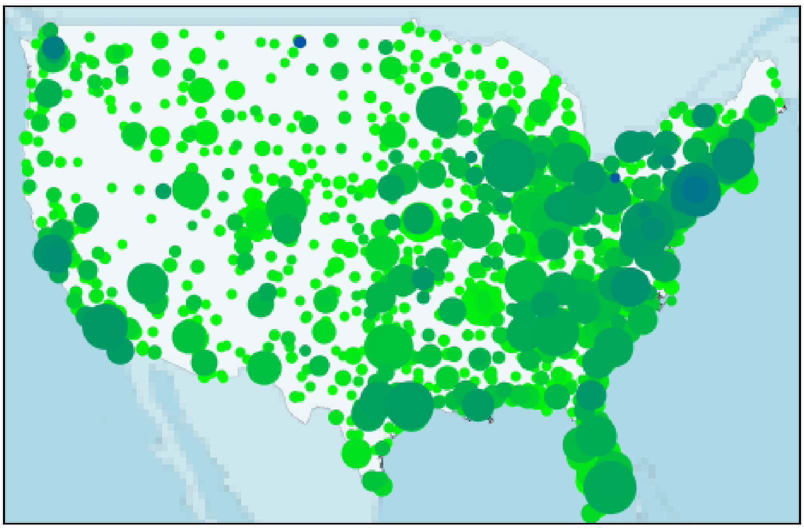

Figure 10. Influence of COVID-19 on airports in the United States, colored from green (small effect) to blue (large effect). (Data source: Flightradar24).

For the United States, we found that the impact of COVID-19 on airports is rather homogeneous, with most airports only partially affected. Some airports along the coastal areas are slightly more affected, usually because of not-yet-recovered intercontinental connections to Asia on the West Coast and to Europe along the East Coast.

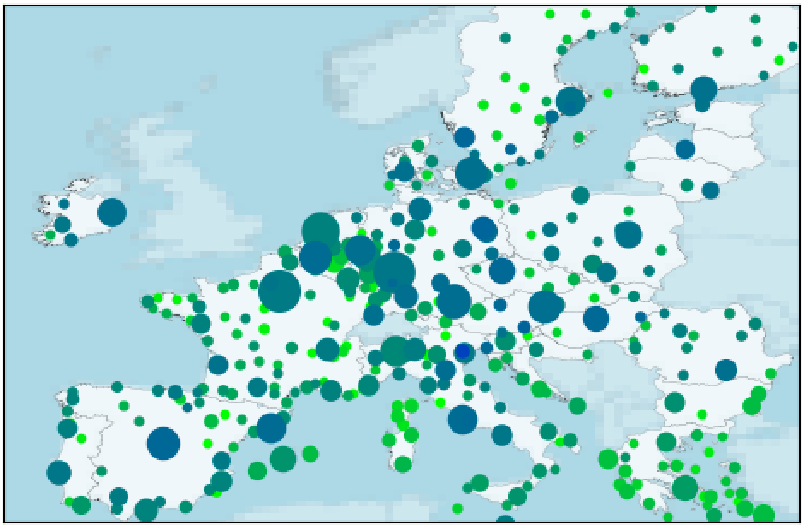

Figure 11. Influence of COVID-19 on airports in Europe, colored from green (small effect) to blue (large effect). (Data source: Flightradar24).

For Europe-27, we found a much stronger impact of COVID-19 on the majority of large airports, particularly in central Europe. There exist, however, many smaller airports, particularly in the south, which have been affected less. Presumably, these airports were able to still attract significant amounts of holiday travelers in summer 2020, in order to compensate for the temporary losses in early and late 2020.

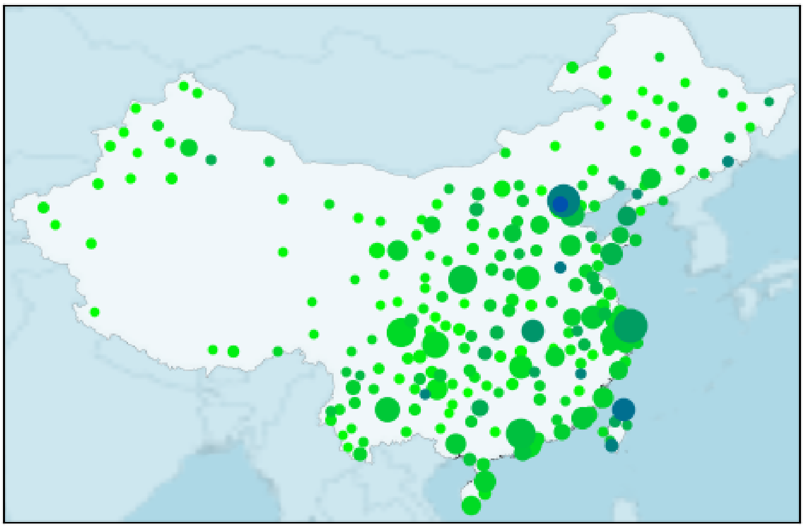

Figure 12. Influence of COVID-19 on airports in China, colored from green (small effect) to blue (large effect). (Data source: Flightradar24).

For China, the impact on airports is rather similar to those in the United States, with many airports only partially affected. China started an early and strong recovery of domestic tourism, partially in order to boost the local economy. Only a few international hubs and the politically important economical centers witnessed comparably stronger flight reductions.

5. Conclusions

To the best of our knowledge, this is the first study that dissects the impact of COVID-19 on air transportation for the three most prolific air transportation regions in the world:

the United States, Europe-27, and China. We used network science and time series analysis as the key tools for investigating the evolution for the whole year 2020, taking the year 2019 as the reference. The impact on the air transportation system was explored from unique perspectives: the international country network, domestic subnetworks, and the heterogeneous effect on airports. The experiments performed as part of our study lead to several avenues for future research.

At its core, our study is preliminary in better understanding the homogeneous responses of different regions of the world—China, Europe, and the United States. From a purely epidemiological perspective, the Chinese approach might be considered the best, based on extreme travel bans and quarantine requirements. From an economic and mobility perspective, the United States approach might be considerable, based on a high degree of domestic traffic, despite increasing pressure from the pandemic. Europe chose a strategy in between. Scientifically, it is difficult to assess which of these strategies should be chosen and at which point to exactly recover. We believe that future work could indeed explore these questions with appropriate tools and data at hand. First, there is a notable limitation of our analysis and results. We relied mainly on the total number of flights between airports as an indicator for analysis, neglecting the actual aircraft size and load factor. Once detailed passenger data are made available at a large scale, future studies could explore the actual number of passengers on flights during COVID-19, leading to a more fine-grained analysis and accurate representation of the impact. Second, it would be very interesting to explore the role of individual countries' decisions regarding flight bans and recoveries, including their timing and strength. Future researchers should aim to better understand the drivers of countries' individual decisions in dealing with the pandemic and air transportation. For instance, one could apply cluster analysis for the selected political, economic, and social factors, analyzing the influence and change in the air transportation system. Third and ultimately, we envision the design of pandemic-resilient air transportation systems, which can keep performing relatively well in spite of external disturbances; more research is needed in this direction, particularly based on network optimization techniques. Finally, there is many broader areas for future work to address, including the nexus between COVID-19, (air) transportation, and the environment [24,25].

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