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Impact of entry restriction policies on international air transport connectivity during COVID-19 pandemic

Siping Li^a, Yaoming Zhou^{a,*}, Tanmoy Kundu^b, Fangni Zhang^c

^a Department of Industrial Engineering & Management, Shanghai Jiao Tong University, Shanghai, China

^b The Logistics Institute - Asia Pacific, National University of Singapore, Singapore

^c Department of Industrial and Manufacturing Systems Engineering, University of Hong Kong, Hong Kong, China

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ABSTRACT

The COVID-19 pandemic has seriously impacted the air transport network (ATN) globally. Policies to restrict international passenger arrivals adopted by many countries are effective responses to control the spread of the virus. This paper studies the impact of two entry restriction policies implemented by some countries against international travelers during COVID-19, i.e., direct flight suspension and complete entry suspension, on the international connectivity (IC) of ATNs. Firstly, the concept of international air transport network (IATN) is defined, and a novel weighted IC index for ATNs is proposed considering flight frequency. Furthermore, to systematically analyze the difference between two policies, the hierarchical structure of the IATN is investigated, followed by studying the change of the IC index assuming different countries impose the two policies. Taking China as an example, this paper evaluates the influence of two policies based on real policy implementation of some countries against travelers from China. Besides, the critical countries affecting the IC are identified, and the network robustness is assessed. Implications for assessing and ranking the impact of different countries under different policies are provided and discussed. Lastly, two extensions are presented to discuss the impact of partial suspension and response actions such as air travel bubble. This work is one of the first to study the impact of country-to-country disconnection on air transport connectivity and deepens our understanding of the performance of ATNs during emergencies.

1. Introduction

The COVID-19 pandemic is an unprecedented global public health emergency that has caused worldwide disruptions to lives, the economy, and businesses. So far, COVID-19 has infected more than 155 million people, with over 3 million deaths globally.¹ Under such fatal circumstances, many countries implement targeted policies to prevent the spread of the disease, including national lockdown, inbound quarantine, international flight suspension, and entry ban to affected areas. These strict restriction policies have greatly influenced the international air transportation industry. Many countries largely reduced their international flights, and some airlines unexpectedly went bankrupt during the pandemic (Suau-Sanchez et al., 2020). The extensive flight disruption results in a sharp decline in the performance of the worldwide air transport network (WATN), and one of the major manifestations is that many countries have

* Corresponding author.

E-mail addresses: lisiping1996@sjtu.edu.cn (S. Li), iezhou@sjtu.edu.cn (Y. Zhou), tltk@nus.edu.sg (T. Kundu), fnzhang@hku.hk (F. Zhang).

¹ Worldometer COVID-19 coronavirus pandemic, <https://www.worldometers.info/coronavirus/> (Accessed 6 May 2021).

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lost connections with some other countries. This country-to-country disconnection is so rare that it has not appeared in the air transportation field before this pandemic.

As is known to all, China is one of the earliest to be affected during the pandemic. Since the emergence of an unknown infectious disease in Wuhan, China has experienced a challenging journey to fight against the COVID-19 pandemic. As of January 31, 2020, more than 10,000 confirmed cases had been reported in China.² Meanwhile, with the consideration of domestic safety, many countries and regions imposed entry restrictions on inbound travelers from China or with a recent travel history to China. For instance, Iran canceled all direct flights with China, except connecting flights via third countries. Singapore introduced the policy that all new visitors, regardless of nationality, with recent travel history to mainland China within the last 14 days, are not allowed entry into or transit through Singapore.³ Typically, there are two main types of entry restriction policies: direct flight suspension as imposed by Iran, and the other is complete entry suspension as imposed by Singapore. Intuitively, for the direct flight suspension policy, travelers from China can still fly to the target country with a stopover in another country that plays the role of a bridge. However, for the complete entry suspension policy, travelers with recent travel history in China cannot enter the target country by any means and are unable to use the flights concerning the countries implementing this policy.

To the best of our knowledge, the impact of entry restriction policies on the performance of the ATN has not been studied in the literature. Therefore, motivated by this special country-to-country flight disconnection and entry restriction policies, we seek to address the following three problems:

- (1) How to characterize this country-to-country disconnection scenario based on the existing ATNs?
- (2) How to quantify the performance change of the ATN when one country implements an entry restriction policy? In extension, how does the performance change when some countries cumulatively make entry restriction policies?
- (3) What is the difference between the two entry restriction policies when being implemented by different countries?

This paper considers Mainland China (China for short in this article) as an example to illustrate a comprehensive method for analyzing the impact of entry restriction policies on the international connectivity of one country's air transportation during the COVID-19 pandemic. The contributions of this paper are four-fold. First, the concept of international ATN (IATN) is proposed to facilitate the characterization of the features on country-to-country disconnections caused by entry restriction policies. Second, a novel weighted international connectivity index is put forward to quantify the network performance of IATNs with consideration of flight frequency. Third, a network layering method is proposed to explore the hierarchical structure of IATNs and the role of different countries (belonging to different layers of the hierarchical network) in the network performance. Finally, the corresponding methods are applied to the Chinese international air transport network (CIATN) to find critical countries and evaluating network robustness under these two entry restriction policies.

The remainder of this paper is outlined as follows. In [Section 2](#), the related literature is reviewed. In [Section 3](#), firstly, the CIATN is defined, and the method used to evaluate the network performance is provided. Then, the network disruption caused by two entry restriction policies is modeled, and the impact of the policies in COVID-19 is presented. In [Section 4](#), a network layering method is applied to systematically analyze the difference between the two policies and the robustness of the CIATN. [Section 5](#) provides discussions on the results and implications. [Section 6](#) presents two extensions on the impact of partial suspension and response actions. [Section 7](#) concludes this study and provides future research directions.

2. Literature review

To highlight this study's positioning and contribution, we review the relevant literature around the connectivity of air transportation and the policies regarding air transportation.

2.1. Air transportation connectivity

The previous studies on the connectivity of air transportation can be divided into two parts. One is from the perspective of airports or cities, and the other is from the perspective of the entire air transportation network (ATN).

The first set of studies explore airports or cities and evaluate the connectivity with consideration of economic factors, operation efficiency, location, and traffic flow, among others. For example, [Matsumoto et al. \(2016\)](#) studied the effect of business connectivity between cities on their air traffic connections and urban hierarchy in East Asia. The results show that intense economic development provides a stronger role in air transport connectivity. [Zhang et al. \(2017\)](#) evaluated the connectivity of 69 Chinese airports and their variation during the period 2005–2016. They found that business cycles and large events influence the airline industry and airport connectivity a lot. [Boonekamp and Burghouwt \(2017\)](#) presented an air freight connectivity model to analyze seven European airports. They found that location is a very significant factor in the connectivity of air freight. [Zhu et al. \(2019\)](#) measured the air transportation connectivity between China and Australia and analyzed the key airports. They discovered that Chinese airlines have made major contributions to the air connectivity between the two countries. [Wang et al. \(2020a,b\)](#) studied air and rail connectivity in China by various statistical and regression approaches. They investigated the city-cluster connectivity patterns and found that improved intra-

² World Health Organization, <https://covid19.who.int/table> (Accessed 19 October 2020).

³ National Immigration Administration of China, <https://www.nia.gov.cn/> (Accessed 19 October 2020)

city-cluster rail connectivity further deteriorates the air-connectivity disparity.

Another set of studies focus on the connectivity of the entire ATNs and employ network topology metrics (such as node degree, node betweenness, clustering coefficient, average shortest path length, and network efficiency) to assess their performance (Wang et al., 2016; Zhou et al., 2021a,b). By representing the ATNs as complex networks, connectivity is defined as the degree to which an airport in a network is connected to other airports (Burghouwt and Redondi, 2013; Wang et al., 2019). Paleari et al. (2010) developed a time-dependent minimum path approach to compare the connectivity of the ATNs in China, Europe, and the U.S. They found that all three networks have small-world structures, with similar degree distributions and clustering coefficients, while the European network possesses the highest percent of destinations. Wei et al. (2014a,b) studied the algebraic connectivity of the ATN and presented the network design strategy to maximize network algebraic connectivity. Allroggen et al. (2015) investigated network structure and performance as well as air transportation market developments to construct a connectivity model. They answered how air transport connects the world and observed the changing trends of connectivity and hub centrality. Zhou et al. (2019a) assessed the connectivity of weighted ATNs using a novel efficiency metric by considering link capacity. They also compared the weighted efficiency with the unweighted efficiency of eight domestic ATNs. Cheung et al. (2020) proposed a global airport connectivity index (GACI) to analyze the evolution of the world air transport network from 2006 to 2016. This index combines degree, closeness, eigenvector, flow betweenness, and regional importance that captures a broad range of air transport network properties. Furthermore, the concept of connectivity is widely used in evaluating the performance of the ATN under disruptions, containing robustness (Lordan et al., 2014; Sun et al., 2017; Zhou et al., 2021a,b), vulnerability (Voltes-Dorta et al., 2017; Li et al., 2019), and resilience (Clark et al., 2018; Zhou et al., 2019c; Wong et al., 2020).

2.2. Air transportation policies

Air transportation policy is a broad topic involving economics, engineering, and the environment that has attracted considerable attention among researchers and practitioners. However, there is not much research on the impact of policies on air transportation connectivity. Fageda et al. (2018) reviewed and discussed the existing transport policies worldwide to provide air connectivity to remote areas, including route-based policies, passenger-based policies, airline-based policies, and airport-based policies. Zhang et al. (2018a,b) built an improved indexing system to measure the openness of Chinese international air transportation policy. The analysis demonstrated that the degree of openness in June 2016 was three times that in 2000 and most partners are high- and upper-middle-income countries. Choi et al. (2019) explored the managerial and policy implications of air passengers' transfer airport choice in the Southeast Asia – North American market. They found that service quality, minimum connection time, and the number of international passengers play critical roles, in addition to traditional factors such as travel time and airfare. Other policy applications concerning air transportation consist of competition and cooperation between air transportation and high-speed rail (Xia and Zhang, 2016; Zhang et al., 2018a,b; Jiao et al., 2020a; Jiao et al., 2020b; Wang et al., 2020b), air cargo industry (Gong et al., 2018; Malighetti et al., 2019; Wang et al., 2020a), and environmental benefits (Martini et al., 2013; Dai et al., 2018; Miyoshi and Fukui, 2018; Qiu et al., 2020).

In summary, most of the previous studies concentrate on air connectivity assessment from the perspective of airports (cities) or the entire ATN, and there is little research on the air connectivity between one country and the others from an international viewpoint. Moreover, none of the previous studies on air transportation discussed the impact of entry restriction policies on the international connectivity of ATNs in a global pandemic like COVID-19. To address the research gap, we present a comprehensive framework to study the international connectivity of the ATN when facing disruptions caused by country-to-country disconnections. Besides, an index of international connectivity and a method for hierarchical structure analysis are utilized to study the impact of entry restriction policies on the international connectivity of the COVID-19 pandemic-disrupted ATNs. Further, the critical countries affecting the connectivity and the robustness of the international ATN are analyzed in detail based on the case of China.

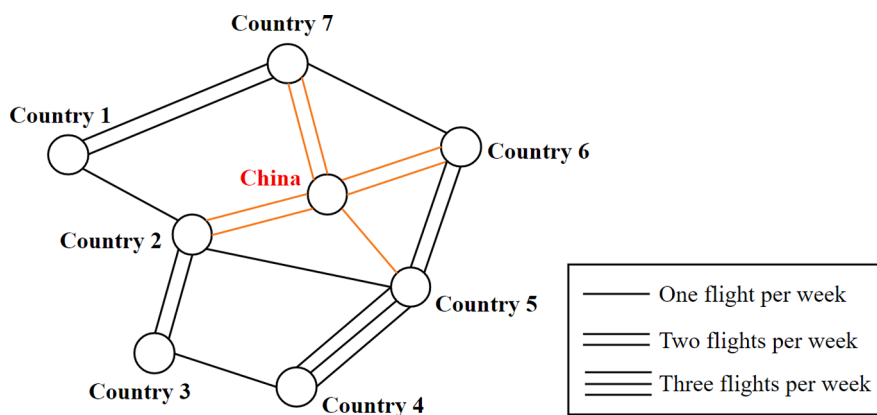


Fig. 1. A simple illustration of the Chinese international air transport network (CIATN), where the number of links between nodes represents the weekly flight frequency.

3. The connectivity of the CIATN in the COVID-19 pandemic

In this section, the CIATN is defined at first. Next, a novel international connectivity (IC) index is proposed to measure the connectivity of the CIATN, and network disruptions caused by two entry restriction policies are analyzed. With these preparations, the connectivity of the CIATN is assessed in different scenarios during the COVID-19 pandemic.

3.1. The definition of the CIATN

During the COVID-19 pandemic, many countries or regions have partially or completely shut down their international flights. To better characterize this type of country-to-country disconnection, the Chinese international air transport network (CIATN) is defined based on the worldwide air transport network (WATN).

As mentioned in previous research (Guimera et al., 2005; Lordan et al., 2014; Cheung et al., 2020), the WATN can be regarded as an undirected network that is made up of nodes (airports or cities) and edges (flight connections). The capacity weight of the edge is the number of scheduled flights between two nodes (Zhou et al., 2019a). Analogously, we model the CIATN as an undirected network where nodes denote countries (in the CIATN), and there is an edge between two nodes if there are direct flights between them. Further, the number of scheduled flights is considered as the capacity weight of the corresponding edge (which represents the country-to-country connection). Fig. 1 gives a simple illustration of the CIATN. In Fig. 1, the number of links between two nodes denotes the corresponding capacity weight. The orange and black links are the flights connecting China and flights between other countries, respectively. For example, the double orange lines connecting China and Country 2 represent two (weekly) scheduled flights between them. The single black line connecting Country 1 and Country 2 indicates that there is only one (weekly) scheduled flight between them. In this way, the connection strength between different countries can be differentiated, which proves to be an important feature in later analysis. Notice that the CIATN consists of not only the connections involving China but also the connections between other countries. Hence, the countries which do not have direct flight connections with China also influence the transportation between China and the other countries by acting as bridges, so they are part of the CIATN as well. It is worth mentioning that only airports in Mainland China are included in the node China, while the others are all connected with the node China by international flights.

3.2. An international connectivity (IC) index

The international connectivity measures the connection level between one country and all the other countries or regions in the world. To quantify this property, an IC index is proposed based on Network Efficiency.

Network Efficiency (E) is a widely used metric for evaluating the connectivity of the ATN and it portrays the interaction between nodes in a network (Zhou and Wang, 2018; Wang et al., 2019; Zhou et al., 2019a,b). According to Latora and Marchiori (2001), Network Efficiency is the average of the reciprocal of the shortest path length between two generic nodes in a given network G :

$$E = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}}, \quad (1)$$

where d_{ij} is the shortest path length between node i and node j , and N is the number of nodes in G . If G is an unweighted network, d_{ij} equals to the number of links in the corresponding shortest path. Besides, $d_{ij} = +\infty$ when node i and j are disconnected.

Next, the definition of the IC index is proposed. Fig. 2 shows a schematic diagram of the unweighted CIATN. In Fig. 2, all the nodes in the CIATN are divided into two parts: (1) the node representing Mainland China; (2) the nodes representing other countries, denoted by set O . Then, by modifying Network Efficiency, the IC index can be defined as

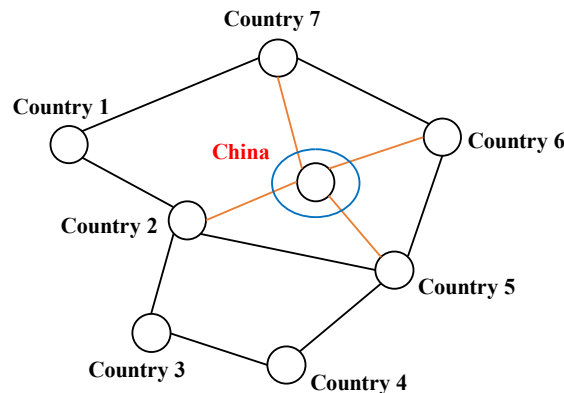


Fig. 2. A schematic diagram of the unweighted CIATN.

$$IC = \frac{1}{C_1^1 * C_{|\mathbf{O}|}^1} \sum_{j \in \mathbf{O}} \frac{1}{d_{China,j}}, \quad (2)$$

where $d_{China,j}$ is the number of links in the shortest path from node China to nodes in set \mathbf{O} , and $|\mathbf{O}|$ is the number of elements in set \mathbf{O} . After simplification, Eq. (2) can be rewritten as

$$IC = \frac{1}{|\mathbf{O}|} \sum_{j \in \mathbf{O}} \frac{1}{d_{China,j}}. \quad (3)$$

From Eq. (3), we can find that the range of IC is $[0, 1]$. If China has direct flights with all other countries, the value of IC will be 1. On the contrary, if China is isolated from all other countries, the value of IC will be 0.

Further, to consider the difference in flight frequency between airports, we extend IC to weighted ATNs and propose a novel weighted IC index (WIC). The main idea of this method is to decompose the weighted CIATN into several unweighted subnetworks at first, then calculate the IC value of each unweighted subnetwork according to Eq. (3), and eventually sum up all IC value to obtain the value of WIC . The formulation is as follows:

$$WIC = IC_1 + IC_2 + \dots + IC_n, \quad (4)$$

where n is the maximum number of direct flights between China and other countries.

An example of this network decomposition procedure is shown in Fig. 3. For each connected node pair in the weighted network, one connection link between them is taken out to construct the first unweighted network. This process repeats on the remaining weighted network until there are no direct flights between China and other countries. Following this decomposition procedure, the weighted network in Fig. 3 can be decomposed into two unweighted networks.

To normalize the weighted IC index, let \widehat{WIC} be the ratio of the corresponding WIC to that at the pre-pandemic stage. It follows

$$\widehat{WIC} = \frac{WIC}{WIC_0}, \quad (5)$$

where WIC_0 is the weighted IC index at the pre-pandemic stage.

3.3. Entry restriction policies and network disruption

3.3.1. Direct flight suspension

If one country imposes the policy of direct flight suspension with China, all direct flights between this country and China will be interrupted. However, passengers from China can still go to this country by having a stopover in another country. Therefore, to describe the influence of this policy on the CIATN, the direct flights between China and the corresponding country are disrupted all at once. Fig. 4 depicts this case wherein Country 2 suspends all direct flights with China, and all the two flights between China and Country 2 are removed from the CIATN.

3.3.2. Complete entry suspension

The influence of complete entry suspension on the CIATN is much more complex than that of direct flight suspension. If one country (consider the case of Singapore) takes the policy of complete entry suspension of passengers (or with recent travel history) from (to) China, then all passengers from China will not be allowed to enter or transit through this country.⁴ Reflected on air transportation, complete entry suspension includes: (1) the direct flights between this country and China are suspended; (2) passengers from China cannot have a stopover in another country to enter this country; (3) it is impossible for passengers from China to transit through this country to other countries and regions. Therefore, all international flights of this country should be disrupted when evaluating the connectivity of the CIATN. Fig. 5 illustrates the case when country 2 takes the policy of complete entry suspension. The removed flights of the CIATN contain not only the links between Country 2 and China but also the links between Country 2 and all other countries.

3.4. The impact of entry restriction policies on IC

In this section, entry restriction policies implemented by different countries during the outbreak of COVID-19 in China are applied to evaluate their impact on the connectivity of the CIATN.

3.4.1. Data preparation

The data of flights used in this paper are obtained from the aviation data provider Official Airline Guide (OAG) (<https://analytics.oag.com/>). Considering the minimum period of flight scheduling, the flights in one specific week at the pre-pandemic stage are utilized

⁴ Note that the entry restriction in this study only considers the complete entry suspension policy imposed by certain countries on the passengers from China or with a recent travel history to China (Within 14 days). Some cases where a passenger can serve a quarantine of 14 days in a third country and then connect to these countries (who imposed entry suspension policy) have not been considered and thus warrant further research.

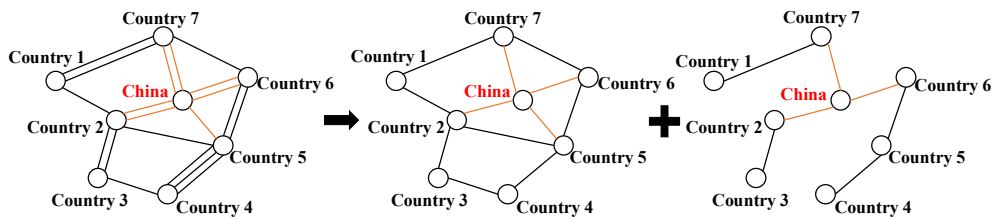


Fig. 3. The example of the network decomposition procedure.

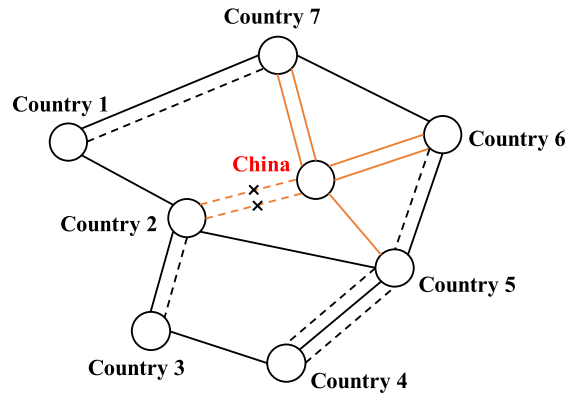


Fig. 4. A case of network disruption caused by direct flight suspension.

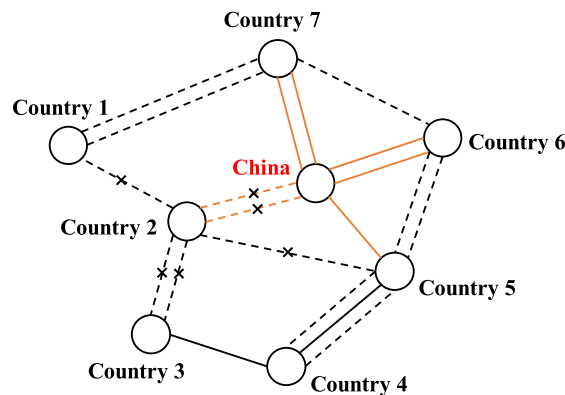


Fig. 5. A case of network disruption caused by complete entry suspension.

to construct the CIATN, which includes 720,137 commercial flights linking 3909 operating airports worldwide from November 21 to November 27, 2019. Each record of the 720,137 flights consists of the following information: departure airport IATA code, arrival airport IATA code, airline IATA code, and flight number. Among them, there are 221,799 international flights. After combining different airports in the identical country and summing up the number of flights, the CIATN is constructed with 228 nodes (countries or regions) and 2638 edges (international connections). The average weight of all the edges is 84.08, indicating approximately 84 weekly scheduled direct flights between any two countries (or regions) in the world on average. However, only 484 edges' weights are larger than the average weight, and there are 906 edges only having no more than ten scheduled flights. Hence, we can find that the distribution of capacity weight on the CIATN is highly uneven. Furthermore, the edge between China and Japan has the largest capacity weight (3020) in the CIATN, which means that 3020 weekly scheduled flights are operating between the cities of China and Japan.

The entry restriction policy data used in this paper comes from the National Immigration Administration of China (<https://www.nia.gov.cn/>). According to the announcement on 6 February 2020, 8 countries had imposed the policy of direct flight suspension on China, and as many as 24 countries adopted complete entry suspension measures. The corresponding countries are listed in Table 1.

3.4.2. The impact analysis

To begin with, we calculate the IC index of the CIATN in the pre-pandemic stage based on 2019 flight data. By decomposing the

Table 1
Countries imposing entry restriction policies on China during COVID-19.

Policy	Country			
Direct flight suspension	Iran	Israel	Italy	Kazakhstan
	Kyrgyzstan	Maldives	Oman	Uzbekistan
Complete entry suspension	Antigua and Barbuda	Australia	El Salvador	Equatorial Guinea
	Fiji	Grenada	Guatemala	India
	Indonesia	Iraq	Jordan	Kuwait
	Marshall Islands	Mauritius	Micronesia	Mongolia
	New Zealand	North Korea	Philippines	Seychelles
	Singapore	Suriname	United States	Vietnam

CIATN into 3020 unweighted subnetworks and summing the IC index of all these subnetworks, eventually, the WIC_0 of the CIATN is 165.83.

Next, all the links between China and the eight countries implementing direct flight suspension policy are removed from the CIATN. By assessment, the WIC of the remaining CIATN is 165.27. It means that the disruption only incurs a 0.34% decline in the connectivity of the CIATN. Further, the connections between China and each of these eight countries are interrupted individually. The variation of \widehat{WIC} and some aviation information is shown in Table 2. As shown, Italy has the greatest effect on the connectivity of the CIATN, and the number of flights with China is the highest of these eight countries. We can find that the ranking of flight frequency with China is relatively consistent with the ranking of policy impact. The number of connected countries also has some influence on the IC due to hierarchy. However, the total number of international flights seems to have a weaker influence.

For the evaluation of the complete entry suspension policy, all international flights of the corresponding 24 countries are interrupted in the CIATN. The WIC of the residual CIATN is 109.13. We can find that the complete entry suspension policy incurs a 34.19% decline in the connectivity of the CIATN, which is far more than that caused by direct flight suspension. The reasons are: (1) more countries take complete entry suspension than those suspending direct flights with China during the outbreak of COVID-19; (2) the complete entry suspension not only influences the connection between the corresponding country and China but also results in a reduction in aviation accessibility of China with some other countries. Table 3 shows the change in \widehat{WIC} when these countries implement complete entry suspension policy separately. We can see that the disconnection with the United States will bring a 18.71% decline on \widehat{WIC} , which is much larger than that caused by the disconnection of other countries. Countries that occupy important positions in global air transportation or have plenty of weekly flights with China are also in the top 5. Besides, an interesting finding is that those countries which do not have direct flights with China still impact the connectivity of the CIATN, such as El Salvador and Kuwait. This is because the transfer to/through those countries is restricted by complete entry suspension.

4. The hierarchical structure of the CIATN

To systematically assess the impact of the potential implementation of entry restriction policies by different countries, the hierarchical structure of the CIATN is analyzed. Based on that, the connectivity decline of the CIATN resulted from the network disruption caused by two policies of different countries inside the hierarchical network is evaluated. Then, the necessity of taking flight frequency into account and assessing network connectivity using the proposed weighted IC index is demonstrated via the comparison with the analysis on unweighted networks. Furthermore, the critical countries are identified, and the robustness of the CIATN is examined.

4.1. Network hierarchy

Seeking to gain the big picture of the influence of entry restriction policies by different countries on the international air transportation of China, a new method for layering the CIATN and positioning different countries according to their air connections with China is proposed. The hierarchizing procedure is as follows.

Step 1: All countries which have direct international flights with China constitute Layer 1. This layer includes the countries that can potentially implement the policy of not only direct flight suspension but also complete entry restriction during the outbreak of COVID-

Table 2
The impact of direct flight suspension on the connectivity of the CIATN.

Rank	Country	Percentage decrease of \widehat{WIC}	Weekly number of flights with China	Number of connected countries	Total number of int'l. flights
1	Italy	0.1438%	92	85	13,708
2	Kazakhstan	0.0610%	46	29	884
3	Iran	0.0451%	34	30	1044
4	Israel	0.0239%	18	50	2465
5	Uzbekistan	0.0239%	18	26	641
6	Maldives	0.0185%	14	20	521
7	Kyrgyzstan	0.0106%	8	8	350
8	Oman	0.0106%	8	33	2174

Table 3
The impact of complete entry suspension on the connectivity of the CIATN.

Rank	Country	Percentage decrease of \widehat{WIC}	Weekly number of flights with China	Number of connected countries	Total number of int'l. flights
1	United States	18.7148%	576	101	29,239
2	Vietnam	2.3602%	690	25	4755
3	Singapore	2.2332%	728	45	7159
4	India	2.1783%	128	56	7675
5	Australia	1.7944%	330	36	3931
6	Indonesia	1.4623%	353	26	4495
7	Philippines	1.4358%	430	28	3451
8	New Zealand	0.7650%	86	26	1473
9	El Salvador	0.4276%	0	14	910
10	Kuwait	0.4026%	0	31	2203
11	Iraq	0.3803%	2	26	1307
12	Guatemala	0.2417%	0	10	582
13	Jordan	0.2187%	0	39	1279
14	Fiji	0.1540%	0	16	262
15	Antigua and Barbuda	0.1009%	0	19	374
16	Mongolia	0.0956%	32	8	130
17	Mauritius	0.0805%	4	20	400
18	Seychelles	0.0557%	0	15	151
19	Grenada	0.0540%	0	6	130
20	Suriname	0.0442%	0	9	122
21	North Korea	0.0425%	16	2	20
22	Equatorial Guinea	0.0230%	0	11	102
23	Micronesia	0.0123%	0	3	24
24	Marshall Islands	0.0106%	0	4	24

19.

Step 2: If passengers from China need to transit through one country in Layer 1 to the destination country, this destination country is classified in Layer 2. For these countries, the possibly conducted entry restriction policy is only the complete entry restriction because they do not have direct flights with China.

Step 3: If passengers from China need to transit through one country in Layer 1 and one country in Layer 2 to the destination country, this destination country is included in Layer 3. It is worth mentioning that the most marginal countries in the CIATN for China are in Layer 3, and passengers from China can fly to any country through at most two intermediate countries. The possible entry restriction policy for these countries to implement is the same as that of countries in Layer 2.

The main feature of this hierarchical network partition is that the country at Layer x is only feasibly connected to the countries in the same Layer, Layer $(x-1)$ and Layer $(x+1)$. The hierarchical partition results are shown in Fig. 6, where the dots represent countries or regions in the corresponding layer, and the lines represent connections with their width proportional to the flight frequency. There are 72 countries and regions having direct flights with China, and they constitute Layer 1. In addition, the number of countries and regions in Layer 2 and Layer 3 are 146 and 9, respectively.

The hierarchical partition of the CIATN enables us to understand the relations between China and other countries in the network. In order to show this relationship more visually, Fig. 7 provides a representation of the WATN in line with the hierarchical partition results. In Fig. 7, the dots represent cities having airports, and the width of the blue lines is proportional to the flight frequency between corresponding city pairs. We can distinctly find that most countries in Layer 1 are geographically close to China, while nine countries (mostly small island countries) in Layer 3 are very far away from China. Although Layer 1 has fewer countries than Layer 2, it takes over most cities having airports in the WATN. Next, we will comprehensively analyze the hierarchical structure of the CIATN and use it to study the impact of two entry restriction policies.

4.2. The structure analysis

4.2.1. Layer 1

Layer 1 contains 32% of countries or regions in the CIATN, and there are 136,210 flights (61% of the total international flights all over the world) whose departure country and arrival country are both in this layer. We can find that Layer 1 includes most countries with developed international air traffic, and most flights in the world are concentrated on this layer. Moreover, there are 18,444 flights between China and countries or regions in Layer 1, and they account for about 8.32% of the total international flights worldwide. It is noted that Layer 1 plays an indispensable role in the international connectivity of the Chinese ATN.

To further investigate the topological structure and flight distribution in hierarchical CIATN, six hierarchical metrics are proposed for each country to obtain some useful findings. Drawing on the work by Du et al. (2016), the six hierarchical metrics are divided into two types: (1) the metrics measuring connection relation and (2) the metrics evaluating flight strength. Following the first type, for each country, we define r_c^{fwd} as the ratio of connections between the layer it belongs to and the previous layer to the total connections of

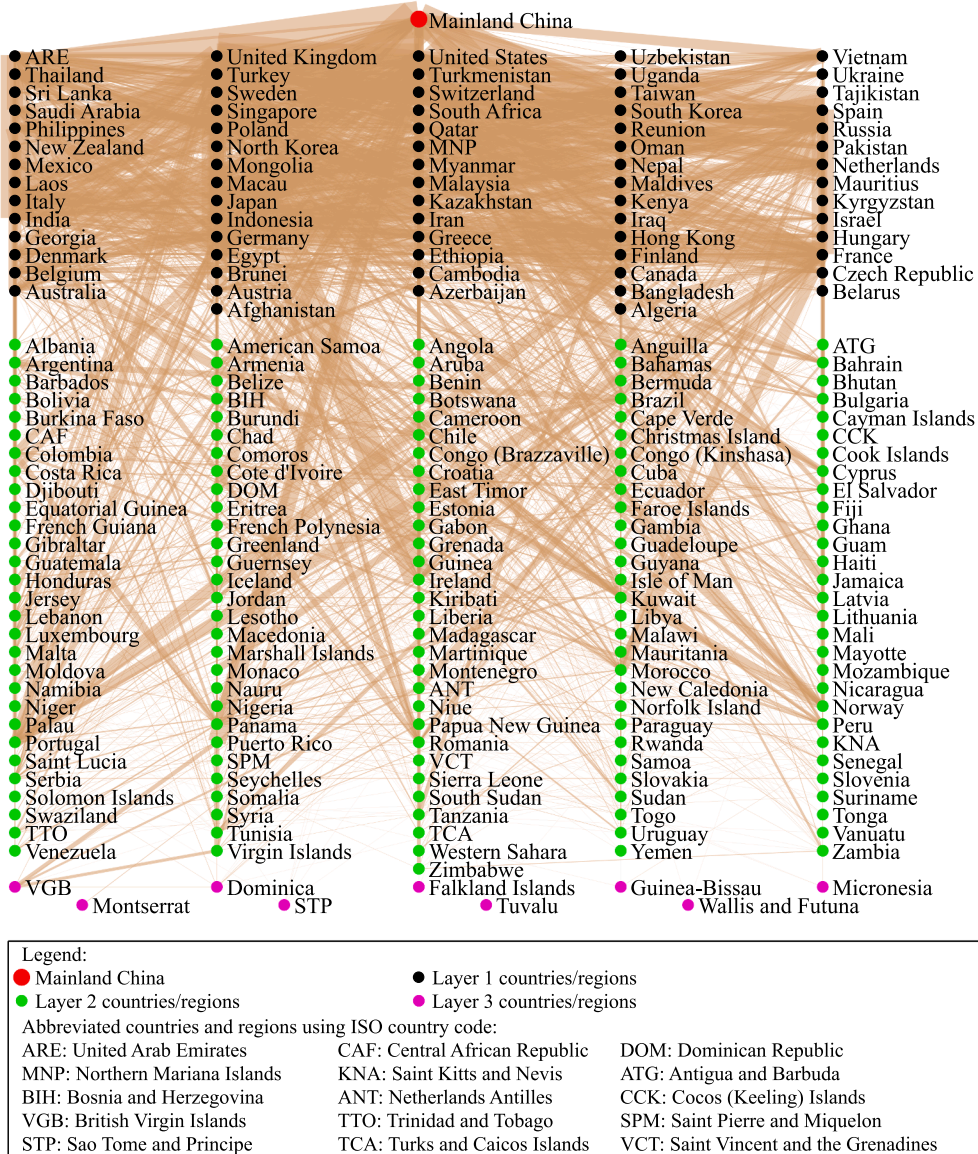


Fig. 6. The hierarchical structure of the CIATN.

the corresponding country, r_c^{in} as the ratio of connections inside the same layer to the total connections of the corresponding country, and r_c^{bwd} as the ratio of connections between the layer it belongs to and the next layer to the total connections of the corresponding country, respectively. Similarly, following the second type, for each country, r_f^{fwd} , r_f^{in} and r_f^{bwd} are used to describe the ratio of flights between the layer this country belongs to and the previous layer (r_f^{fwd}), inside the layer it belongs to (r_f^{in}), and between the layer it belongs to and the next layer (r_f^{bwd}) to the total international flights of the corresponding country. By definition, it holds $r_c^{fwd} + r_c^{in} + r_c^{bwd} = 1$ and $r_f^{fwd} + r_f^{in} + r_f^{bwd} = 1$ for each country or region in Layer 1 and Layer 2. The hierarchical metric results of the top 10 countries or regions having direct flights with China are listed in Table 4. We can find that the proportion of connections inside the layer it belongs to is greater than 0.8 for these ten countries, which indicates that countries with direct flights with China tend to connect with each other. Specifically, Vietnam and Cambodia have no flight connection with countries in Layer 2. While for the distribution of flights, it is shown that the number of flights with China for some countries accounts for a considerably high proportion, and most of their international flights are with Layer 1 countries.

Fig. 8 shows the hierarchical metrics of the countries in Layer 1 with the order of node degree in the CIATN. Each country in Layer 1 corresponds to three points (one red, one green, and one blue) located in one vertical line in each subfigure. The abscissa of the three

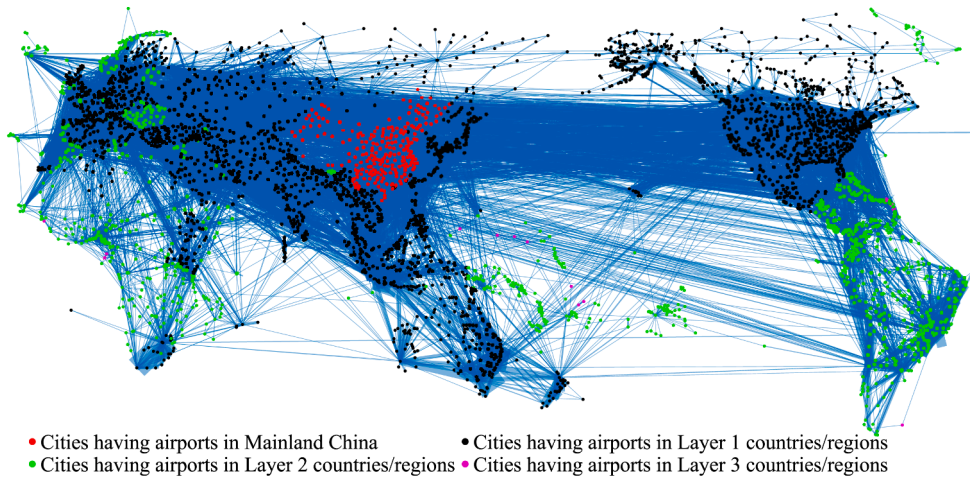


Fig. 7. The WATN based on the hierarchical partition results.

Table 4
The hierarchical metrics of top 10 countries or regions having direct flights with China.

Rank	Country/Region	Weekly number of flights with China	r_c^{fwd}	r_c^{in}	r_c^{bwd}	r_f^{fwd}	r_f^{in}	r_f^{bwd}
1	Japan	3020	0.021	0.894	0.085	0.280	0.703	0.018
2	Thailand	2504	0.018	0.891	0.091	0.261	0.731	0.008
3	South Korea	2284	0.020	0.898	0.082	0.252	0.729	0.019
4	Hong Kong	1304	0.022	0.935	0.043	0.207	0.791	0.002
5	Taiwan	1146	0.033	0.900	0.067	0.194	0.804	0.003
6	Singapore	728	0.022	0.911	0.067	0.102	0.896	0.003
7	Malaysia	709	0.028	0.917	0.056	0.106	0.894	0.001
8	Vietnam	690	0.040	0.960	0.000	0.145	0.855	0.000
9	Macau	673	0.083	0.833	0.083	0.404	0.592	0.004
10	Cambodia	613	0.071	0.929	0.000	0.352	0.648	0.000

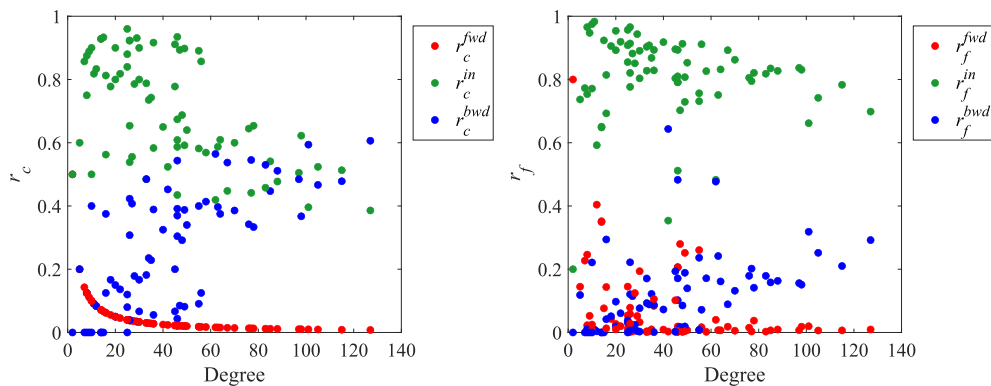


Fig. 8. The hierarchical metrics of the countries in Layer 1.

points is the number of countries directly connected to this country in the CIATN, and the sum of the ordinates of them is equal to 1 according to the definition of hierarchical metrics. It is clear that r_c^{fwd} and r_f^{fwd} show a downward trend with the node degree, which indicates that countries with more developed international air traffic systems have a smaller proportion of flights with China. Moreover, we can find that $r_c^{in}(r_f^{in})$ is larger than $r_c^{bwd}(r_f^{bwd})$ for most countries or regions, and the larger the degree of countries, the higher the ratio of connections and flights with the next layer. Notably, some countries with a large number of total connections (such as the United States and France) hold the condition of $r_c^{bwd} > r_c^{in}$. These countries in Layer 1 behave as a bridge for connecting China and countries or regions in Layer 2. It can also be inferred that these countries can maintain the connectivity of the CIATN and be the transit hubs when other countries or regions take entry restriction policies on travelers from China.

4.2.2. Layer 2

Layer 2 is comprised of 146 countries, which account for 64% of the total countries. Although the number of countries in Layer 2 is the largest among the three layers, the proportion of flights within this layer is very small. Only 12,978 flights are inside Layer 2, which is smaller than the total number of Chinese international flights. However, the number of flights between Layer 2 and Layer 1 is up to 53103, and it takes up a very large proportion of flights involving countries in Layer 2. These observations again confirm the significance of Layer 1 to the connectivity of the CIATN. Fig. 9 is drawn to present the hierarchical metrics of each country in Layer 2 with the order of node degree in the CIATN. We can find that most countries in Layer 2 have no connection with Layer 3 except for a few countries, which play a pivotal role in the CIATN. If the countries connecting Layer 3 take complete entry suspension, the connectivity of the CIATN will be influenced to some extent. For each country (or region) in Layer 2, there is no obvious regular pattern of r_c^{fwd} , r_c^{in} , r_f^{fwd} and r_f^{in} . Nevertheless, we can find that r_f^{fwd} is greater than r_f^{in} for 86 countries in Layer 2, which reveals that most countries in Layer 2 tend to have more flights with countries in Layer 1.

The previous section focuses on the comparison between metrics of the same type. To investigate the relative size of connection metrics and flight metrics, Fig. 10 shows the comparison of r_c^{fwd} & r_f^{fwd} , r_c^{in} & r_f^{in} , and r_c^{bwd} & r_f^{bwd} of every country or region in Layer 1 and Layer 2. In Fig. 10, the straight line $y = x$ is drawn as a benchmark for comparing the value of the corresponding connection metric and flight metric. If a point is above the line, it means that, for this country, fewer connections sustain more flight flow. Hence, the average flight strength of these connections is relatively strong. On the contrary, if the point is below the line, the average flight strength of these connections is relatively weak. In Layer 1, r_f^{fwd} is larger than r_c^{fwd} for most countries or regions, indicating that these connections with China sustain relatively higher flight flow. These flights improve the connectivity of the CIATN and sometimes provide backup routes when other countries take the policy of direct flight suspension. Besides, we can see that r_f^{in} is greater than r_c^{in} while r_f^{bwd} is less than r_c^{bwd} for most countries or regions. On the contrary, for most countries or regions in Layer 2, r_f^{in} is less than r_c^{in} while r_f^{fwd} is greater than r_c^{fwd} . That is to say, the average flight flow for a connection within Layer 2 is much smaller than that of a connection between Layer 1 and Layer 2. The bond between the two layers is the key for China to connect with countries in Layer 2. Moreover, r_f^{fwd} is less than or equal to r_c^{fwd} for Layer 2 because countries in Layer 2 rarely have connections to countries in Layer 3.

In short, the international flights of China and the flights between different layers ensure the connectivity of the CIATN. For the impact of entry restriction policies, the disruption caused by direct flight suspension can be compensated by alternative routes. However, the complete entry suspension prohibits travelers from flying to the destination country, and it also influences the accessibility from China to the connected countries and regions in the next layer.

4.3. Critical countries affecting the connectivity of the CIATN

To investigate the impact of entry restriction policies implemented by different countries or regions, numerical studies are conducted assuming that each country or region is taking either policy. From the simulation results, the most critical countries affecting the connectivity of the CIATN in terms of these two entry restriction policies can be identified.

4.3.1. Critical countries in terms of direct flight suspension

The policy of direct flight suspension can be conducted by all the countries or regions in Layer 1, so we first analyze the decline in \widehat{WIC} of the CIATN when these 72 countries or regions individually suspends direct flights with China. The top 25 countries are shown in Table 5, and the following observations can be drawn.

- (1) The countries and regions in Table 5 are summarized as three groups. The first group is the countries or regions which are geographically close to Mainland China and have plenty of direct flights with China, such as Japan, Thailand, South Korea, Hong Kong, and Taiwan. These countries or regions also have relatively high ranks in Table 4 due to frequent flights with China. The second group consists of the countries that have an all-around connection with China and other countries, such as the United States, Russia, Singapore, and the United Arab Emirates. The last group is the countries with the developed international air transport system but have a few flights with China. France, the United Kingdom, and Germany are the representatives of this group.
- (2) We can see that Japan is the top-ranked country, indicating that the direct flight suspension with Japan would incur the greatest decrease in China's international connectivity. With relatively smaller (576 compared to 3020 with Japan) weekly direct flights with China, the United States is in second place. The impact of the United States is much larger than Thailand and South Korea, while Thailand and South Korea have more direct flights with China. This shows that the identification of critical countries cannot be based solely on the number of international flights with China. In the last two columns of Table 5, the average decrease of \widehat{WIC} per flight with China, and the corresponding rank of these countries are displayed. We can find that according to the rank based on average decrease per flight, countries with wide international air transport connections have higher ranks (most from the abovementioned group 2&3). In contrast, the rank of countries from the first group drops a lot. This finding indicates that when policymakers consider suspending flights with pandemic-involved countries, they should give priority to the neighboring countries having low ranks in terms of average decrease, as indicated in Table 5. For example, when Japan and

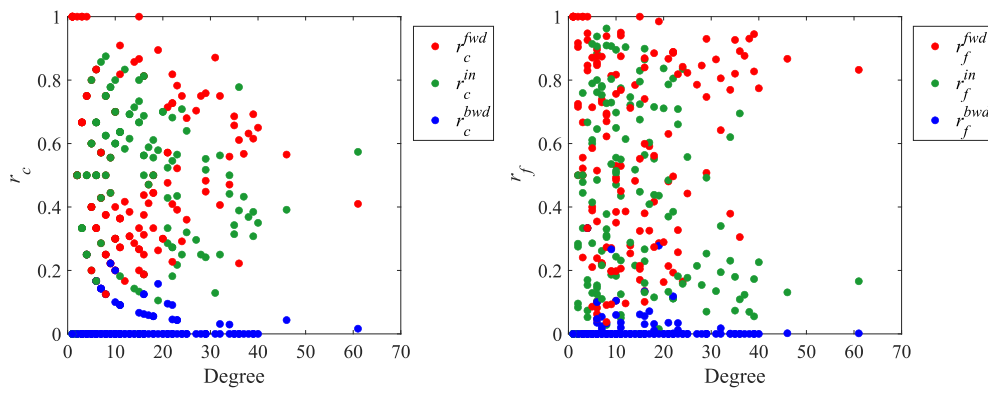


Fig. 9. The hierarchical metrics of each country in Layer 2.

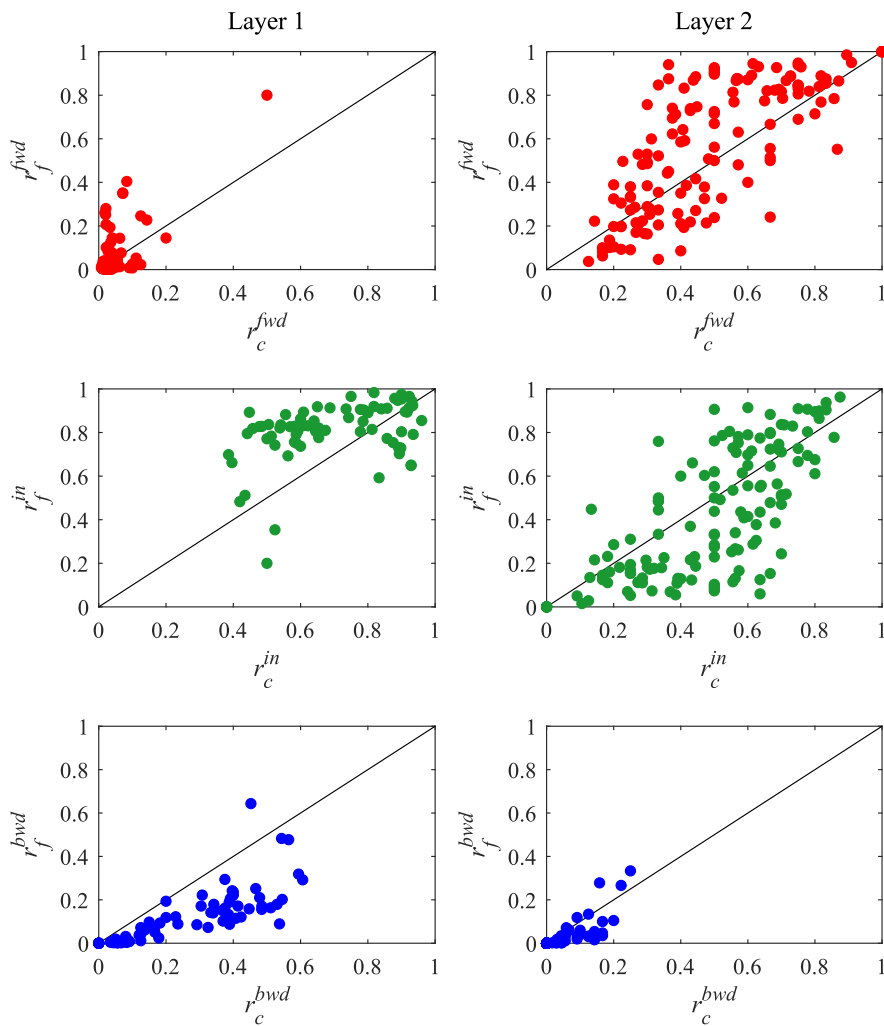


Fig. 10. The relative size of connection metrics and flight metrics.

Table 5

Top 25 countries or regions in terms of \widehat{WIC} decrease caused by direct flight suspension.

Rank	Country	Percentage decrease of \widehat{WIC} (d_1)	Weekly number of flights with China	Number of connected countries	Weekly number of total int'l. flights	Average decrease per flight with China	Rank by average decrease
1	Japan	6.8481%	3020	47	10,793	0.0022%	9
2	United States	6.0847%	576	101	29,239	0.0105%	1
3	Thailand	5.8662%	2504	55	9612	0.0023%	8
4	South Korea	4.1525%	2284	49	9073	0.0018%	13
5	Hong Kong	2.3868%	1304	46	6310	0.0018%	12
6	Taiwan	1.5221%	1146	30	5916	0.0013%	25
7	Macau	1.4796%	673	12	1665	0.0021%	10
8	Russia	1.4178%	296	78	7899	0.0047%	2
9	Singapore	1.1349%	728	45	7159	0.0015%	16
10	Cambodia	1.0971%	613	14	1743	0.0017%	14
11	Malaysia	0.9948%	709	36	6715	0.0014%	19
12	Vietnam	0.9164%	690	25	4755	0.0013%	22
13	United Arab Emirates	0.7486%	202	98	11,062	0.0037%	4
14	Australia	0.6317%	330	36	3931	0.0019%	11
15	France	0.5757%	153	127	16,331	0.0037%	3
16	Philippines	0.5711%	430	28	3451	0.0013%	23
17	United Kingdom	0.5671%	156	105	25,214	0.0036%	5
18	Myanmar	0.5312%	364	14	1042	0.0014%	18
19	Indonesia	0.4777%	353	26	4495	0.0013%	21
20	Germany	0.4763%	172	97	23,794	0.0027%	7
21	Canada	0.2421%	177	67	9680	0.0013%	20
22	India	0.1961%	128	56	7675	0.0015%	17
23	Ethiopia	0.1768%	56	62	1398	0.0031%	6
24	Laos	0.1567%	118	7	519	0.0013%	24
25	Italy	0.1438%	92	85	13,708	0.0015%	15

Table 6

Top 25 countries or regions in terms of \widehat{WIC} decrease caused by complete entry suspension.

Rank	Country	Layer	Percentage decrease of \widehat{WIC} (d_2)	Weekly number of flights with China	Number of connected countries	Total number of int'l. flights	Impact difference d_2/d_1
1	United States	1	18.7148%	576	101	29,239	3.076
2	Japan	1	12.4710%	3020	47	10,793	1.821
3	Thailand	1	7.1435%	2504	55	9612	1.218
4	South Korea	1	7.0015%	2284	49	9073	1.686
5	United Kingdom	1	3.8062%	156	105	25,214	6.711
6	France	1	3.5661%	153	127	16,331	6.194
7	Germany	1	3.4766%	172	97	23,794	7.298
8	Hong Kong	1	3.4640%	1304	46	6310	1.451
9	Taiwan	1	3.4149%	1146	30	5916	2.243
10	Russia	1	3.3146%	296	78	7899	2.338
11	Vietnam	1	2.3602%	690	25	4755	2.575
12	United Arab Emirates	1	2.2472%	202	98	11,062	3.002
13	Singapore	1	2.2332%	728	45	7159	1.968
14	India	1	2.1783%	128	56	7675	11.107
15	Malaysia	1	2.0680%	709	36	6715	2.079
16	Australia	1	1.7944%	330	36	3931	2.840
17	Macau	1	1.7878%	673	12	1665	1.208
18	Cambodia	1	1.6284%	613	14	1743	1.484
19	Turkey	1	1.4991%	60	115	9139	14.658
20	Indonesia	1	1.4623%	353	26	4495	3.061
21	Philippines	1	1.4358%	430	28	3451	2.514
22	Puerto Rico	2	1.2937%	0	16	2306	-
23	Canada	1	1.2755%	177	67	9680	5.267
24	Italy	1	1.1323%	92	85	13,708	7.869
25	Spain	1	1.0824%	44	83	16,011	11.985

the United States suspend the same number of direct flights, the impact incurred by the latter is about five times that of the former.

4.3.2. Critical countries in terms of complete entry suspension

Different from direct flight suspension, complete entry suspension can be taken by all the countries or regions in the world. Therefore, numerical studies of complete entry suspension by all the 227 countries or regions from three layers are conducted. For each country or region, all international flights will be removed when evaluating the connectivity of the CIATN. Table 6 presents the top 25 countries or regions that affect the connectivity of CIATN while considering a complete entry suspension policy for travelers from China. From Table 6, there are a couple of findings as follows.

- (1) For complete entry suspension, the United States holds the top position, and the percentage decline arising from its complete entry suspension is larger than 18%. Conversely, the rank of some countries and regions close to China (such as Taiwan, Macau, and Cambodia) drops, indicating that although the number of their international flights with China is very high, they are not very important to the connection with other countries and regions for China. Also, the rank of countries with developed international air transport systems rises a lot in Table 6. For example, France ranks 6th in the scenario of complete entry suspension, which is nine places ahead compared with that when suspending direct flights. The reason is that France has a very developed international ATN. On the one hand, travelers can conveniently reach France by transferring from other countries when the direct flights between China and France are suspended. On the other hand, if France implements a complete entry suspension policy, travelers from China can no longer transfer from France to other countries.
- (2) It is interesting to note that Puerto Rico, which is in Layer 2, has a considerable impact on the connectivity of the CIATN when taking a complete entry suspension policy. Apart from it, countries such as Dominican and Bahamas in Layer 2 are also ranked in the top 30. Although these countries do not have direct flights with China, they are connected to many other countries and regions in the world. When the complete entry suspension policy on China is adopted, the connection between China and Layer 2 and 3 countries will be affected a lot. It indicates that those countries which do not have direct flights with China may also incur non-negligible impacts on China's international connectivity when implementing entry policies.
- (3) The last column of Table 6 presents the ratio of \widehat{WIC} percentage decrease of two entry restriction policies implemented by the corresponding country in Layer 1 to exhibit the difference of policy impact. It can be seen that for the United States, the impact of complete entry suspension on the connectivity of the CIATN is three times that of direct flight suspension. Besides, some countries having large impact differences, such as the United Kingdom, France, and Germany, that have few direct flights with China, own well-developed international aviation systems. However, the impact difference of countries geographically close to China is relatively small because of their exorbitant influence in direct flight suspension policy.

Combining Tables 5 and Table 6, we find that for the same country or region, the impact of complete entry suspension is much greater than that of direct flight suspension, and the ranks of countries in terms of two policies vary a lot. This is because complete entry suspension not only causes direct flight disruption with China but also eliminates the possibility of transit to or through the corresponding country in the network.

4.3.3. Comparison with unweighted network analysis

In order to characterize the role of flight frequency in evaluating the impact of entry restriction policies, the unweighted IC index as defined in Eq. (3) is employed to assess the connectivity of the unweighted CIATN for comparison. Table 7 displays the impact of two entry restriction policies on the connectivity of the unweighted CIATN. The top 10 countries in terms of two policies are listed. We can see that the effect of different countries enforcing the same policy is very close in terms of unweighted CIATN. The impact of entry restrictions of some countries is the same with utilization of the unweighted IC index. In addition, the impact difference between two policies implemented by the same country is also quite close, compared with the difference obtained by weighted connectivity measures. In all, the results show that analysis based on the unweighted network can hardly distinguish the impact of two policies and

Table 7

Top 10 countries in terms of IC decrease caused by two policies in the unweighted CIATN.

Direct flight suspension				Complete entry suspension			
Rank	Country	IC	Decrease	Rank	Country	IC	Decrease
1	United Kingdom	0.6468	0.7882%	1	United Kingdom	0.6417	1.5765%
2	United States	0.6468	0.7882%	2	South Africa	0.6431	1.3513%
3	Australia	0.6475	0.6756%	3	United States	0.6431	1.3513%
4	France	0.6475	0.6756%	4	France	0.6439	1.2387%
5	South Africa	0.6483	0.5630%	5	Australia	0.6453	1.0135%
6	Belgium	0.6490	0.4504%	6	Canada	0.6453	1.0135%
7	Canada	0.6490	0.4504%	7	New Zealand	0.6453	1.0135%
8	New Zealand	0.6490	0.4504%	8	Belgium	0.6468	0.7882%
9	Spain	0.6490	0.4504%	9	Spain	0.6468	0.7882%
10	Germany	0.6497	0.3378%	10	Germany	0.6475	0.6756%

the impact of different countries on the international connectivity of China. Hence, our proposed weighted IC metric is necessary for the analysis.

4.4. Robustness of the CIATN

The robustness of the CIATN is also evaluated by assessing its ability to maintain connectivity when the other countries cumulatively implement the two policies against China. Fig. 11 shows the change of the normalized weighted international connectivity with the increase of the number of countries implementing the policy of direct flight suspension. Fig. 12 shows the change of the normalized weighted international connectivity with the increase of the number of countries implementing the policy of complete entry suspension. In this work, the order of implementation of entry restrictions policy is determined by the countries' individual impact on \widehat{WIC} and the layer it belongs to. These countries are assumed to implement the policies in ascending and descending order, respectively. For the ascending order, countries with smaller individual impact on \widehat{WIC} implement the policy earlier; for the descending order, countries with larger individual impact on \widehat{WIC} implement the policy earlier. We have the following findings from the experimental results.

- (1) For direct flight suspension, countries or regions that affect the robustness of the CIATN are all in Layer 1. From Fig. 11, we can see that the IC index decreases sharply in the ascending order of countries. A small fraction of critical countries taking the policy of direct flight suspension could incur a large reduction of network connectivity. For instance, when the top 10 countries or regions suspend their direct flights with China, the IC index will drop to 58% of the original value. However, if the order is reversed, the IC index does not have a significant decrease until the last few countries implement the policies. If all countries and regions take the policy of direct flight suspension except for Japan and the United States, the value of \widehat{WIC} is up to 0.66, which means that the CIATN can maintain 66% of its usual connectivity only with the international connections with Japan and the United States. On the contrary, if only these two countries implement the direct flight suspension policy, the incurred connectivity decrease is only 14%. This asymmetric phenomenon is attributed to the abundant alternative routes inside the CIATN. Specifically, when some of the countries suspend their direct flights with China, some alternative routes by transferring from other countries can maintain the connectivity of the CIATN. We can infer that the dense flights in Layer 1 ensure this alternative connection relationship. However, when all the countries suspend direct flights to China, China would be isolated from the world, and the weighted IC index will quickly drop to zero.
- (2) For complete entry suspension, the implementation of the policy by all the countries or regions in three layers will affect the connectivity of the CIATN. However, it is worth mentioning that if all countries or regions in Layer 1 carry out the entry ban suspension, the IC index will drop to 0 (see Fig. 12 for details) because all the international flights involving China are disrupted in the CIATN. The changing trend of the IC index in terms of ascending order is similar to that in Fig. 11. While the shape of the decline curve in descending order varies a lot with that in Fig. 11. It is a noticeable ladder-like shape, where each step corresponds to a layer. Within each layer, there is an acceleration of the decreasing trend. Besides, we can find that the complete entry suspension of countries or regions in Layer 2 and 3 does not have much impact on the connectivity of the CIATN. If all the international flights between them and China are interrupted, the IC index will only decrease by 26.3%.
- (3) No matter which type of entry restriction policy is implemented, the impact of critical countries on the robustness of the CIATN is dramatically huge. The cumulative implementation of direct flight suspension or complete entry suspension of these critical

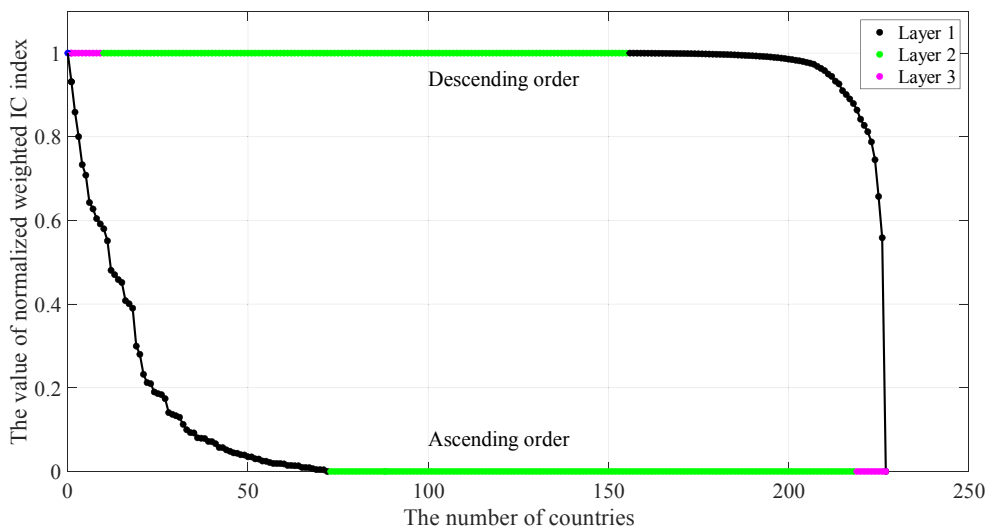


Fig. 11. Robustness of the CIATN against direct flight suspension.

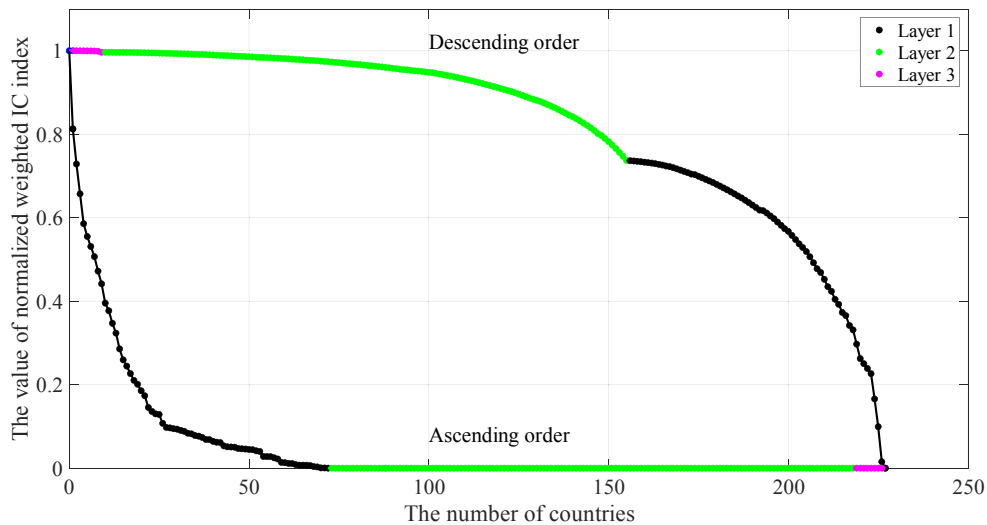


Fig. 12. Robustness of the CIATN against complete entry suspension.

countries not only affects their connection with China but also blocks the transit channel for China to many other countries or regions. It is noteworthy that the United States and Japan are the first (last) two countries to implement policies in ascending (descending) order under two entry restriction policies. However, the impacts on air transport connectivity are very different. For direct flight suspension, the connectivity decline caused by Japan and the United States being the first two countries to implement direct flight suspension is much smaller than that when they are the last to do that, as shown in Fig. 11. The reason is that these two countries not only have a substantial frequency of direct flights with China but also connect many countries and regions all over the world. On the contrary, for complete entry suspension, the connectivity decline caused by the United States and Japan being the first two countries to implement complete entry suspension is relatively larger than when they are the last to do so, as shown in Fig. 12. This is because the decrease of the connectivity in the latter case is only attributed to the interruption of flights between China and these two countries.

It is rather remarkable that the robustness assessment of the CIATN is quite complex, and more practical factors should be considered. The illustration here is substantially based on two entry restriction policies with our hierarchical structure partition. More attention with consideration of the spatiotemporal analysis of IATNs and the actual policy implement sequence should be paid to this topic in the future.

5. Results and implications

Based on the analysis above, this section provides discussions on the results, and several implications are derived.

- (1) The connection strength, quantified by flight frequency, is essential for assessing the international connectivity of ATNs. As shown in Table 7, the disconnection of a single country has little impact on the connectivity of the CIATN when it is treated as an unweighted network, no matter what policy is implemented. Moreover, the difference between various countries is subtle, mostly ranges from 0 to 1%. This is mainly because the worldwide ATN is a well-connected complex network with a high density of connections. However, after flight frequency is considered, the impact of different country's entry policies on the connectivity of the CIATN changes and varies a lot. Specifically, if all the direct flights between China and Japan are shut down, the connectivity of the CIATN will decrease by 6.8%. If the United States carries out a complete entry suspension on China, the CIATN will lose 18.7% of its connectivity. It indicates that when assessing and ranking the impact of entry policies implemented by different countries, the results can be various, depending on the pandemic stage.
- (2) For the same country, the impact of complete entry suspension is about 1 to 15 times greater than that of direct flight suspension on the connectivity of the CIATN, depending on both its air connection with China and the other countries, as shown in Table 6. In the case of Thailand, the impact of complete entry suspension is 1.2 times that of direct flight suspension, indicating that although the air traffic flow between Thailand and China is large, the disconnection with Thailand would hardly affect China's international connection with the other countries. In contrast, for the United Kingdom, the impact of complete entry suspension is 6.7 times that of direct flight suspension, suggesting that although the air traffic flow between the United Kingdom and China is relatively low (less than 10% of that between China and Thailand), the disconnection with the United Kingdom could have some knock-on effect on the international connection of China. Thus, the information in Table 5 and Table 6 can provide a reference for implementing different policies with different countries.

- (3) The CIATN can be hierarchized into three layers, with Mainland China at the center and the other countries or regions at different layers according to their connection with China, as shown in Figs. 6 and 7. The countries in the first layer all have direct flights with China and are also bridges for connecting China with the more countries in the second layer. It is found that the connection between different layers and inside different layers varies a lot, as shown in Table 4 and Figs. 8–10. Specifically, the connections inside Layer 1 are very dense, i.e., the high redundancy and alternative routes make the CIATN robust to disconnections caused by direct flight suspension from countries in Layer 1. As shown in Fig. 11, as long as China maintains its direct flights with the top 5 countries, 80% of its international connectivity can be maintained. However, the situation for complete entry suspension is different. Fig. 12 shows that even if the countries in Layer 1 implement entry suspension policy in descending order, the international connectivity of the CIATN will decrease significantly. It indicates that the redundancy in the network can only increase its ability to resist direct flight suspension but not complete entry suspension.
- (4) The ranking of different countries in terms of their impact on China's international connectivity when implementing entry restrictions cannot be determined merely based on their weekly flights with China or their distance from China. The importance of a country is determined by its position in the IATN and the specific entry policy being adopted, as shown in Table 5 and Table 6. Generally, countries with more weekly flights with China or more international flights among themselves tend to have a more significant impact on China's international connectivity if they carry on entry restrictions on China. However, there are exceptions. For example, the United Kingdom and Germany have many international flights, but their impact on the connectivity of CIATN is not that significant, as shown in Table 5. In contrast, Macau, which has only one airport and fewer flights than the above two, has a more significant impact on China's international connectivity. Concerning the complete suspension policy, most of the top countries are in the first layer of the CIATN, as shown in Fig. 6 and Table 6. Whereas, there are also several countries in the second layer having considerable impact on China's international connectivity, such as Puerto Rico. It implies that although similar countries (like Puerto Rico) do not have direct flights with China, their implementation of entry suspension to travelers from China would still incur nonnegligible impact on China's connection with other countries.
- (5) Although this paper assumes the policies are implemented by other countries, the results can also provide a reference for the Chinese civil aviation authorities when considering suspending flights from/to other countries. The average decrease of international connectivity resulted from suspending one direct flight with China by different countries, as presented in Table 5, suggests the priority of countries when suspending direct flights. Comparing Japan with the United States, if the same number of weekly flights are suspended, the connectivity decrease caused by the latter one is around five times the former one. It implies that other conditions being equal, China should give priority to suspending flights with Japan. Generally, neighboring countries tend to have smaller average impact on the international connectivity of China, and quantitative results can be found in Table 5. According to the rank in the last column of Table 5, the top 5 countries that China should be cautious of when considering suspending direct flights include the United States, Russia, France, the United Arab Emirates, and the United Kingdom in order to maintain emergency safe travel connectivity for its residents.

6. Extensions

This section discusses two extensions of the above-presented method and analysis, namely the impact of partial flight suspension and response actions such as air travel bubble.

6.1. Partial flight suspension

In some cases, one country may not entirely suspend the direct flights but partially shut down its flights with certain countries. It is necessary to investigate the impact of partial flight suspension on international connectivity. As shown in Section 3.2, the proposed international connectivity index is evaluated by dividing the weighted ATN into different layers according to the number of flights on the connections. Therefore, this method can be effectively utilized to quantify the impact of partial direct flight suspension.

Table 8 reports the \widehat{WIC} decrease of the CIATN caused by the top 25 countries when carrying out four different levels of direct flight suspension. It is found that although Japan, United States, Thailand, South Korea, and Hong Kong are the top 5 countries or regions under each of the four levels of suspension, the specific rankings vary slightly. Fig. 13 visualizes the changing trend of the IC value of the CIATN when the top 5 countries or regions individually carry out different levels of flight suspension. It shows that the relationship is approximately linear, with slight derivations at some points.

6.2. Development of air travel bubble

Recently, with an aim to restore the previously suspended international air travel due to COVID-19 travel restrictions, temporary air travel arrangements named as 'travel bubble' have been proposed by many countries. Travel bubbles, also known as air transport bubbles, are essentially an agreement between two or more countries that allow travelers to fly freely within the bubble without on-arrival quarantine requirements.⁵ This strategy has been successfully implemented among some European and Asian countries. However, maintaining a travel bubble largely depends on the pandemic situations of the member countries. It is usually a dynamic policy.

⁵ What is a Travel Bubble, <https://blog.wego.com/whats-a-travel-bubble/> (Accessed 24 May 2021).

Table 8

Top 25 countries or regions in terms of the \widehat{WIC} decrease of the CIATN caused by different levels of direct flight suspension.

Rank	100% direct flight suspension		75% direct flight suspension		50% direct flight suspension		25% direct flight suspension	
	Country	Percentage decrease of \widehat{WIC}	Country	Percentage decrease of \widehat{WIC}	Country	Percentage decrease of \widehat{WIC}	Country	Percentage decrease of \widehat{WIC}
1	Japan	6.8481%	Japan	5.2141%	Japan	3.7895%	Japan	2.0056%
2	United States	6.0847%	Thailand	4.9127%	Thailand	3.3259%	Thailand	1.6630%
3	Thailand	5.8662%	United States	4.6786%	United States	3.1322%	South Korea	1.5168%
4	South Korea	4.1525%	South Korea	3.2927%	South Korea	2.3231%	United States	1.3616%
5	Hong Kong	2.3868%	Hong Kong	1.9538%	Hong Kong	1.5208%	Hong Kong	0.8660%
6	Taiwan	1.5221%	Macau	1.2565%	Russia	0.9017%	Russia	0.5138%
7	Macau	1.4796%	Russia	1.2328%	Macau	0.8926%	Macau	0.4463%
8	Russia	1.4178%	Taiwan	1.1410%	Taiwan	0.7611%	Cambodia	0.4064%
9	Singapore	1.1349%	Cambodia	0.8939%	Cambodia	0.6894%	Taiwan	0.3799%
10	Cambodia	1.0971%	Singapore	0.8932%	Singapore	0.6442%	Singapore	0.3174%
11	Malaysia	0.9948%	Malaysia	0.7066%	Malaysia	0.4702%	Malaysia	0.2351%
12	Vietnam	0.9164%	Vietnam	0.6867%	Vietnam	0.4582%	Vietnam	0.2285%
13	United Arab Emirates	0.7486%	United Arab Emirates	0.6453%	United Arab Emirates	0.4193%	Germany	0.2019%
14	Australia	0.6317%	Australia	0.4481%	United Kingdom	0.3099%	United Arab Emirates	0.1902%
15	France	0.5757%	United Kingdom	0.4334%	Germany	0.3002%	Myanmar	0.1687%
16	Philippines	0.5711%	Philippines	0.4277%	Australia	0.2922%	United Kingdom	0.1607%
17	United Kingdom	0.5671%	Myanmar	0.4104%	Myanmar	0.2896%	Australia	0.1452%
18	Myanmar	0.5312%	Germany	0.3980%	Philippines	0.2856%	Philippines	0.1421%
19	Indonesia	0.4777%	France	0.3925%	France	0.2663%	France	0.1342%
20	Germany	0.4763%	Indonesia	0.3520%	Indonesia	0.2338%	Indonesia	0.1169%
21	Canada	0.2421%	Canada	0.1767%	Canada	0.1169%	Canada	0.0584%
22	India	0.1961%	India	0.1483%	India	0.0934%	India	0.0509%
23	Ethiopia	0.1768%	Ethiopia	0.1392%	Italy	0.0815%	Italy	0.0407%
24	Laos	0.1567%	Laos	0.1169%	Ethiopia	0.0801%	Laos	0.0385%
25	Italy	0.1438%	Italy	0.1133%	Laos	0.0784%	Nepal	0.0319%

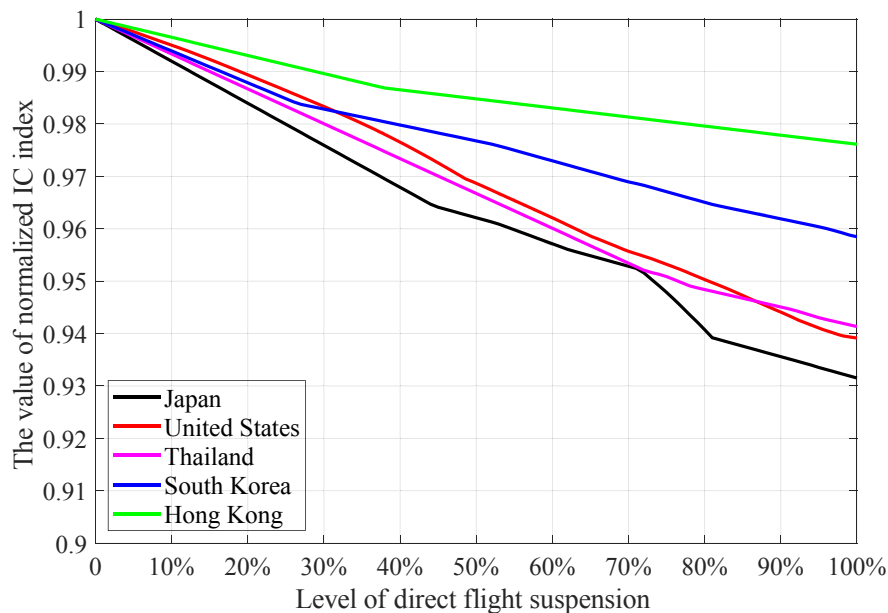


Fig. 13. Normalized IC value of the CIATN when the top 5 countries or regions individually carry out different levels of direct flight suspension against travelers from China.

The method proposed in this paper can be used to assess the international connectivity of a certain country when a travel bubble strategy is implemented. Given the countries that carry out suspension policies against the focal country and the partner countries in

the same travel bubble, the IATN of the studied country can be constructed, and in turn, the international connectivity can be quantified. Therefore, the IC index presented in this paper can help prioritize the candidate countries to form travel bubbles.

7. Conclusion

Motivated by the challenges and disruptions posed by the COVID-19 pandemic on the air transportation networks, this study conducts a systematic analysis to investigate the impact of entry restriction policies imposed by different countries on the international connectivity of air transport networks during COVID-19. The current research contributes to the air transportation literature on policy and practice by demonstrating a novel problem of ATNs connectivity during pandemics using network performance measurement and network topology metrics. Taking China as an example, the Chinese international air transport network (CIATN) is constructed to characterize this country-to-country disconnection where nodes represent countries or regions, and edges denote the direct international flight connections. To measure network performance, a novel IC index is developed to evaluate the connectivity of the CIATN by taking flight frequency into account. For the network topology features, the hierarchical structure analysis is implemented to the CIATN. Further, six hierarchical metrics are provided to explore the topological structure and flight distribution for each layer. This paper identifies the critical countries and evaluates the robustness of the CIATN under two typical entry restriction policies. The results are discussed, and several implications are provided.

It is noted that our analytical method on the impact of two entry restriction policies on the international connectivity of ATNs can be applied to every country, and not just China. We expect the results of the analysis on other countries will be similar.

Future work can be conducted in the following directions. First, more detailed data on link capacity can be used when assessing international connectivity, such as the number of seats and average daily passengers. Second, the resilience of the ATN based on this country-to-country feature can be studied with the consideration of flight recovery. Third, the impact of this country-to-country disconnection on different airlines is also an interesting avenue for future research. Finally, as discussed in the previous section, the concept of the air transport bubble for the safe recovery of the air transport industry can be investigated and thus warrants further research.

CRedit authorship contribution statement

Siping Li: Methodology, Software, Validation, Writing - original draft. **Yaoming Zhou:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Tanmoy Kundu:** Supervision, Writing - review & editing. **Fangni Zhang:** Supervision, Writing - review & editing.

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