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Assessing impacts of the Russia-Ukraine conflict on global air transportation: From the view of mass flight trajectories

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ABSTRACT

Air transportation has been severely affected by the Russia-Ukraine conflict. The closure of involved Russian and Ukrainian airspace made a great number of flights suffer from a dramatic transportation cost increase. Accurately estimating the conflict's impact can help us better comprehend the susceptibility of international airlines and optimize flying routes for global airlines. In this study, we quantitatively analyzed the impact the conflict has brought on global air transportation. The detour of airlines and the variation of flights caused by the conflict were assessed from the view of mass flight trajectories. A flight cost increment index is proposed to reveal the extra costs of involved countries. The impacts on each involved country are further analyzed and the airlines influenced the most are identified. The results show that the flight cost of 6.23% of global international flights significantly increased by 13.32% due to the conflict. Furthermore, as one of the few researches that analyze the impact of regional events on global air transportation, the result of the study reveals the vulnerability of international airlines and provides instruction for flying route optimization.

1. Introduction

As the most important part of the global transportation system, air transportation transported over 1.811 billion international passengers in 2019 (Gössling and Humpe, 2020), and the value of global trade carried by air occupies 35% of global goods value (IATA, 2016). However, air transportation can be easily affected by many factors like economic development (Karsner, 1997), the financial crisis (Azadian, 2020), the variation of fuel prices (Wadud, 2015), wars (Dobruszkes, 2019) or the global pandemic (Lemetti et al., 2023). Evaluating the impacts brought by a specific event is helpful to assess the vulnerability of international airlines and to optimize the airline's flying route (Miyoshi et al., 2018).

The closure of airspace is a common problem faced by the air transportation. Niger's airspace and airports were closed to all flights on July 26, 2023, Sudan's airspace is closed to all civilian flights since April 2023, Libya's airspace is closed since the civil war began at 2014, etc. The Russian-Ukrainian conflict has been ongoing since 2014. With a major escalation saw in February 24, 2022 (Reuters, 2022b), the consequences of the conflict have led to wider global impacts in numerous realms. Commodities producers' prices have risen significantly worldwide, notably for oil and natural gas (IMF, 2022; Mbah and Wasum, 2022). Over 7.8 million refugees fleeing from Ukraine have been recorded across Europe (UNHCR, 2022), it was named Europe's largest refugee crisis since World War II (Harding, 2022; Teke Lloyd and Sirkeci, 2022).

Global aviation transportation was also severely affected by the conflict. Ukrainian government shut down its airspace the current day (BBC, 2022). On 28 February, the European Union (EU) declared to close its airspace to Russian airplanes. Then Russia also closed its airspace to 36 countries in the same day as well (Crisis24, 2022). All the restrictions are still being conducted till the research was done, and some experts estimated that the reopening will take longer time than expected (Switzerland Times, 2022). The directly related airspace includes about 17,879,000 square kilometers of Russian airspace and 674,000 square kilometers of Ukrainian airspace. Before the conflict, nearly half of the polar airlines have to fly through the airspace for their shortest path. Fig. 1 shows two typical affected airlines with their regular flight routes before and after the conflict.

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The great circle route is the shortest path that connects two airports on earth. In Fig. 1, the closure of Russian airspace forced the flights taking off from Frankfurt to detour from Central Asia, which leads to a 22.1% increment in flight distance and a 28.7% increment in flight time compared with its regular route. For airplanes that chose to fly over the North Pole via Alaska flight distance and time were raised by 31.4% and 31.3% respectively. At the same time, flights from Atlanta to Incheon suffered a 5.3% raise in flight distance and 15.8% raise in flight time due to the font wind of the northern hemisphere's prevailing westerlies near the Aleutian Islands. With the flight cost of parts of airlines increasing considerably, global aviation transportation was impacted unavoidably.

Plenty of reports have called for people's attention on the consequences the Russia-Ukraine conflict brought to global aviation transportation (BBC, 2022; Crisis24, 2022; Reuters, 2022a; Switzerland Times, 2022). Some researches analyzed the impact from an international relation view with a conceptual approach (Satria Unggul Wicaksana et al., 2022; Sopamena, 2022). While the complexity of international air transportation and the interaction effects of COVID-19 recovery with the war makes it hard to be quantitatively assessed. Only a few preliminary researches have been done. Researchers from Kyiv estimated the war's impact on global aviation, their results indicated that about 14 thousand hours of flights departing from Ukraine have been canceled, and flights trajectories from North European to Asian airports have been re-planned (Ostroumov and Kuzmenko, 2022); Ostroumov et al., 2022). However, their research only evaluated flights connected with airports in Ukraine and did not propose a global view of conflict impacts. The factsheet from International Air Transport Association (IATA) presents the impact the conflict brought on air passenger traffic, cargo traffic and jet fuel price (IATAd, 2022a,b,c,d).

In this research, we quantitatively evaluated the impacts the Russia-Ukraine conflict has brought to global international air transportation from a data driven view. Based on all the global international airlines' trajectories in February and March, accounting for 1,149,799 sorties in total, we distinguished airlines that might be affected by the conflict and tested their variation before and after the conflict to confirm which of the airlines are forced to detour. According to the global situation, we calculated the accumulated detour increment to assess the severity of the influence the conflict caused on global international aviation. After that, with an increment index, the research assessed the increased flying cost by nation, which aimed to find out countries suffered the most from the consequence of the conflict. We also evaluated the decline of airlines due to the impact of the conflict. Moreover, we explored the refugee crisis by mining added airlines after the conflict began. This study mainly made the following contributions.

- The research quantitatively evaluated the influence the Russia-Ukraine conflict has brought to the world international aviation. The increment of flying cost and deduction of airlines caused by conflict was calculated. 6.23% of all international flights have to endure an average 13.32% detour. And the global international air transportation cost has raised by 0.637% in total.
- We assessed the impacts on each country with a flight cost increment index and the interruption of air traffic. The conflict forces 4.32% of global international airlines completely stopped. Based on the results, we pointed out two flying routes affected most severely.

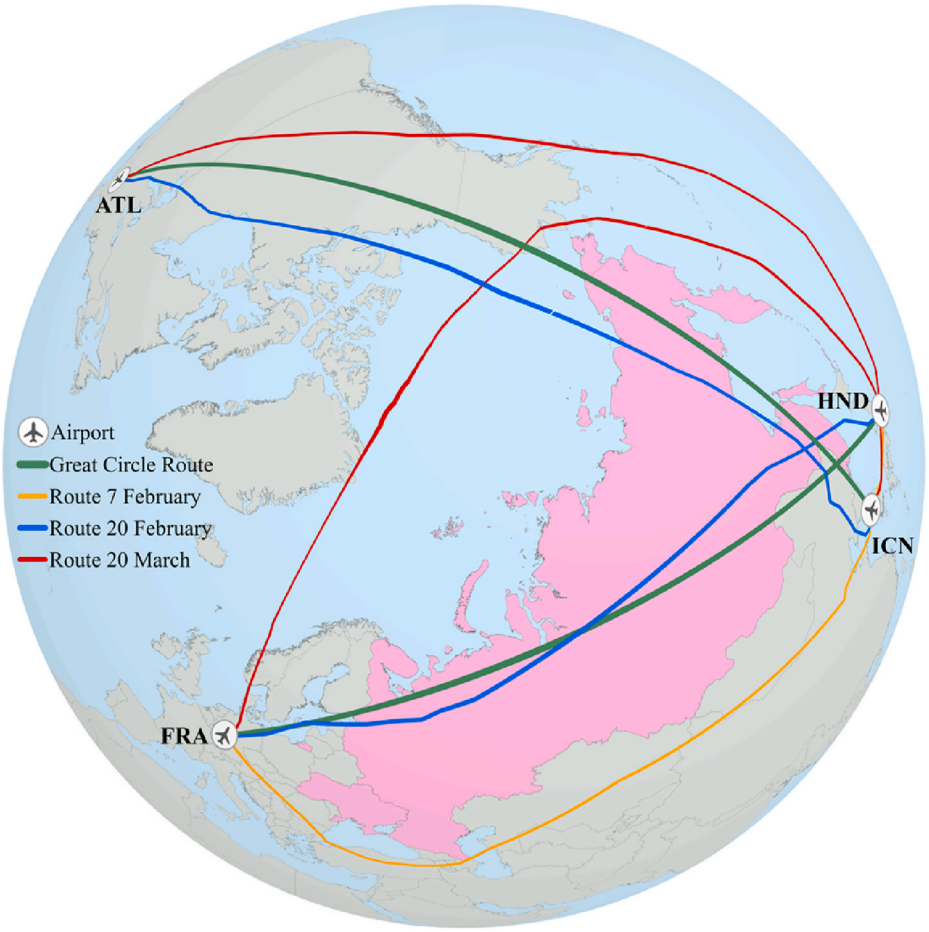

Fig. 1. Flight routes of Frankfurt International Airport, Germany (FRA) to Tokyo International Airport, Japan (HND) and Flight routes of Atlanta International Airport, the US (ATL) to Incheon International Airport, Korea (ICN).

- The research revealed the refugee crisis from a transportation view. We found out the evacuation directions of refugees and the target destinations' spatial distribution of refugees, which were proven by data from the United Nation.

2. Dataset and methodology

To quantitatively evaluate the detours and canceled flights caused by the conflict, the research extracted airlines that are likely to be affected by the closure of Russian and Ukrainian airspace. Then we conducted a statistical test on the difference in the flight cost and the number of flights in each airline before and after the conflict. Airlines that passed the statistical test significantly are regarded as being affected by the conflict. Then we measured the flight cost increment of each country to evaluate the impact the conflict has brought to the world.

2.1. Dataset

The research employed ADS-B data to track aircraft trajectories. The installation of ADS-B products has been mandatory for commercial airlines in most countries and aircraft operators are encouraged by administrations to install ADS-B systems on their productions (Transport Canada, 2021; FAA, 2022). Therefore, it is fair enough to assume that ADS-B data has covered the vast majority of global international flights, including flights for both passengers and goods. Examples of ADS-B trajectory are shown in Table 1.

The ADS-B trajectory records planes' IATA code, departure and arrival airport, and positioning points. Each positioning point includes a Unix time stamp, longitude, latitude, and the airplane's altitude and ground speed at the moment. According to the dataset, there were 514,402 sorties of international flights recorded in February and 635,397 in March. The average time interval between two positioning points is 30.06 s. Fig. 2 shows the global density distribution of ADS-B positioning points of international airlines in February(a) and March (b) 2022.

The comparison of high-density regions between February (Fig. 2(a), (b)) and March (Fig. 2(c) (d)) briefly shows the impact the conflict has brought on international air transportation. The most obvious change happened in the airspace of Ukraine and its nearby area. The ADS-B density reduced significantly due to the closure of its airspace. Another change was caused by the shutting down of Russian airspace to related countries. In Fig. 2(c), there was an obvious decline in the number of aircraft flying over Siberia airspace. The remaining trajectories only connect some of the central Asia airports.

According to the planes' ADS-B trajectory, we recorded all flights flying over Russian and Ukrainian airspace before February 24th. These flights are grouped by their airline, which is represented by paired Origin and Destination airports (OD). An OD with more than 50% of its flights going through related airspace is regarded as an OD that might be affected by the conflict. The statistical result shows that 14,949 global international OD airlines conduct more than one flight per week, among which 9.26% of those OD airlines conducted their regular routes passing Russian and Ukrainian airspace.

Table 1
Example of flight's ADS-B trajectory.

IATA Code	Date	Departure	Arrival	Trajectory
ACA6754	20220226	LHR 19:26:00	WAW 21:34:00	[1645874765, −0.4430, 51.4650, 0, 163], [1645874775, −0.4312, 51.4653, 3, 167], … … [1645882464, 20.9744, 52.1576, 0, 144]
… …	… …	… …	… …	… …
CAL9371	20220304	AMS 17:15:00	MAN 18:05:00	[1646385303, 4.7373, 52.3023, 0, 161], [1646385310, 4.7332, 52.2974, 3, 166], … … [1646388324, −2.2644, 53.3588, 0, 147]

2.2. Flight cost statistical analysis

The selection of flight route by an international airline is determined by many factors, which can be divided into permanent factors and temporary factors (Dobruszkes, 2019; Carreras-Maide et al., 2020; Murça et al., 2020). Permanent factors like ground relief affect the route optimization of every airplane at all times, and temporary factors like weather or wars can also dramatically affect the route during a period of time (Dobruszkes and Peeters, 2019). In order to understand how these two kinds of factors affect the flight cost of different flight trips in an airline, we drew the probability distribution of the variation of flight time of all airlines before and after the conflict in Fig. 3.

In Fig. 3, the variation of flight time refers to the difference between the flight time of each flight trip and the average flight time of the corresponding airline. Both distributions are symmetric, which means that once the OD airports are settled, the flight route and traveling time are relatively fixed by existing permanent factors. While the flight time of each airplane is fluctuated due to the variant of temporary factors. Hence, airplanes' flight costs in an OD are assumed to follow a normal distribution $N(\mu, \sigma^2)$. The mean μ is determined by permanent factors between the OD, while the standard deviation σ is affected by the temporal factors. To further validate the assumption, we employed the Kolmogorov-Smirnov test (Fasano and Franceschini, 1987) on all airlines, which is used to verify whether a collection of the flight costs in an airline is drawn from a normal distribution. The result shows that the flight cost distribution of 91.0% of airlines can be regarded as a normal distribution (p-value <0.05).

Based on this assumption, to evaluate whether the flight cost has changed significantly after the conflict, and to prove the dynamic of flight cost is not a random effect caused by varying temporary factors but the constant long-term effect of the detour, the statistical test method is employed to compare the differences between flight costs before and after the conflict of each OD paired airports.

Instead of flight distance, the research employed flight time to represent the air transportation cost. Because the traveling time is widely adopted in modeling flight consumption by the aviation industry (Betts, 1998; Sridhar et al., 2011). Another important factor is the statistical interval. It plays a role in eliminating effects from other events. If the interval is too long, long-term trends like the recovery from COVID-19 (IATA, 2022b) and the seasonal climate variation will take precedence as the main causes of the differences. Oppositely, when the interval is too short, the samples included cannot be sufficient enough to come into statistical conclusions. Considering international airlines usually follow a weekly basis, the research sets 2 weeks as statistical intervals to conduct the statistical analysis. Flights that took off 14 days before 24 February 2022 are recorded into the before conflict dataset to represent the flight cost of each OD in regular condition. Considering most of the air restrictions were issued at the end of February, flights that took off 14 days after 3rd March are recorded into the after conflict dataset to match the day of the week with the before conflict dataset.

One tail T test and Mann–Whitney U test are employed to compare the difference between two temporal intervals. The formulation for the t-test is as follows:

$$t^{OD} = \frac{\overline{X}_b^{OD} - \overline{X}_a^{OD}}{\sqrt{\frac{(n_b^{OD}-1)S_b^{OD^2} + (n_a^{OD}-1)S_a^{OD^2}}{n_b^{OD}+n_a^{OD}-2} \times \left(\frac{1}{n_b^{OD}} + \frac{1}{n_a^{OD}}\right)}} \quad (1)$$

where S^2 is the variance of data, $\overline{X}$ is the mean of data, n_b and n_a

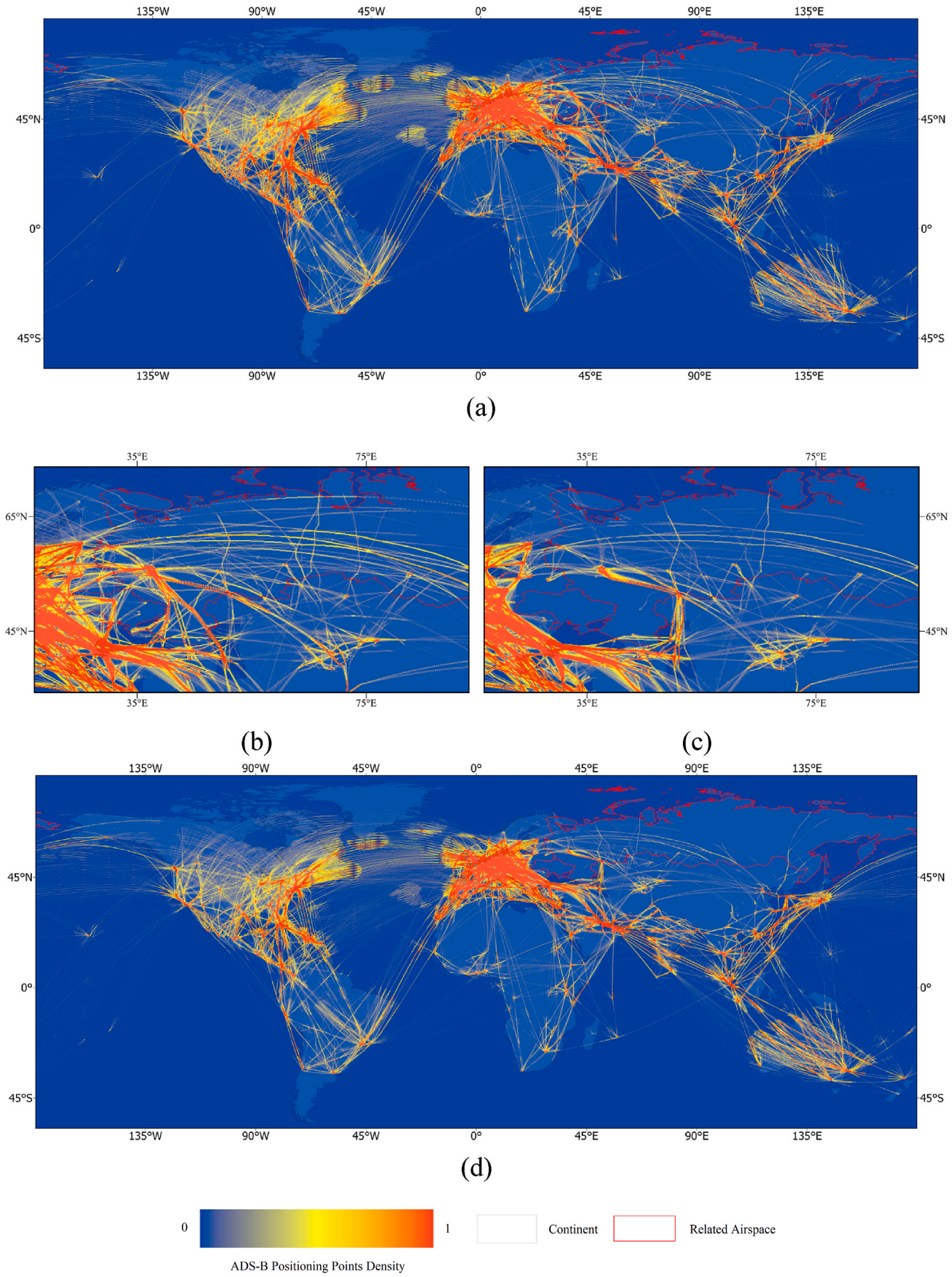

Fig. 2. Global ADS-B positioning points density of international airlines in February (a)(b) and March (c)(d), 2022.

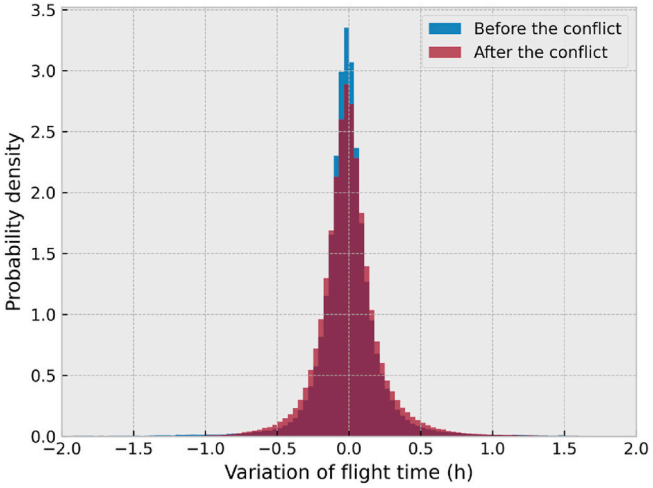

Fig. 3. The probability density distribution of the variation of flight time before and after the conflict.

respectively represent the number of flights before and after the conflict in an *OD*. The basic assumption of the T-test is that the sample mean from the dataset follows a normal distribution, or the samples were sufficiently large enough to justify their use based on the Central Limit Theorem. To satisfy the requirement, only for those ODs that have more than 30 flights in both before and after conflict datasets, we employed a one-side T-test to test whether the flight cost of a specific airline increased after the conflict. When an OD is not a primary airline or it was severely impacted by the conflict, which leads to either of the datasets containing less than 30 sampled flights, we conduct a one-side Mann–Whitney *U* test (Fay and Proschan, 2010) to test the significance of the increment of the flight cost. The nonparametric test is appropriate to the dataset that may not follow a normal distribution. Statistic results of 4 typical ODs are shown in Fig. 4 to illustrate the flight time dynamic.

As shown in Fig. 4, two ODs with flight in limited numbers are shown in the boxplot. With 21 flights in 2 weeks before the conflict and 20 flights in 2 weeks after it, the France to Japan airplane has shown a significant improvement in flight time (p-value < 0.05). For the China to Singapore airline, the p-value of the Mann–Whitney *U* test is greater than 0.05 and the null hypothesis is accepted that the increment did not happen in this OD airline. In Fig. 5, the conflict caused a significant increment in the flight time of airline Canada to Korea. The Switzerland to England airline was not affected and failed to pass the one-side increased T-test. Data in both ODs present a structure of normal distribution.

2.3. Increment index

The restriction policies are carried out by each individual nation, so we further analyzed the severity of influence that each country suffered. Based on the test results of global international ODs, we extracted ODs that flight costs were significantly changed and flight thought the conflict affected airspace before. The flight cost variation in these airlines is believed to be caused by the conflict. To assess the impacts each country suffered quantitatively, we proposed an increment index, which calculates the accumulated increment of all impacted flights of a country.

$$Increment_c = \sum_{a=1}^{N^c} \left(\frac{\sum_{f=1}^{n_b^{OD}} Before_f^{OD}}{n_b^{OD}} - \frac{\sum_{f=1}^{n_a^{OD}} After_f^{OD}}{n_a^{OD}} \right) \times n_a^{OD} \quad (2)$$

In the formula, $Before_f^{OD}$ represents the flight cost of flight *f* in airline *OD*, and so does the $After_f^a$. n_b^{OD}, n_a^{OD} represents the number of flights in airline *OD* before and after the conflict. N^c represents the number of international airlines in country *c*. $Increment_c$ represents the accumulated increment index of flight cost of country *c*. The unit of the index is hours per week. For example, the index for Finland is 96.2 h/week, which means, for every week the conflict continued, in total, airplanes taking off from Finland has to spend 96.2 h more flight time to avoid flying across the closed airspace. As an index that reveals the severity of the impact on a country is affected, the detailed analysis of the index of each country is shown in the result section.

2.4. Traffic analysis

To analyze the dynamic of traffic caused by the conflict, the research conducted a statistical test on the air traffic of each OD. Flight traffic of an airline often follows a weekly schedule, which means the number of flights of the same day in different weeks is directly relevant. Therefore, to test whether the number of flights in an OD was reduced or increased, we conducted a dependent *t*-test for the paired day of 2 weeks before and after the conflict. Two typical airlines are shown in Fig. 6.

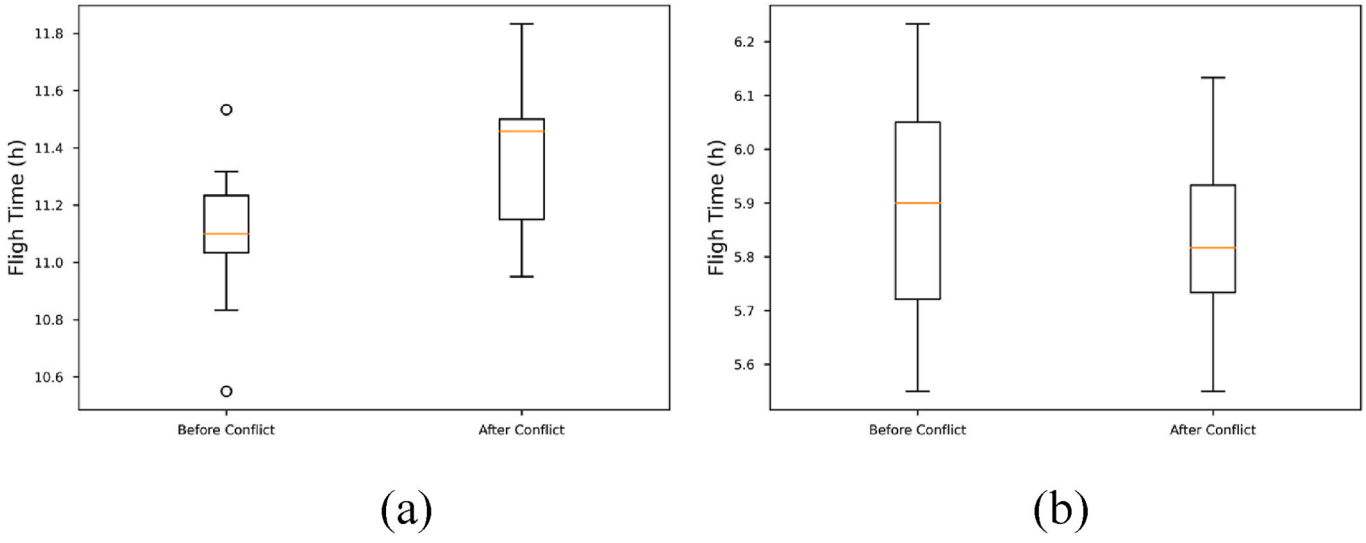

Fig. 4. Boxplot of flight time records in before and after conflict datasets.
(a) Paris, France to Tokyo, Japan (p = 0.0016689). (b) Beijing, China to Singapore (p = 0.76825).

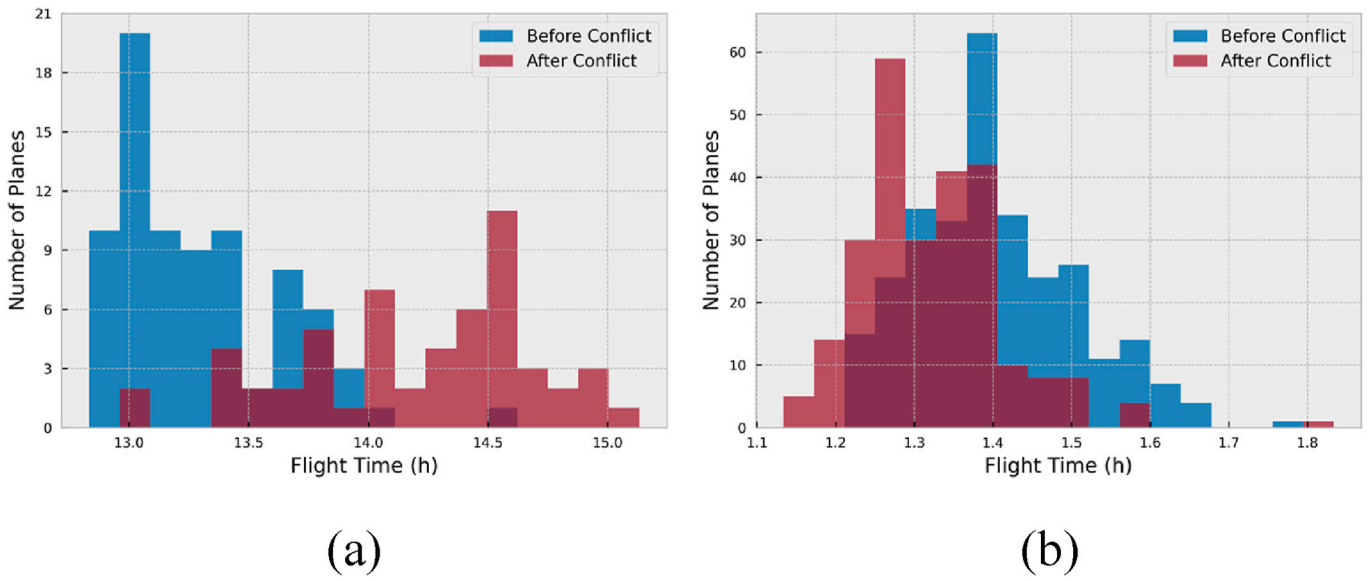

Fig. 5. Histograms of flight time between an OD airport.
(a) Toronto, Canada to Inchon South Korea (p = 2.6488e-17). (b) Geneva, Switzerland to London, the UK (p = 1.0).

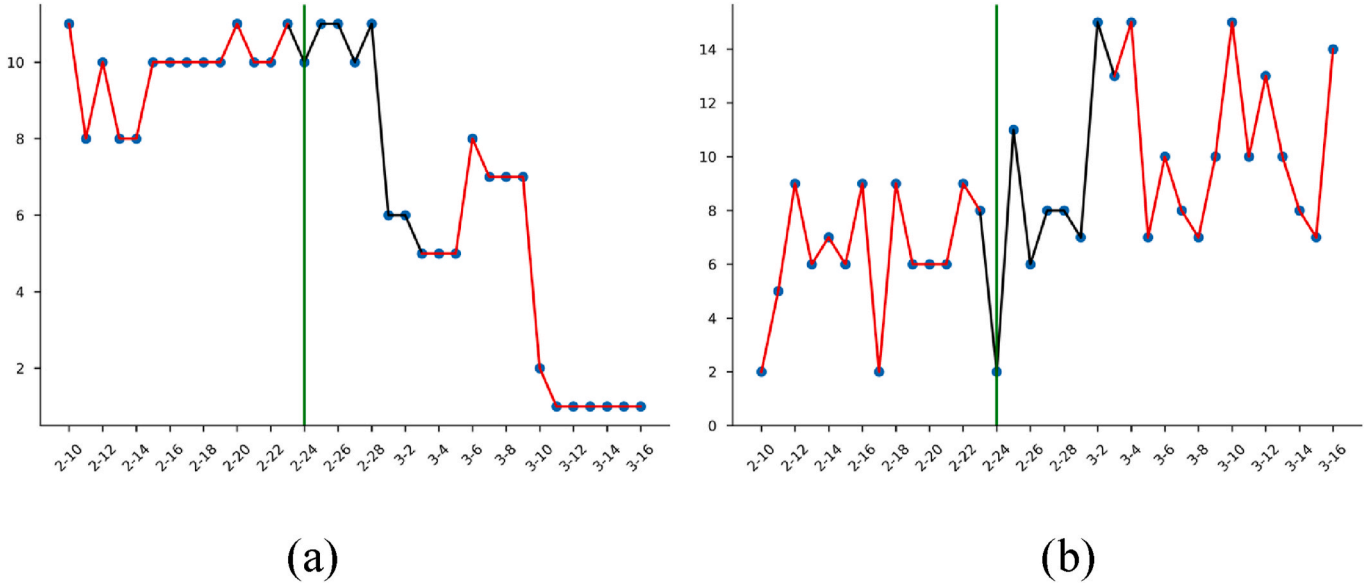

Fig. 6. Variation of flight number in two typical airlines.
(a) Sheremetyevo Alexander Pushkin International Airport (SVO) in Moscow, Russia to Istanbul International Airport (IST) in Turkey (b) Otopeni International Airport (OTP) in Romania to Charles de Gaulle International Airport (CDG) in Paris, France.

Variation in Fig. 6(a) demonstrates how the number of flights from Moscow to Istanbul significantly decreased after the conflict began, with a one-sided dependent *t*-test P value of 0.001. In Fig. 6(b), the number of airplanes from Romania to Paris airline varied oppositely. It presents a significant increase and passed the one-side dependent *t*-test. The increment test and decline test were conducted in all the international airlines.

3. Result

3.1. Flight cost increment

Flying across the Siberia is the quickest path connecting European and the Eastern Asia. And it is also the only way for airplanes from North America to Asia to avoid flying against the strong front wind from jet streams of the northern hemisphere's prevailing westerlies. The closure of broad Siberia airspace made flight costs of related flights increase dramatically to detour the airspace.

By testing the flight time difference before and after the conflict broke out, it was found out that the flight cost of 3.41% of global international airlines has significantly increased ($p < 0.05$). The affected airlines include 6.23% of global flights. And the average increment of flight cost for each airplane is up to 13.32%. As a result, due to the detour of flights caused by the Russia-Ukraine conflict, the global international air transportation cost has increased by 0.637% in total. With global international air transportation continuing its recovery from COVID-19, the affected flights will increase and the extra cost will keep growing in the next few years.

The flight Cost Increment of each country is calculated by formula (1). The top 10 affected countries are listed in Table 2. And we mapped

Table 2
Top 10 affected countries.

Country	Flight Cost Increment Index (hour/week)	Number of Detoured Airlines	Detoured Airline Percentage (%)
Russia	474.3	92	0.5068
Turkey	268.2	21	0.0511
Japan	262.4	15	0.1239
Korea	201.8	17	0.1931
China	190.5	44	0.1260
Germany	133.4	34	0.0355
United Kingdom	124.0	26	0.0257
United States	119.6	26	0.0171
Belarus	102.1	13	0.9285
Finland	96.2	10	0.1111

the number of detoured airlines and the cost increment magnitude of each country to understand the influences the conflict has brought to the world in Fig. 7.

Furthermore, we performed a linear regression between the number of detoured airlines and the increment index, to evaluate the impact severity on each airline. The result is shown in Fig. 8.

As shown in Fig. 8, the result of linear regression can be used to reveal the pattern of the impact suffered by each country. The increment index is largely decided by the number of detoured flight trips and their average detour increment. While the number of detoured airlines refers to the number of airlines that are affected by the conflict, which is decided by the locations of origin and destination airports. The countries lie above the regression line suffered a more severe impact on each affected airline. For example, for airlines take off from Japan, even though there are only 15 airlines are significantly affected, the average detour cost increment of each flight is up to 1.49 h per flight, which is more than twice as high as the global average of 0.65 h per flight. And the countries that are below the regression line stand less increment. From instance, there are 34 airlines are significantly affected in Germany, while the average detour cost increment of each flight is only 0.52 h per flight.

More specifically, according to Fig. 7 and Table 2, with the air travel cost increased by 474.3 h per week, Russia's air transportation is suffering from western sanctions. The military operation directly forbade civil airlines from passing through the war zone, which led to airplanes taking off from western Russia flighting south being forced to detour and entered its neighbor countries' airspace to avoid flying through the combat airspace. Besides the detour, half of its international airlines are forced to detour to avoid the conflict airspace and airspace of the sanctioned country. Besides that, 34.7% of all its airlines were completely stopped, and passengers had to transfer from other countries to achieve their journey. The consumption of transfer is excluded from the detour increment, so the real impact on Russia might surpass the number.

Turkey ranks in second place. It is one of the countries still connected with Russia. 377 flights are traveling between two countries before the conflict per week, and there still has 285 flights per week after that. It also is one of the countries closest to the combat zone. Its northern airspace is directly contiguous to the combat zone in the Black Sea. The forbidden zone forced the airlines between Turkey and Russia to make detours, which leads to an up to 31.7% raise in the flight cost between the two countries. Fig. 8 also proves that there are more sorties of flights in each affected airline, so the accumulated cost increment is higher than average.

As developed Asian countries, Japan and Korea have strong air connections with European and North American countries. The closure of Russian airspace led to a direct impact on their international air transportation. The geographic location of these countries determines most of the shortest flight routes to western countries have to go through Siberia or Caucasus. 12.39% of Japanese and 19.4% of Korean international flights went through Russian airspace before the conflict. Considering the long traveling distance of their flights, even a slight change in their routes can lead to a greater increment. Combined with Fig. 7, we can come into the conclusion that flights take off from countries like Japan and Korea have to pay an extra cost than the global average increment.

Germany and the UK have one of the busiest airports by passenger traffic in Europe, Frankfurt Airport (FRA) and Heathrow Airport (LHR), ranked 4th and 1st respectively. The countries have strong connections

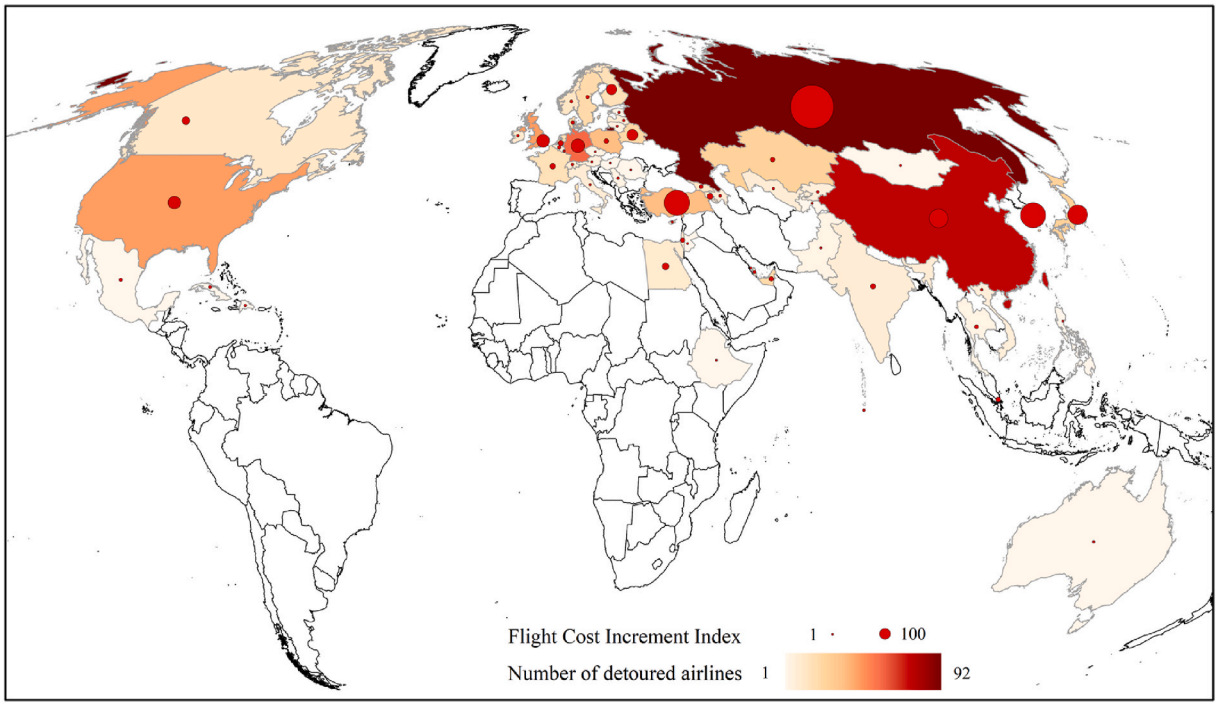

Fig. 7. Global view of flight cost increment and number of detoured airlines.

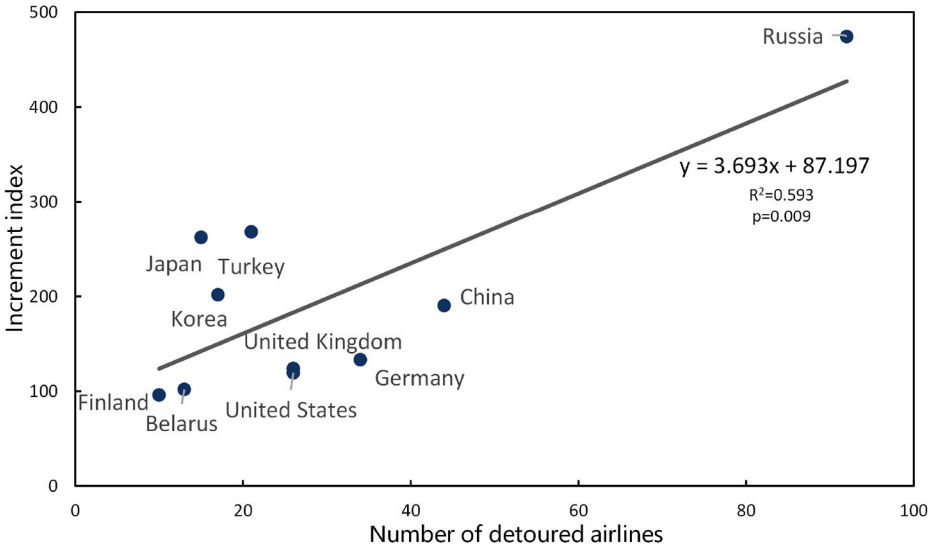

Fig. 8. Linear regression between the number of detoured airlines and increment index.

with Asian countries like Singapore, Japan and India. The closure of airspace forced the airlines to make their way to went through the North Arctic or central Asia, either of which would lead to a significant detour. As the most important global aviation hubs, detours from every global airline will be accumulated to the countries.

China has the highest number of affected airlines, while the increment of the flight cost is relatively low. China is not on the sanction list of Russia, so the only constriction added to Chinese airplanes is the forbidden zone of war. Therefore, the traveling cost of each affected flight taking off from China only raised by 7.25%, which is lower than the global average. Besides, air transportation is still in recovery from the pandemic, and the number of flights traveling by each airline is relatively small. Both effects keep the accumulated increment in a small number.

As for the US, it has the world's largest air transportation network but was not affected severely. Although, 6.19% of its international airlines passed Russian airspace before the conflict. Its geographic location determines that the restriction can usually be avoided with only a small alteration in most flight paths. Consequently, only 1.71% of its international airlines have shown a significant increase in the traveling cost, and the cost only raised by 3.53% for every affected flight.

3.2. Decline in air traffic

The closure of Ukrainian airspace resulted in the country losing all its airlines. And for other countries, the rising flight cost and political sanctions also lead to the decline of airlines. Based on the statistical result of a day of week paired T test, airlines with its daily flight number significantly decreased are extracted. Then, according to planes' trajectories, airlines reduced caused by the direct impact of airspace closure are extracted. As a result, the conflict made 4.32% of global international airlines completely stop. Other than that, 1.45% of global international airlines decreased by 64.4%. Among the declined airlines, 30.8% of them are from countries other than Ukraine and Russia.

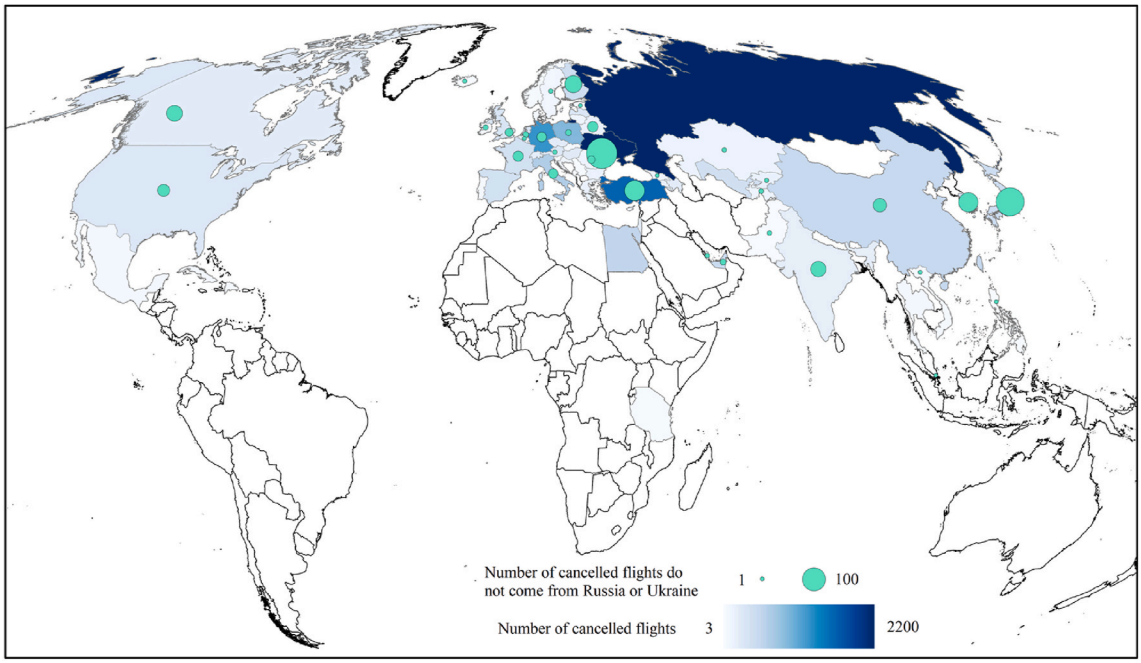

Fig. 9. Number of canceled flights in each country.

Overall, there are 4138 international flights canceled each week due to the impact of the conflict, accounting for 3.17% of the world's total international flights. We also mapped the severity of the decline on the map in Fig. 9.

As shown in Fig. 9, Russian international air transportation was hit most severely by sanctions. 63.0% of Russian international airlines significantly declined ($p < 0.05$), which includes 34.7% completely stopped. The other 4 countries that lost the most flights are Turkey, Germany, Poland and Italy, they are mainly affected by the loss of flights from Russia and Ukraine. This impacts both cargo and passenger transportation, it is estimated by IATA that European cargo volumes in October 2022 saw an 18.8% decrease compared with the same month in 2021, and it is mainly attributed to the conflict (IATA, 2022a).

Except for the reduction of flights from two conflict countries, Moldova, Japan, Turkey, Korea and Finland suffered a loss of 139, 127, 86, 82, 70 flights per week for detours or other reasons. Half surrounded by Ukraine, Moldova lost nearly all its airlines the day the conflict began to avoid the threat of the conflict. But the traffic recovered to a pre-war level in May and even surpassed the pre-pandemic level in June. This is attributable to the refugee crisis. The decline in the other four countries is caused by the dramatic increase in the traveling cost, and it tends to become a long-term effect.

It is worth noting that the increase in flight costs caused by the detour of airlines and the decline in air traffic obviously has an inverse effect on the overall impact on the global air transportation. The canceled flights directly caused by the conflict resulted in a decline of around 16,590 h of flight time per week. The detour caused by the conflict resulted in a raise of around 2802 h of flight time per week. Apparently, the reduced flight time is much larger than the increased. However, there are many other effects may also contribute to the emission, like the increased transfer flights caused by the stopped airlines, the secondary effect of the detour of airlines, recovery of air transportation from the pandemic, etc. These effects are not able to be evaluated through current flight data. Therefore, the overall impact still requires further research.

3.3. Airlines increased

Excepted for the declined airlines, airlines with a raising number of flights after the conflict were also found. These airlines are mostly taking off from the border countries of Ukraine. Considering the airspace of Ukraine was closed right after the conflict began, these increased flights could be a sign of the escaping direction of refugees.

Air transportation is one option for those refugees who tend to travel far. Support from Europe also encourages the choice, for example, Wizz Air offered Ukrainian refugees 100,000 free seats on all continental Europe flights departing from Ukraine's border countries (EU, 2022).

Border countries of Ukraine, Poland, Slovakia, Moldavia, Romania, Hungary and Belarus all accepted a number of refugees after the conflict began. Refugees' evacuation has brought extensive impacts to their aviation. In 3 weeks after the conflict, 107 new airlines were launched, and 22.4% of original airlines departed from these countries have shown significant growth in the number of flights ($p < 0.05$). Overall, there were 734.5 more flights added per week, which leads to a raise of 25.6% compared with the total number before the conflict. Fig. 10 shows the added flight flow of border counties of Ukraine, and Fig. 11 presents the flight flow of Ukraine's border countries in a Sankey diagram.

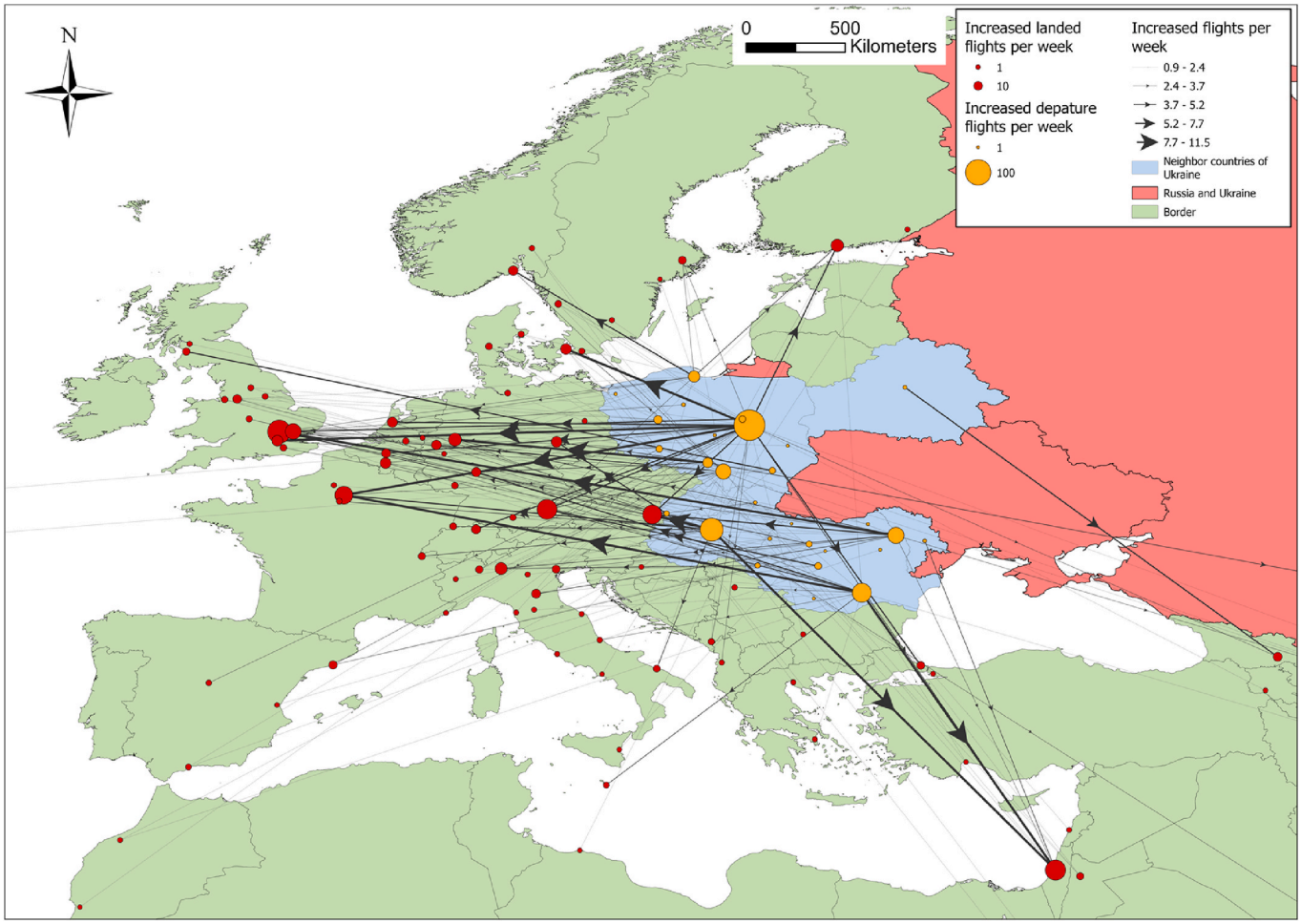

Fig. 10. OD airports flow of added flights after the conflict.

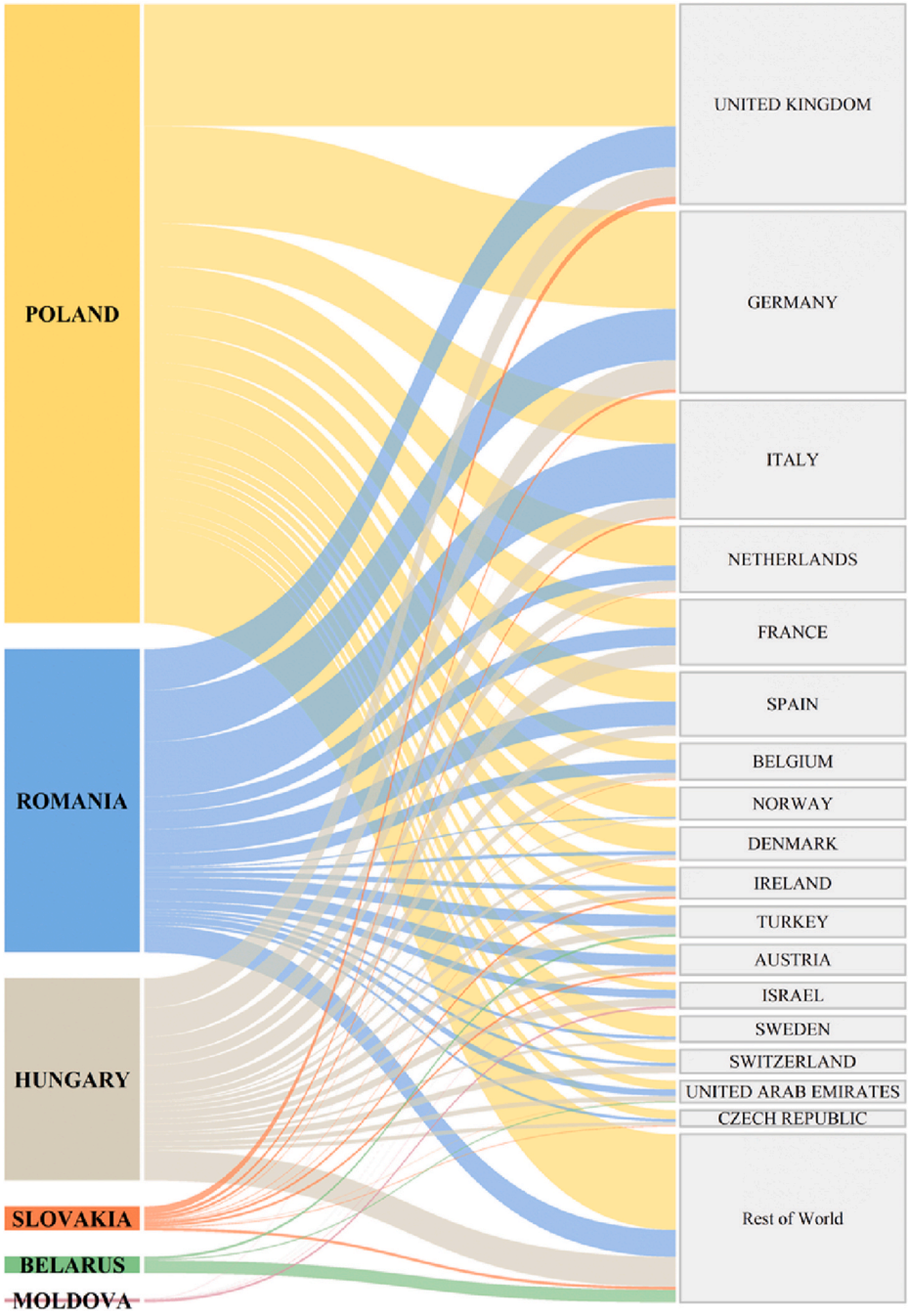

Fig. 11. Total flights flow from Ukraine's border countries after the conflict.

Fig. 10 shows the transition flow of added flights after the conflict. The destination of added flights can partially unravel the refugee flow. In Germany, Munich and Dortmund are the top two destinations for added flights. According to data from the German government, two states these two cities belonged to receive the largest number of refugees in Germany (FOMR, 2022). The coincidence of the two figures illustrates the correlation between destinations of increased airlines and refugees' receiving cities.

Fig. 11 shows the total number of flights departed from Ukraine's border countries. The top receiving countries are the United Kingdom, Germany, Italy and Netherlands. Compared with that, the top destinations countries for added flights are the United Kingdom, Germany, Italy, France and Israel. Considering trains and other public transportation were also offered to refugees for free when going to destinations in a short distance, flights may not be their first option. This explains why the Czech Republic is the top 3 countries that received refugees but only increased a small number of flights. Most refugees took trains or cars to get to the country from Hungary.

As for cities receiving refugees, the destination cities in UK and France are relatively concentrated. 69.2% of added flights to the UK land at London, and 81.7% of added flights arrived at France landed at Paris. The receiving cities in Germany and Italy are more distributed and refugees were not allocated to the biggest city or capital. Munich only landed 30.8% of all added flights in Germany. And for Italy, the largest increment happened in airlines to Milan, the second largest city in Italy, which attracts 24.5% of added flights. The capitals of the two countries Berlin and Rome only attract 1.99% and 3.23% or increased flights.

Most added flights take off from Poland and then Romania. The flight

traffic at Romania's Iasi International Airport (IAS), located near the border of Romania, has increased 4.2 times, which is the biggest increasing ratio in Global airports in March. These phenomena indicate that Poland and Romania serve as the main air transfer stations for refugees and are primary fleeing directions for refugees. The inference is proved by the border crossing data from United Nations High Commissioner for Refugees (UNHCR) (UNHCR, 2022).

As for Moldova, 86.2% of entered refugees left the country (UNHCR, 2022). Although, the air transportation of Moldova was struck in the first few weeks of the conflict, it rapidly recovered to the pre-war level in May. After that, Moldova's air transportation sustained the growing trend and surpassed the pre-pandemic traffic in June. The growth of transportation is believed to be relevant to the evacuation of refugees entered into the country. Therefore, we believed that Moldova served as the refugees' transfer station on land after the first few months of the conflict due to its geographical location. With the conflict stabilized, its order is back on track and it will continue to serve as the transfer station for refugees.

In the north, the number of refugees entered into Belarus is one of the smallest in all European countries. The only increased airline is to Georgia.

The refugee crisis caused by the Russia-Ukraine conflict is called Europe's largest refugee crisis since World War II (Harding, 2022). In this research, we analyzed the added airlines after the conflict. Even if only a small part of refugees is transported by airplanes, the analysis can still provide important details such as the evacuation direction and the destination cities.

4. Discussion

In this research, we unveiled the impacts the Russia-Ukraine conflict has brought to global aviation. Air transportation is more delicate compared with other transportation options. It is easily affected by factors like weather, wind and countries' policy. Even the change of season can lead to a shift in traveling time for most of the aircraft on earth. Therefore, the variation in an airline is the mixture of effects from all factors. To quantitatively evaluate the impact caused by one specific event, effects from temporal events are required to be removed. In this research, we take every OD airline as a statistical unit. Because the expectations of traveling time and traveling distance between each OD are determined by its permanent factors, which are settled down with the airline. Furthermore, we choose 3 weeks as the statistical period before and after the conflict, a relatively short term. It minimizes the influence of other long-term tendencies, such as the recovery of air transportation from COVID-19's strike and the change of wind and climate caused by the spring-to-summer shift. At last, we take flight time instead of flight distance to represent the traveling cost of an airplane, to remove the effect of flight route optimization based on real time factors. These preparations make the variation of temporal factors cannot lead to a significant difference in the two periods. So once the airline is tested to have a significant difference, it can be attributed to the target event.

Conclusions in this research are conducted from the perspective of global airlines. However, from passengers' and goods' perspectives, the traveling destinations for them are hard to extract from data. This made it impossible to measure the increment caused by airline transfers. The situation is suitable for passengers from Russia who tend to go to a banned country. They have to fly to a third country like Turkey or Qatar, the top two destinations for airplanes from Russia after the conflict, and then transfer to their real destinations. So, the actual detour suffered by passengers could be more severe.

After the devastation caused by the COVID-19 pandemic, the world has turned into the recovery phase (IATA, 2022c). Although, the Russia-Ukraine conflict has caused tons of negative effects on global international aviation, international air transportation in most countries is still growing dramatically (IATA, 2022b). With more airplanes forced to detour from the constricted airspace, the increased traveling cost will definitely rise. What is worth mentioning is that Russian airspace is opened to civil airlines in the 1990s after the collapse of the Soviet Union. The opening of airspace has earned the government lots of money for charging the passing airplanes. And the opening also boosted the international airline by saving a lot of time for global traveling. As the conflict raged higher, it seems that the closure of Russian airspace would have a more enduring impact on the world's air transportation.

In this research, we explore the added airlines after the conflict began to partially reveal the evacuation directions and destinations of refugees. What is worth to mention is that, the transportation capability of aviation is limited compared with the land transportation. Therefore, the refugee flow revealed by aviation data can only represent part of the mobility pattern of refugees. To validate the utility of the airline data, we combined our analysis with the official refugee data from the UNHCR. The result shows that the number of added flights is strongly correlated with the officially recorded number of refugees in European countries. This verifies the representativeness of aviation data at the national scale. As for the city scale analysis, we verify the result by analyzing data from the German government, in which it mentioned that in Germany Munich and Dortmund are top two destinations for Ukrainian refugees, this is same as the result we get from aviation data. Verification from two official datasets support the result of the research, so the analysis could be instructive in some extent. At the same time, we also have to admit that the limitation is obvious, the aviation transportation only carried very few parts of refugees, and the result is hard to validate through detailed official data, because it is hard to collect and narrowly published.

5. Conclusions

In this research, we analyzed the impacts the Russia-Ukraine conflict brought to global aviation transportation. The closure of airspace is one of the direct impacts caused by the conflict. For international civil aviation, the forbidden airspace can be divided into two parts. The first part is the combat zone, which includes all Ukrainian airspace and part of the airspace on the Black Sea. The second part is the airspace of Russia. It was closed to all the EU counties and several other "unfriendly countries". The closed airspace forced airlines to come across the area and changed their regular shortest routes. It forced 6.23% of global flights to make detours, which leads to a 0.637% increment in the total cost of global international air transportation. This increment will still exist as long as the airspace of Russia is closed to certain countries. On the other hand, the conflict made 4.32% of global international airlines completely stop and the number of flights in 1.45% of global international airlines decreased by 64.4%. In total, 3.17% of international flights are canceled globally. The raised flight cost and declined airlines delay the recovery of global air transportation from COVID-19. Combined with the impact of rising jet fuel prices caused by conflict, global international aviation costs have increased dramatically. Over $528.3 million extra cost will be paid for the detour.

By quantitatively evaluating the impact on each country, this study also assessed the flight cost increment and the decline of airlines due to the conflict. The result unveiled that the detour and decline of airlines in each country are decided by their geographical locations and development levels of aviation. There are two major airlines affected most severely. The first one is the airline connects Asia and European. The other airline is from the North America to Eastern Asia. As a result, Japan, South Korea, Finland and even Singapore are countries that suffered the most from the closure of the Siberia airspace. Turkey and Belarus are suffering from detouring caused by the threat of combat airspace.

We also analyzed the refugee crisis in the conflict. Refugees have significantly increased the air traffic in Ukraine's neighboring countries, 734.5 flights were added per week in the first month of the conflict. And the increasing trend in some of those airports remained even until the end of the year 2023. The evacuated refugees mainly landed at London,

Paris, Munich, Vienna and Dortmund. Combined with the UNCHR refugee data, we confirmed that Poland and Romania are the main fleeing directs for refugees who tend to go further by airplane. And refugees who fled to Hungary are more likely to take trains or cars to their next stops.

As global aviation continuously recovering from the COVID-19 and the war keeps going on, the closure of airspace will affect more international flights, and the impact of the conflict will definitely keep affecting the recovery of global air transportation. The research provides a framework for analyzing the global impact caused by a specific aviation event. As far as we know, even though many news reports have called for people's attention on the impact the conflict has brought to air transportation, there are very few researches focus on quantitatively analyzing it. We hope our research could be instructive to relevant researchers and the public. And the framework of analyzing could be extended to other events.

Author statement

Chen Chu: Conceptualization, Methodology, Programming.
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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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