The Impact of COVID-19 on Flight Networks

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***Abstract*—As COVID-19 transmissions spread worldwide, governments have announced and enforced travel restrictions to prevent further infections. Such restrictions have a direct effect on the volume of international flights among these countries, resulting in extensive social and economic costs. To better understand the situation in a quantitative manner, we analyzed the OpenSky Network data to clarify flight patterns and flight densities around the world. Then we observed relationships between flight numbers with new infection cases and the economy (the unemployment rate) in Barcelona. We found that the number of daily flights gradually decreased and then suddenly dropped 64% during the second half of March in 2020 after the United States and Europe enacted travel restrictions. We also observed a 51% decrease in the global flight network density decreased during this period. Regarding new COVID-19 cases, the United States had an unexpected surge regardless of travel restrictions. Finally, the layoffs for temporary workers in the tourism and airplane business increased by 4.3 fold in the weeks following Spain's decision to close its borders.**

I. Introduction

As COVID-19 transmissions spread worldwide, governments announced and enforced both domestic and international travel restrictions. These restrictions affected the trend of flight networks around the world such as major airlines [1] and tourism-dependent cities [2]. All or a portion of flights connecting these restricted countries and areas were cancelled. The date of travel restriction enforcement varies by country, therefore the period and degree of flight reductions also vary by country and continents.

We quantitatively investigated how flight restrictions affect domestic and international travel in countries and continents through time-series analytics and graph algorithms. We also investigated the negative effect of these restrictions on employment and the number of infected cases in Barcelona, where the majority of revenue depends on the travel industry.

The structure of this paper is as follows: In Section II, we introduce the flight dataset which we used for our analysis. We summarize the statistical analytics of airport and flight data by country and continent, and then compare it with other flight datasets and discussed the limitations and potential biases. In Section III, we analyze the number of daily flights globally as well as by region (continent and country level), and discuss the relationship between government announcements and the decline of flights. In Section IV, we visualize flight networks and apply graph analytic techniques to the network to evaluate the quantitative impacts on travelers. In Section V, we evaluate the relationship between incoming flights from Europe and the number of new infection cases in the United States. We also examine economic effects on travel restrictions and cities depending on tourism industries in Barcelona [3] in Section VI. Finally, we discuss our findings, limitations and related work in Section VII, and explain the summary and future perspectives of our research in Section VIII.

*Toyotaro Suzumura and Hiroki Kanezashi contributed equally to this work.

II. Overview of Flight Data

A. Flight Network Dataset

For time-series flight analytics, we used an open dataset [4] from the OpenSky Network [5]. The dataset contains flight records with departure and arrival times, airport codes (origin and destination), and aircraft types. We used an airport dataset of OurAirports [6], and extracted 616 major airports categorized "large_airports" from the dataset.

The flight dataset includes the following flight information during 2020 January 1 to April 30. The dataset for a particular month is made available during the beginning of the following month. Note that the year of all of the following dates is 2020. In total, our dataset is composed by:

- 655,605 (35%) international flights
- 1,213,100 (65%) domestic flights
- 616 major airports covering 148 countries (out of 195 world countries)

B. Distribution of the Number of Airports

Figure 1 describes the number of major airports per continent and country. Currently, approximately 33% of the world's airports belong to North America and 170 airports (27.6%) in the United States. 27% (166) and 26% (162) belong to Asia and Europe respectively, and China (5.7%) and the United Kingdom (4.4%) have the highest number of airports within each continent.

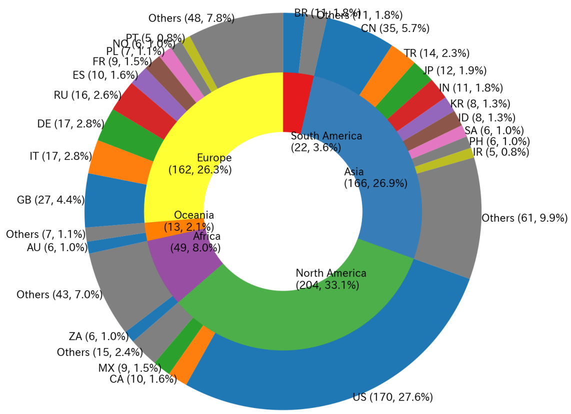


Fig. 1: Number of Major Airports per Continent and Country

C. Number of Flights per Area and Country

Figure 2 describes the total number of flights from January 1 to April 30 in 2020 for each continent and country. More than half of flights were from Europe. Each about 10% of international flights departed from Germany (10%) and the United States (10.7%). In Asia, Hong Kong, the United Arab Emirates, and Singapore had the highest number of flights (2.9%, 2.6%, and 2.2% respectively), yet there were very few flights connecting to China. The number of flights in South America, Africa, and Oceania were too small to analyze, therefore these continents were excluded from the following sections.

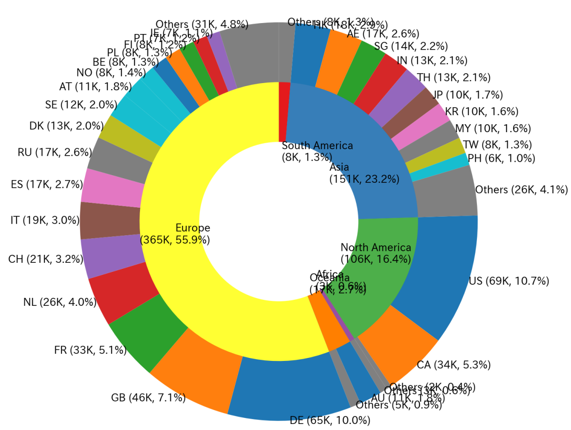


Fig. 2: Number of Departed Flights per Continent and Country

D. Number of Potential Passengers

The OpenSky Network dataset does not contain the final number of passengers for each flight. However, since the data contained each aircraft type used, we used this to estimate the number of passengers for each trip. The information regarding the flights were extracted from the capacity data of each aircraft type from their respective Wikipedia pages [7].

The proportion of international passengers travelling from Asia was approximately 31.2% of all passengers, and the number of flights were 23.5% of overall flights. On the other hand, the total number of passengers of international flights within Europe is about 46.5% while the proportion of international flights outside of Europe is 55.5%. The gap of proportions between passengers and flights comes from the difference in capacities of the aircraft.

III. Descriptive Analysis of Time-series Flight Data

A. Overview

Announcements and enforcement regarding lockdowns (border closures and travel restrictions, etc.) were implemented to slow the rate of transmissions and prevent overburdening of health facilities. The date of implementation, length, and extent vary by country. The Secretary of Health and Human Services in the United States declared a public health emergency on January 31 [8]. The government of the United States suspended incoming flights from Europe (Schengen Area) on March 14 [9], and closed the border with Canada on March 18 [10]. Germany closed borders with neighboring countries on March 16 [11], and other countries in the European Union agreed to reinforce border closures and restrict non-essential travels from March 17 [12] onwards. In this section, we show the changes in the number of daily flights in each region, and discuss the correlations between travel restrictions and the number of flights in each country.

B. Overall International Flights

Figure 3 describes the number of daily international flights in the world. Before the end of February, the daily number of international flights was approximately 8,000. However, the number of daily flights gradually decreased to 6,000 by early March and then drastically dropped to less than 1,000 (around 10% of regular seasons) by the end of March.

C. Inter-continental Flights

Figure 4 describes the number of intercontinental flights that departed from each continent. Inter-continental flights from Europe, Asia, and North America drastically decreased from March 13. The decrease probably reflects the declaration of pandemic by WHO on March 11 and national emergency in the United States on March 13.

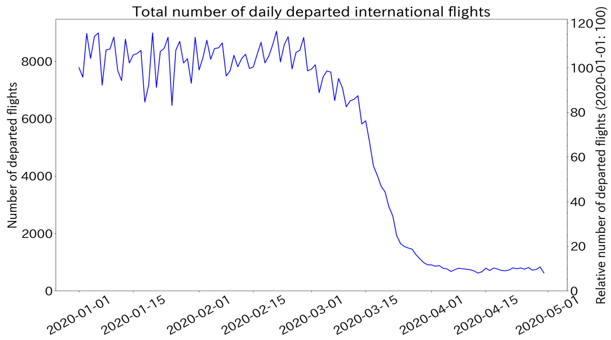


Fig. 3: Total Number of Daily Departed International Flights

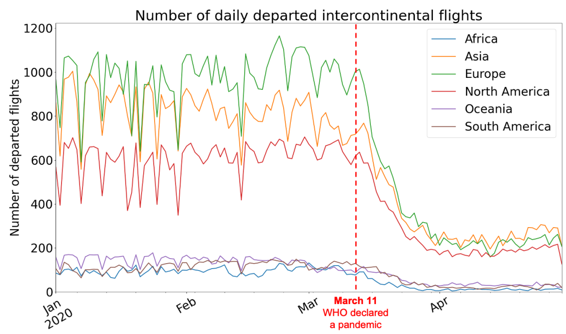


Fig. 4: Number of Daily Departed Inter-continental Flights

D. Continental Flights

Figure 5 describes the number of continental flights within each continent. In Europe, more than 5,000 flights were operating per day until the beginning of March, but dropped to 10% of the regular number of flights at the end of March. In Asia, the number of flights has gradually decreased from February. In North America, the number of flights was steady until mid-March, before dropping significantly.

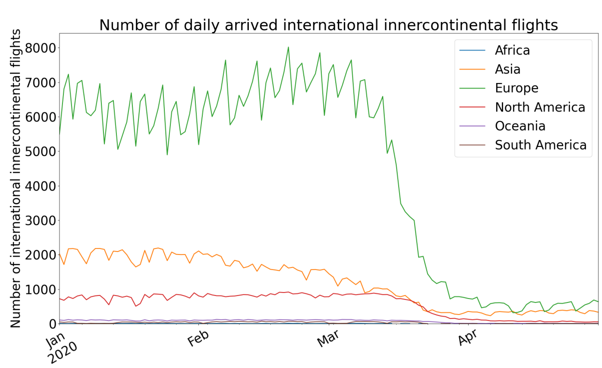


Fig. 5: Number of Daily International Flights per Continent

In Europe, the UK, Ireland, and Germany had the highest number of flight passengers [13]. In Germany, international flights decreased from the beginning of March and then dropped after the nation closed its borders on March 16 (Figure 6). This reflected the European Union's agreement of travel restrictions from outside the European Union, UK, and Switzerland on March 17.

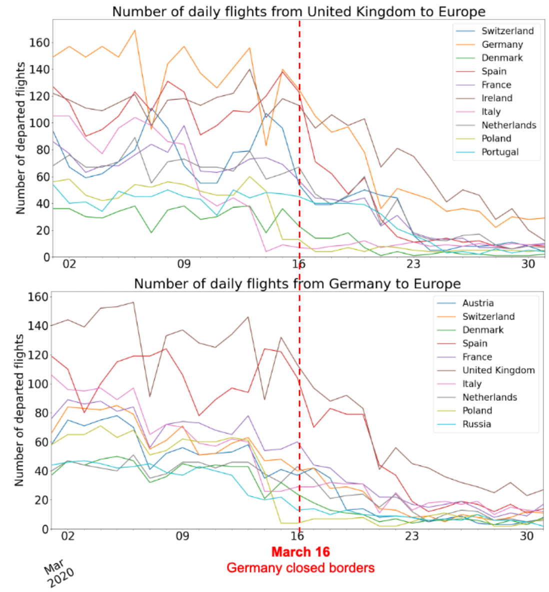


Fig. 6: Number of Daily Flights from the United Kingdom and Germany to Other European Countries

Most of the continental flights had been operating in North America (the United States in particular) until mid-March and half number of these flights in the Beginning of January are still in operation today around the end of March. On the other hand, the number of flights in Asia, Europe, and Oceania have dropped to less than 20% to that of January 1.

E. Domestic and International Flights in the United States

In the United States, the number of domestic flights suddenly dropped from mid-March. However, roughly 50% of all regular flights were still in operation on March 31 (Figure 7), although the United States government and airlines planned to ban or reduce flights by that point [14]. In April, the number of flights gradually declined but 30% of regular flights were still in operation.

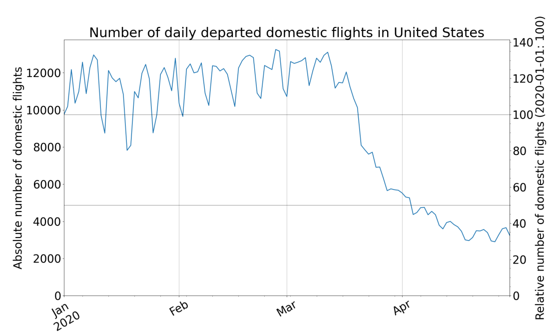


Fig. 7: Number of Domestic Flights in the United States

The number of flights from European countries to the United States suddenly dropped after March 14 (Figure 8). The United

States suspended incoming travel from Europe (Schengen area) from March 13. In the overall number of international flights, the primary destination is Canada (orange lines in Figure 9). The number of daily flights between the United States and Canada gradually decreased after these governments agreed to close their border on March 18.

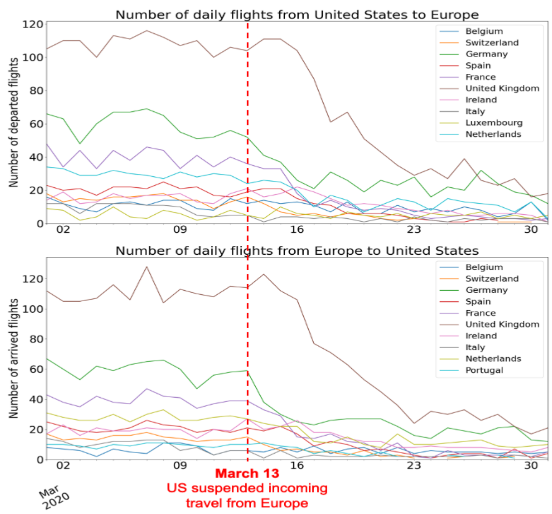


Fig. 8: Number of Flights Between the United States and European Countries

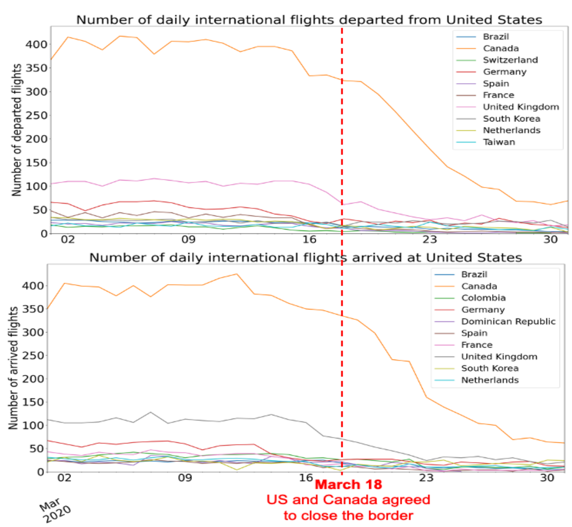


Fig. 9: Number of Flights Between the United States and top-10 Countries

IV. Graph Analytics on the Flight Network

A. Overview

With travel restrictions, the global flight network gradually became more sparse, which prevented travelers from:

1) Using direct flights to their destinations
2) Returning to their origin once they depart from the airport
3) Departing from their current location due to absence of flights in nearby airports

By constructing daily flight networks, we quantitatively evaluated these effects through graph analytics. Each vertex and edge represent an airport and a flight, respectively.

1) Distribution of the number of neighboring airports and flights (degree and neighborhood distributions)
2) Strongly connected component (SCC) extraction
3) Isolated vertex extraction

In the construction of flight networks, we aggregated multiple flights with the same origin and destination and date into a single weighted edge in the flight network construction (Figure 10). The edge weight is the total number of flights. While multiple flights are in operation every day, not all flights are operated every day (e.g., three days a week). To detect long-term trends more precisely, we also aggregated flight edges by week as an optional process.

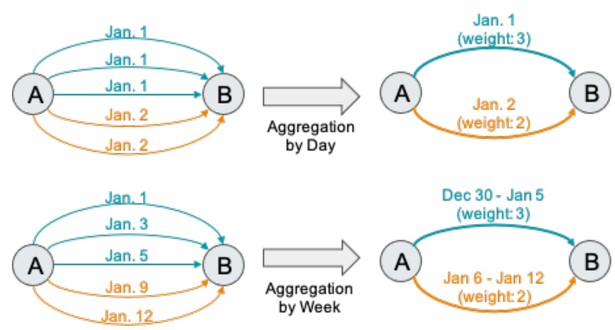


Fig. 10: Flight Edge Aggregations by Day and Week

B. Connecting Airports and Flights

In regular times, many flights (edges in the flight network) connect from the airport (vertices in the flight network) to the airport. That helps travelers to get to more destinations with fewer transfers. However, travel restrictions prevent them from using direct flights and getting to their destinations. To measure the effect quantitatively, we computed the following metrics for each airport and each date (Figure 11).

1) Number of flights (edges) from the airport
2) Number of 1-hop neighboring airports from the airport (the number of reachable destinations with a nonstop flight)
3) Number of 1,2-hop neighboring airports from the airport (the number of reachable destinations with a single connecting flight)

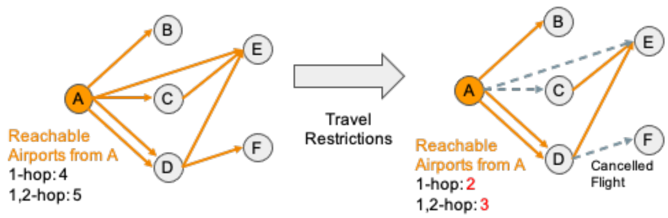


Fig. 11: Number of Flights and Neighboring Airports from the Airport A

The color and size of each vertex in Figure 12 indicate the number of departed flights from the airport. From mid-March to the beginning of April, many flights were gradually canceled, except for domestic flights in the United States and international flights between the United States and Europe. The number of flights in Europe suddenly decreased from March 16 (the day before EU countries closed borders) to March 23. In April, only a few flights were operating and many airports became isolated. In North America, most of the flights in North America were operating in the United States and Canada. In the United States, most of the domestic flights were operating as usual, even at the end of April.

C. Density and Clustering Coefficient

With denser flight networks, travelers can reach more destinations. As the barometer of the flight network density, we computed the following metrics.

Density: The ratio of the actual number of edges after aggregation against the number of edges of the complete graph.

Clustering Coefficient: The ratio of the total number of triangles against the total number of triplets (connected three vertices). This is mainly used for social network analytics to measure the connectivity of friendships.

The density (red lines in Figure 13) of the global flight network rapidly decreased by 52% during March. In Europe, drastic decreases in the flight network density was similar to that of the global network, and fell by approximately 84% compared to the peak. In the United States on the other hand, the density gradually decreased, but it was only 12% of the maximum value. From March 13, the clustering coefficient (blue lines) of the global flight network gradually decreased by half in the next two weeks. In Europe, it rapidly declined to about a quarter in the same period. In the United States, the decline of the clustering coefficient is only about 12% at the end of April.

D. Strongly Connected Component and Isolated Airports

In regular seasons, travelers departing from any airport can typically go to any destination and return to their airport of origin. This is due to flight networks being a strongly connected component (SCC), within which travelers can go from/to any airports in the same SCC. With travel restrictions, however, many flights (gray dotted arrows in Figure 14) were canceled and the original large SCC (a whole network with all vertices in Figure 14) has decomposed into three smaller SCCs (subgraphs consist of blue, green and red vertices in Figure 14). In the result, travelers cannot:

1) Go to other airports outside local flight networks
2) Return to their origin (a red arrow from E to D)
3) Depart from isolated airports (a red vertex)

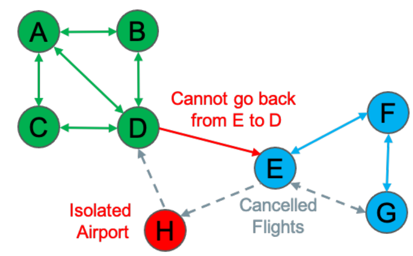


Fig. 14: SCC Decompositions of Flight Networks

In the global flight network (Figure 15a), the size of the largest SCC (red line) decreased by 15% from March 12 (306) to April 7 (260), and the number of isolated airports (blue line) increased by 15% (from 300 to 346). In Europe (Figure 15b), the largest SCC size decreased by 32% from March 12 to April 7, and the number of isolated airports increased by 55%. In the United States (Figure 15c), the largest SCC size and isolated airports are almost stable (around 90 and 80 respectively). Although the largest SCC size gradually decreased from March 12 to April 7, the rate of the overall decrease is only about 10%.

E. Diameter and Radius of Flight Network

When many flights are canceled, more transfers are required for travellers to reach the destinations compared to regular seasons. In order to measure the number of required transfers, we applied the eccentricity (the maximum distance from a specified vertex to all other connected vertices) to the flight networks. An eccentricity of an airport vertex corresponds to the number of required transfers to other destinations in the worst case. With travel restrictions, the diameter (the maximum value of eccentricities) and the radius (the minimum value of eccentricities) of the flight network become larger.

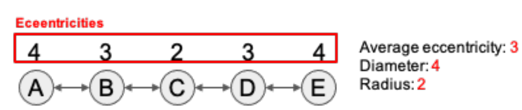
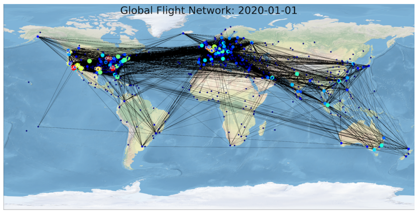


Fig. 16: Average Eccentricity, Diameter and Radius

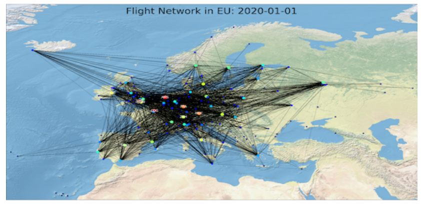
The diameter (red line in Figure 17), radius (blue line), and average eccentricity (green line) of the largest SCC size (black line) in the global flight network increased from April. In Europe, diameter and radius more drastically increased from March 16 in two weeks. The overall flight network's trend in the United States did not change until the end of April.

F. Flight Edge Weight and Density

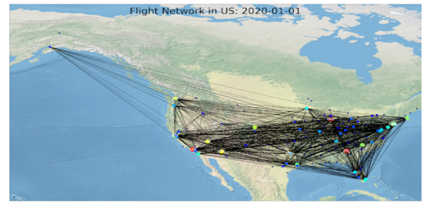
Although some flights still exist among most of the airports, the frequency has gradually decreased. To measure the decline



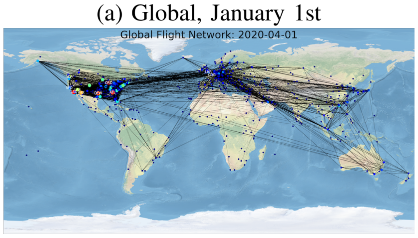
(a) Global, January 1st



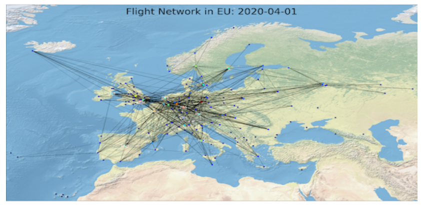
(b) Europe, January 1st



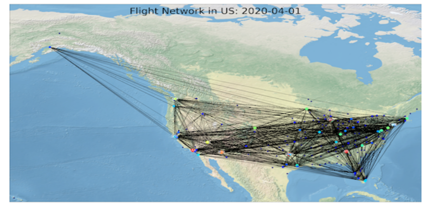
(c) North America, January 1st



(d) Global, April 1st

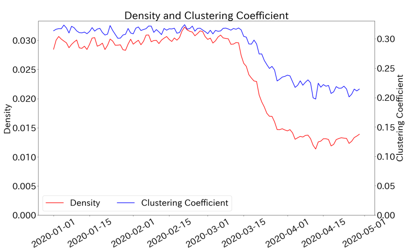


(e) Europe, April 1st

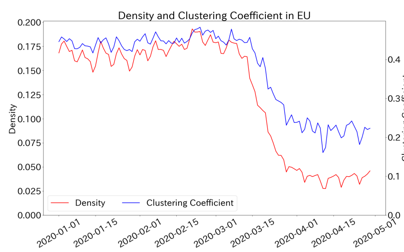


(f) North America, April 1st

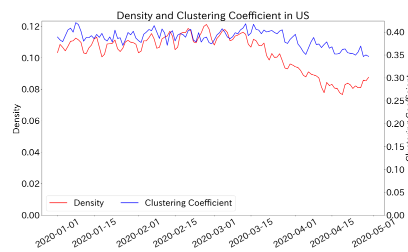
Fig. 12: Flight Networks on January 1st and April 1st in 2020. Images: Natural Earth [15]



(a) Global

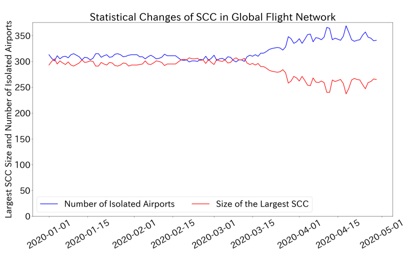


(b) Europe

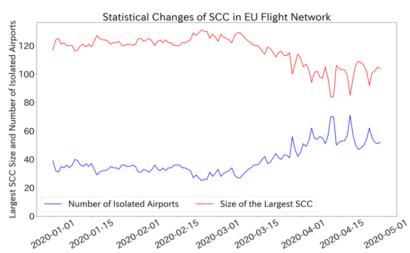


(c) The United States

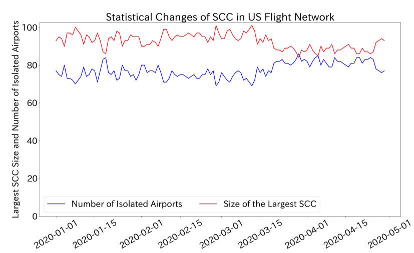
Fig. 13: Density (red line) and Clustering Coefficient (blue line) of Flight Networks



(a) Global



(b) Europe



(c) The United States

Fig. 15: Largest SCC Size (red line) and the Number of Isolated Airports (blue line) of Flight Networks

of flight frequencies, we defined the "relative weight" for each flight edge (pair of vertices as connected airports) and network density with the weighted edges such as Figure 18.

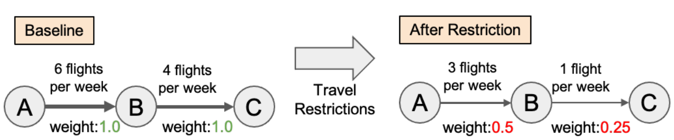
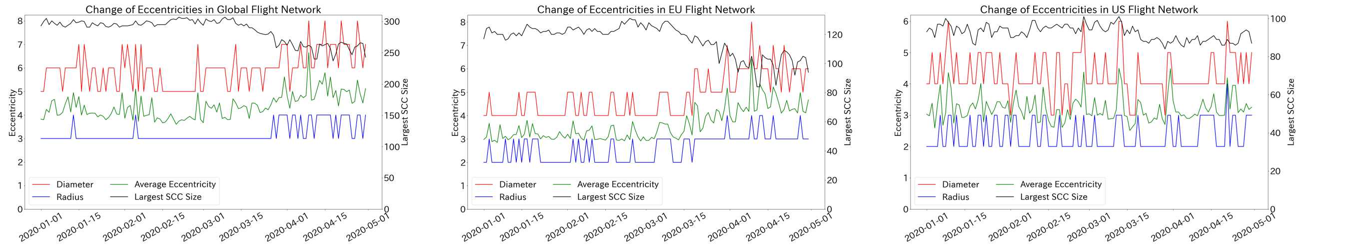


Fig. 18: An Example of Relative Edge Weight

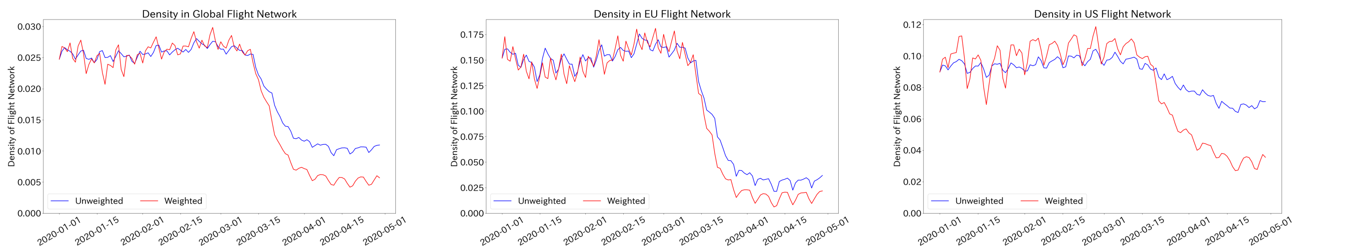
First, we computed the moving average of the number of daily flights for each pair of vertices, and then computed the ratio of the total number of flights in a week against the baseline of the specified week (January 12 - January 18), to define the ratio as the relative weight of the edge. Besides the topological density described in IV-C, we used the density of the whole flight network with the weighted edges.

The blue and red lines in Figure 19 represent the density of the daily flight network with the unweighted and weighted flight edges respectively. The density of the whole flight network with weighted edges in Europe dropped to almost zero in April. In the United States, the density with weighted edges has dropped by half in March, and around 30% of March 1 in the end of April. Although the flight network remains topologically unchanged, the frequency of domestic flights significantly decreased as seen in other continents.



(a) Global (b) Europe (c) The United States

Fig. 17: Diameter (red line) and Radius (blue line) of Flight Networks



(a) Global (b) Europe (c) The United States

Fig. 19: Density of Flight Networks with Unweighted (blue line) and Weighted (red line) Flight Edges

V. Incoming Flights and Infection Cases in the United States

A sequence analysis of COVID-19 virus found out the virus type of the most infection cases in New York City is from Europe [16]. The first case was confirmed in the State of New York on February 29, and infection cases gradually increased from March 15 (Figure 20). To investigate the effects of incoming flights from Europe, we analyzed the number of daily flights and new infection cases in the United States.

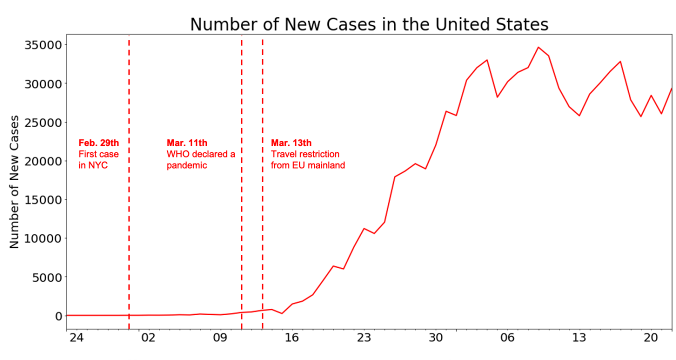


Fig. 20: Number of New Infection Cases in the United States

A. Number of Infection Cases in European Countries and the United States

The trend of increase in newly infected cases in Europe began a week before the United States (Figure 21). In particular, confirmed new infections in Italy started to increase in the beginning of March. Spain and Germany also confirmed cases before the United States (Figure 22). The United States announced to enforce travel restrictions from Europe on March 13 (EU mainland) and March 14 (the UK and Ireland). Infection cases in the United States gradually increased from March 15 and exceeded 30,000 on April 2.

B. Number of Incoming Flights from Europe and Infection Cases in the United States

With the travel restrictions from European countries to the United States, the number of incoming flights (blue line in Figure 23) suddenly decreased from March 13 to March 24. However, the number of infection cases (red line in Figure 23) began to increase just after these restrictions. However, the latent period of COVID-19 is commonly five to six days as we mentioned in Section VI-B, therefore we cannot rule out the possibility that the infections had already spread out before the United States enforced these restrictions.

European countries such as Italy, Spain and Germany have already reported a certain number of infection cases before travel restrictions. Figure 24 shows the number of daily international flights from these countries to the United States and the number of daily new infections in the United States (red line). In Italy (blue line), more infection cases were reported than other European countries from the beginning of March (green line in Figure 22), but the number of flights to the United States became almost zero just after the travel restriction was enforced. On the other hand, some flights from Spain (brown line) and Germany (green line) to the United States were still in operation, even after the travel restrictions were announced and infection cases in the United States began to increase. These flights may be one of the reasons for the gradual increase of infections.

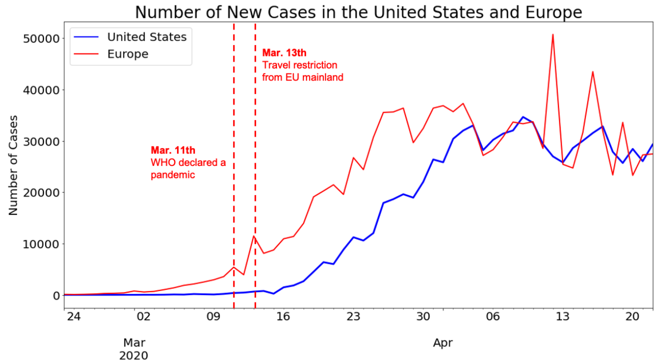


Fig. 21: Total Number of Daily Infection Cases in the United States (bold blue line) and Europe (red line)

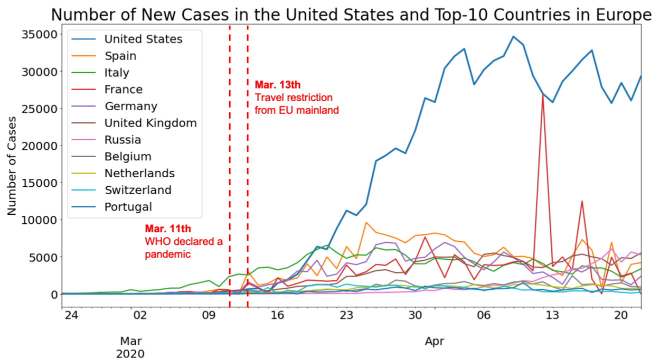


Fig. 22: Number of Daily Infection Cases in the United States (bold blue line) and Top-10 Countries in Europe

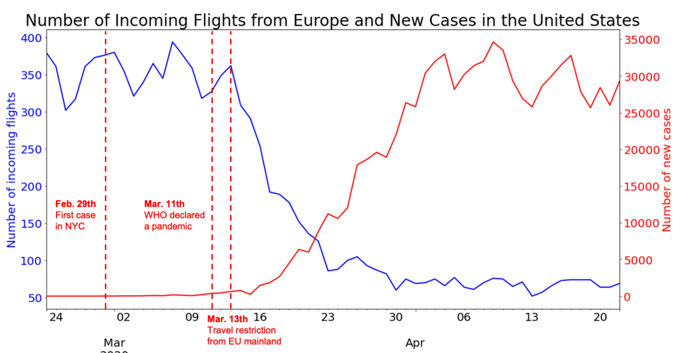


Fig. 23: Number of Daily Incoming Flights from Europe and New Infection Cases in the United States

VI. Impact on the Travel Industry in Barcelona

Travel restrictions have a large impact on travel industries and tourism-dependent countries. In this section, we investigate the correlation and causal association between the decline of incoming flights, the number of infection cases, and the unemployment in Barcelona. We firstly analyzed the Barcelona as the first case, and we will work on other cities for future work once their data become available.

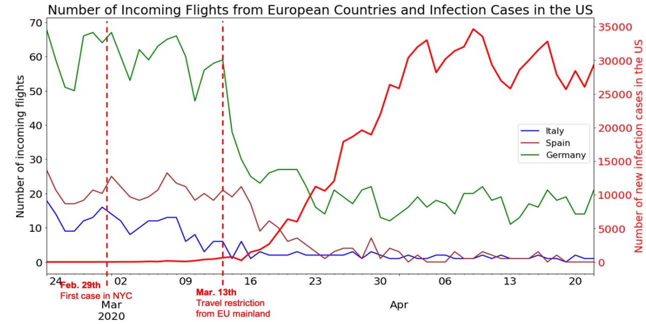


Fig. 24: Number of Incoming Flights from Italy, Spain and Germany and New Infection Cases in the United States

A. Unemployment and New Infection Cases in Barcelona

According to the unemployment dataset [17], the number of affected temporary workers (red line in Figure 25) gradually declined in April after it suddenly increased on March 24. The number of flights (blue line) to Barcelona gradually decreased until the beginning of April. These numbers seem to have some correlations, but more investigation is required to understand the causality and relationships.

The number of flights to Barcelona has been decreasing since the beginning of March, and suddenly halved on March 16 just before Spain closed its borders [18]. Then, the number of affected temporary workers (red line) suddenly increased by 4.3 times (from 15,901 on March 23 to 68,170 on March 25). It is notable that the dataset regarding the number of affected workers became available from March 23. The number of new infection cases in Spain (green line) gradually increased from March 12 and peaked at almost 10,000 on March 25.

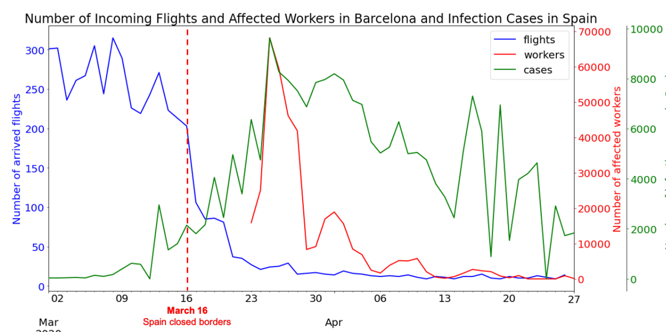


Fig. 25: Number of Affected Temporary Workers in Barcelona and New Infection Cases in Spain

B. Flights to Barcelona and New Infection Cases in the Major Origin Countries

Approximately half of all flights to Barcelona (BCN) come from France, Germany, and the UK. The government of Spain closed its borders on March 16, and the number of flights from these three countries decreased by half during the following day. However, the number of new infection cases for these countries has been gradually increasing even before border closures. Considering the latent period of COVID-19 is commonly five to six days [19], the reason the trend of increase of new infection cases continued for a week after the border closure may be due to the immigration of infected individuals before the border closure.

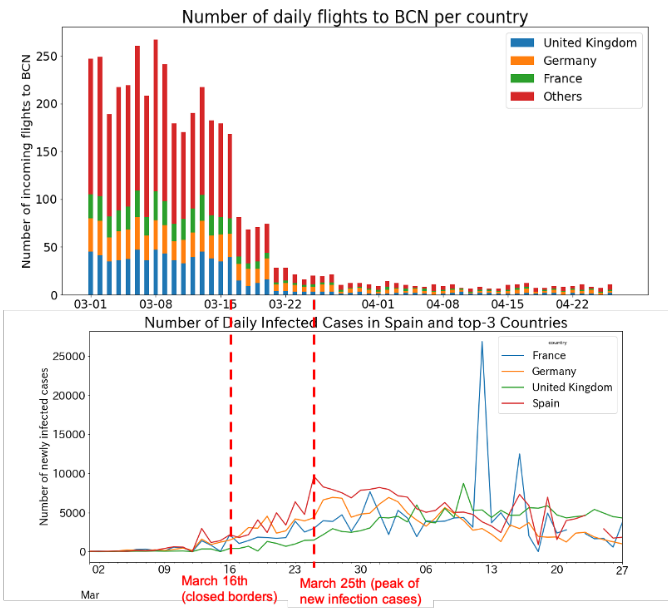


Fig. 26: Number of Incoming Flights and New Infection Cases of the Top-3 Origin Countries

VII. Discussion

A. Findings

In Section III, we found out when and how international flights in each continent and countries declined due to travel restrictions. The number of flights on April 1 had dropped to 10% of that of regular seasons. The number of flights from Europe sharply decreased in the second half of March after the United States announced the travel restriction from most of European countries on March 11 and the EU agreed to close borders on March 17. On the other hand, half of regular domestic flights in the United States were still in operation at the end of March.

Besides counting the number of daily flights, we also applied several graph analytics to daily flight networks in order to explain how these networks became sparse in Section IV. With the result of analytics, we found out the density of the global flight network halved in March, and it has been divided into small strongly connected components from the mid of March to the end of April.

We also investigated the relationship between the number of flights from Europe to the United States and infection cases in the United States in Section V. We found the trend of daily infections in Europe began a week ahead of the United States, and that some European countries confirmed cases from March 1 while the number of infection cases in the United States began to increase from March 15. We also found flights from Europe were still accepted in the United States even after travel restrictions were announced on March 14.

In Section VI, we evaluated the effect of reduction of incoming flights to Barcelona on the tourism industry (e.g. the number of affected temporary workers). The number of incoming flights dropped just after the travel restriction by the government of Spain on March 16, and the number of affected workers drastically increased after the government of Catalonia published the number of these workers from March 23. However, the number of infection cases still increased even after travel restrictions were announced.

B. Limitations and Possible Bias

Since the flight dataset from the OpenSky Network is aggregated voluntarily, it has some limitations. First, some flight entries do not contain origin or destination airport codes. We excluded such entries before analysis to construct valid flight networks. Moreover, the dataset also has a significant regional bias as we discussed in Section II-C. For example, most of the international and domestic flights connecting China, Oceania, South America, and some countries in Africa are missing.

C. Related Work

Many researches have conducted evaluations and estimations how COVID-19 infections affected international flights.

Stefano et al. [20] evaluated the economic impact of travel restrictions on flights. They constructed several scenarios of travel restrictions based on the past pandemic cases such as SARS in 2003 and MERS in 2005, and estimated the loss of global GDP may amount up to 1.98% and that the number of unemployment could reach up to 5 millions.

Hien et al. [21] evaluated the correlation of domestic COVID-19 cases and flight traffic volumes with the OpenSky Network dataset, and concluded the number of international flight routes and passengers have a correlation with the risk of COVID-19 exposures.

VIII. Conclusion

A. Overall Conclusion

After the declaration of a pandemic by WHO on March 11 and government announcements of travel restrictions during the following week, the number of international flights around the world drastically declined, particularly in Europe. Although many domestic flights were still in operation in the United States, the overall frequencies gradually declined.

The number of newly infected cases in the United States increased after travel restrictions were declared on March 16, most likely due to COVID-19's longer latency period. Moreover, these travel restrictions affected tourism-dependent countries. In Barcelona, many temporary workers made applications regarding their unemployment soon after the government opened applications on March 23.

B. Future Directions

Due to the limitation of publicly available data, we could not conduct the same analysis for many countries as Barcelona in Section 6 for this paper. Therefore, we aim to analyze relationships among the number of flights, infection cases, and the impact on the economy for more countries and continents by combining various other data sets with the flight data in our next analysis. We also aim to focus on counties where the number of infections has soared, and investigate how the increase of cases and reduction of flights affect the economy.

Currently there is no precise way to estimate the number of actual passengers other than based on the capacity of passenger aircraft, and sufficiently reliable data are not available. In this time we used the number of passengers, but we plan to include it in future analyses if more accurate data are available.

We also plan to trace and predict viral mutations with the flight network data. The type of COVID-19 virus varies from region to region [22], [23], and this may provide insight to analyzing the route of infections with viral types. With the daily flight network data, we hope to estimate the date and route of infections more precisely.

In order to predict the economic impacts such as propagations of revenue declines in travel industries for each region, we will apply advanced machine learning techniques for time-series graph data such as Graph Convolutional Network (GCN). We will also evaluate the importance of flight network features as well as demographic features of regions (countries and continents) in our next analysis.

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