Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 6622031, 13 pages
https://doi.org/10.1155/2021/6622031

Research Article

Resilience Modeling Method of Airport Network Affected by Global Public Health Events

Jiuxia Guo,[1,2] Xinping Zhu,[2] Chenxi Liu,[3] and ShuzhiSam Ge[1]

[1] *School of Computer Science and Engineering, Center for Robotics, University of Electronic Science and Technology of China, Chengdu, China*
[2] *Civil Aviation Flight University of China, Guanghan 618307, Sichuan, China*
[3] *University of Washington, Seattle 98195, WA, USA*

Correspondence should be addressed to Jiuxia Guo; didiyes@163.com

Received 21 October 2020; Accepted 16 December 2020; Published 4 February 2021

Academic Editor: Luigi Rodino

The COVID-19 global pandemic hit the aviation industry hard since the end of 2019. It has had an immediate, dramatic impact on airport traffic and revenue. Airports are the important nodes in the aviation system network, and the failure of a single airport can often affect the surrounding airports. The purpose of our analysis is to show how is the resilience and recovery of airports in the global public health crisis. Much research on resilience can be found in air transportation networks facing natural hazards or extreme weather, which focus on the robustness of the airport network. These methods are not suitable for the global public health event. Therefore, based on the collection of existing data, we combined with existing resilience measurement methods to analyze the resilience and recovery of airports during the global public health crisis. The resilience metrics results reflect the recovery of airports very well under different strategies. Here, we analyze airport network resilience by considering the performance-based methods. We integrate some metrics such as aircraft movements, passenger throughput, and freight throughput in the resilience metrics model, comparing the resilience evaluation under different preventive and control strategies, which can reflect the airport's recovery speed during the COVID-19 pandemic. Our analysis indicates that the aviation system network deteriorates soon after the COVID-19 outbreak, but the recovery level of the aviation industry depends on what measures are taken to prevent and control the COVID-19 epidemic. In particular, the recovery of the aviation system network in Europe takes longer than in China, due to different prevention and control strategies for COVID-19. The study proves that the emergency response ability of the country for the public health crisis has a significant positive impact on speeding up the recovery of the aviation system.

1. Introduction

The novel coronavirus disease (COVID-19) was the SARS-coronavirus-2 that emerged in 2019. However, there are no clinically approved vaccines or specific therapeutic drugs available for COVID-19 at present [1]. Considering the person-to-person transmission of COVID-19, Hubei Province was placed under lockdown approximately three weeks after the start of the COVID-19 outbreak [2]. Then, social distancing, mandatory quarantine, city lockdown, and a series of control methods are implemented in all regions of China [3], and finally, the number of infected cases goes down in May 2020. However, as the time of writing (30th Sept 2020) the COVID-19 has caused 1,007,769 global death and 33,642,602 confirmed cases according to global COVID-19 outbreak statistics maintained by the Center for System Science and Engineering (CSS) at Johns Hopkins University [4], from the data of COVID-19 in the world, the speed in which countries respond to pandemics directly affects the development trend of the epidemic. The research studies prove that the countries implemented rapid government interventions and strict public health measures for quarantine and isolation, and the spread of infection was successfully halted and prevented it exploding exponentially [5]. Besides, many governments around the world have implemented the active prevention and control actions, such as social distancing, mobility constraints, pro-active testing, and isolation of detected cases [6]. China has gradually resumed domestic flights and built a relatively complete set of antiepidemic monitor system to prevent imported cases, such as the health QR code system, which is proved effective [7, 8].

Air traffic is characterized by high safety and security concerns coupled with airlines, airports, and air traffic control departments. The aviation system network consists of nodes (airports) with strict regulations and interdependencies between vehicles and journeys and links (flights) with high degrees of freedom concerning flight path and speed [9]. Airports are an integral part of the aviation ecosystem and currently face a crisis in which sudden and prolonged collapse occurs in traffic levels due to public health events. As the public health event was a disturbance, how to deal with the impact on the aviation system after the crisis, so that system can restore resilience to reduce the loss of the aviation system.

With the global public health outbreak, the resilience of the system in several industries is considered. Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances. In the past, the research on aviation safety management mainly focused on system failures or catastrophic accidents because these events have large economic and safety impacts. And the disturbances of the system focus on hardware, software, human, and environment. For humans as the key elements of aviation, there are more studies about human errors [10]. Therefore, Hollnagel et al. [11] introduced the resilience concept into the safety science domain in 2006. Resilience Engineering is an important tool and method of system development and system safety in many industries, such as the ecosystem and transportation system [12, 13]. In transportation networks, research on resilience mainly faces natural hazards or extreme weather [14, 15]. The qualitative resilience assessment approaches include conceptual frameworks and semiquantitative indices [16]. Research about the resilience of the air transport system mainly focuses on air traffic management (ATM) system [17, 18]. And Europe had the Sharing of Authority in Failure/Emergency Condition for Resilience of Air traffic Management (SAFECORAM) project, whose purpose was eventually to deal with the reallocation of tasks between residual resources of the system after a disturbance to minimize the system loss of global performance. There are twelve study reference scenarios in the resilience 2050 project of Europe, which are a potential hazard of the ATM system, such as Taxiway incursion during take-off taxiing, Big airport closure due to snow, and activation of a temporary segregated area due to natural disaster [19].

However, most research studies [20–22] have dealt with modeling and estimating the resilience of an air transport network effect by various disruptive events; they are only considered the impact of an airport network after the interruption of some airport affected by the disruption and did not consider how global disruptive events affect the global airport network. Few studies have quantified and forecast the aviation system performance parameters such as capacity, cost/benefit, and environment under multiple pandemic scenarios, and the method proposed in the paper is desperately needed. To the date, studies focused on the aviation network impacts of the COVID-19 pandemic are the interactive dashboards developed by the International Civil Aviation Organization (ICAO) and the COVID-19 pandemic impact on the European air traffic network. From the perspective of safety management, we have a new cognitive of resilience engineering. Therefore, global public health is a disturbance of the aviation system; how to deal with it so that the system can quickly recover is the first considered issue of aviation. Besides, ICAO proposed eleven Key Performance Areas (KPAs) of aviation [23], and many research studies focus on capacity, safety, environment, and efficiency in pre-COVID-19. In the paper, based on the existing resilience metric measures methods, we develop a model of the airport network resilience following the collectible data of airport operation in different countries, which obtains the results of the rapid emergency response of various national airports facing sudden global public health events.

The main contributions of this study are summarized as follows. First, this study is studying the global public health impact on the airport network resilience and recovery. Second, this study developed a resilience metric measure model based on existing resilience measures to apply to the global public health crisis. By comparing the production data of China's four regional airports during the first half of 2020, the resilience index of the eastern and western airports is higher. In addition to a comparison of production recovery of airports in China and Europe, the recovery of airports in mainland China is better than in Europe. The main reason for this is that China takes strict epidemic prevention and surveillance system to quickly stop the spread of the virus. The resilience metric of airports in different countries shows the prevention and control measures and policies are a very important factor to recover the normal operation of the aviation system. After the disturbance occurs, how to quickly restore the system to normal levels is a problem worthy of our consideration.

The remainder sections are structured as follows. Section 2 introduces the economic impact of the COVID-19 and the resilience measure model of the airport. Section 3 introduces the case study of the resilience analysis of airports in China and Europe and analyses the resilience difference of different airports. Finally, Section 4 provides the conclusions and outlines the finding and future work.

2. Materials and Methods

2.1. System Resilience Frame Generic Model. The definitions of resilience include aspects of a system withstanding disturbances, adapting to the disruption, and recovering from the state of reduced performance. Resilience metrics can be divided into three types which are attribute-focused metrics, data-based indicators, and performance-based methods. Most resilience metrics for transportation networks are categorized as performance-based methods as they focus on impacts of flows across the network during recovery activities. The properties of social system resilience can be defined as the following [24]:

Robustness: strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function

Redundancy: the extent to which elements, systems, or other units of analysis exist that are substitutable

Resourcefulness: the capacity to identify problems, establish priorities, and mobilize resources when conditions exist which threaten to disrupt some element, system, or other units of analysis

Rapidity: the capacity to meet priorities and achieve goals promptly to contain losses and avoid future disruption

Vugrin et al. [25] proposed the generic concept of disruption and recovery underlying performance-based approaches, which is a time-dependent function $F(t)$. Under normal operating conditions, the system performance measure F has a nominal value, until the system suffering a disruption at the time t_0, as illustrated in Figure 1.

The resilience formulation is the ratio of recovery to loss:

$$R(t) = \frac{F(t) - F_{\min}}{F_0 - F_{\min}}. \tag{1}$$

Figure 1 shows the system performance deteriorates at a specific rate over time after being affected by the impact of a disruptive event. The resilience of complex networks is interpreted as the ability to retain performance during and after disruptions and to return to the normal state of operation quickly after disruptions. It has three capacities: absorptive capacity, adaptive capacity, and restorative capacity. Some researchers introduced resilience to the ATM system [17, 26]. Meanwhile, resilience formulation is also used in the airport network. There are many disruptive events impacting airport network operation, such as bad weather, failure of facilities and equipment, and public health events. Deterioration of the nominal performance of airports by the impact of COVID-19 can reflect their resilience. Ren et al. [27] proposed a three-dimensional resilience triangle model in the complex engineered systems (CESs), including defensive capability, adaptive capability, and recovery capability. Therefore, we can propose the three-dimensional resilience triangle model of airport networks under the epidemic crisis, which includes absorptive capacity, adaptive capacity, and restorative capacity (see Figure 2).

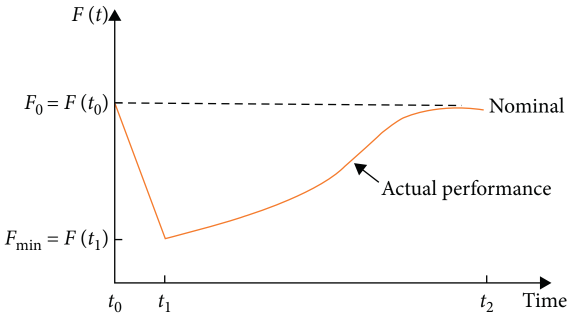


Figure 1: The generic concept of disruption.

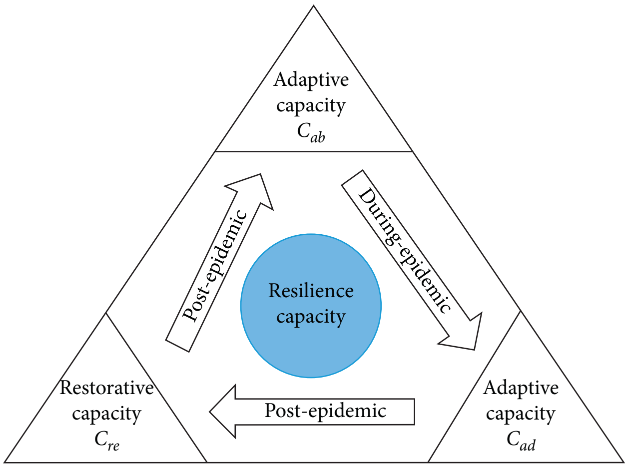


Figure 2: Three-dimensional resilience triangle model of airport networks.

Figure 3 depicts system performance as a function of recovery decisions. As shown in Figure 3, the system operation state includes four stages, such as initial steady-state at the time t_0, disruptive state from time t_d to t_r, recover state from time t_r to t_{ns}, and nominal state. Two possible paths that the system recovers with different actions that may follow are represented by the solid red line and blue line in Figure 3. The red line represents the system performance will gradually recover with action a_1; the blue line represents the system performance to recover the nominal state with action a_2 need more time than action a_1. For example, the epidemic prevention measures of airport networks may be built quickly for the passengers' health safety when COVID-19 outbreak. Different measures are taken to recover system performance with different results, and EUROCONTROL has produced two scenarios to illustrate the possible impact of the COVID-19 for recovering airports operation, which are the Coordinated Measures Scenario and Uncoordinated Measures Scenario [30].

2.2. Airport Network Resilience Measure Model.

The proposed model assesses the ability of airport network resilience and recovery using four KPAs such as airport capacity, safety, environment, and cost/benefit, respectively.

The paper mainly discussed the public health safety impact of the airport network. Therefore, the models only consider two KPAs, denoted by $i = 2$ and $A_i = \{A_1, A_2\} = \{\text{capacity area, safety area}\}$.

Following the previous studies [23], the airport capacity variable is used to measure the influence of infrastructure quality on the performance of resilience, and it includes three key performance indicators (KPI), that is,

$$\begin{aligned} & i = 1, j = 3, \\ \mathrm{KPI}_j^{A_i} &= \left\{\mathrm{KPI}_1^{A_1}, \mathrm{KPI}_2^{A_1}, \mathrm{KPI}_3^{A_1}\right\}, \\ &= \{\text{passengers volume, freight volume, aircraft movements}\}. \end{aligned} \tag{2}$$

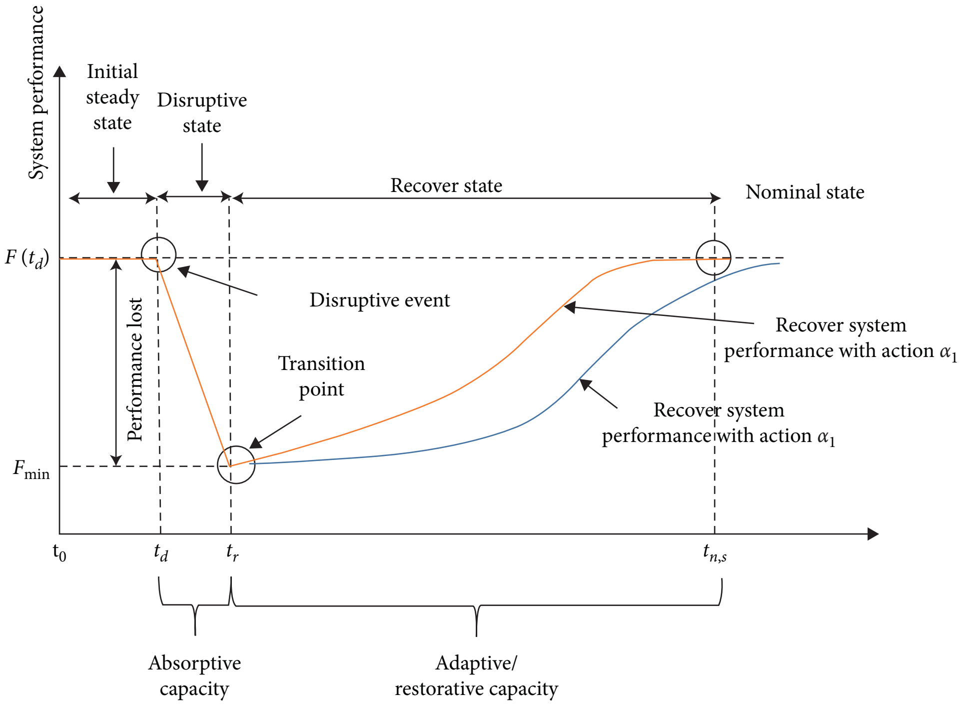


Figure 3: An illustration of the airport resilience affected by COVID-19. Source: revised and upgraded based on [25, 28, 29].

And safety contains aircraft operation safety, runway safety, and health safety, that is,

$$\begin{aligned} & i = 2, j = 1, \\ \mathrm{KPI}_j^{A_i} & = \left\{\mathrm{KPI}_1^{A_2}, \mathrm{KPI}_2^{A_2}, \mathrm{KPI}_3^{A_2}\right\}, \\ & = \{\text{aircraft operation safety, runway safety, public health safety}\}. \end{aligned} \tag{3}$$

In [20, 29], general resilience metrics (GR) for an airport network is as follows:

$$\begin{aligned} \mathrm{GR} &= f\left(R, \mathrm{RAPI}_{\mathrm{DP}}, \mathrm{RAPI}_{\mathrm{RP}}, \mathrm{TAPL}, \mathrm{RA}\right), \\ &= R \times \left(\frac{\mathrm{RAPI}_{\mathrm{RP}}}{\mathrm{RAPI}_{\mathrm{DP}}}\right) \times (\mathrm{TAPL})^{-1} \times \mathrm{RA}, \end{aligned} \tag{4}$$

wherein R represents the robustness of the system, which quantifies the minimum measurement of performance (MOP) value between t_d and t_{ns} in Figure 2. t_d is the starting time of affection of the system performance by the impact of the COVID-19 pandemic. t_{ns} is the ending time of recovery of the system performance after the end of impact COVID-19 pandemic. $\mathrm{RAPI}_{\mathrm{DP}}$ represents the rapidity and performance loss of the system in the disruptive state during the period $[t_d, t_r]$, which refers to the rate of performance decline during the disruptive state. t_r is the starting recovery of the system performance under the sustained impact of the COVID-19 pandemic:

$$\mathrm{RAPI}_{\mathrm{DP}} = \frac{\mathrm{MOP}\left(t_d\right) - \mathrm{MOP}\left(t_r\right)}{t_r - t_d}, \tag{5}$$

where $\mathrm{RAPI}_{\mathrm{RP}}$ describes the rate of system recovery during the recovery state:

$$\mathrm{RAPI}_{\mathrm{RP}} = \frac{\mathrm{MOP}\left(t_{ns}\right) - \mathrm{MOP}\left(t_r\right)}{t_{ns} - t_r}. \tag{6}$$

TAPL is the Time Average Performance Loss in the disruptive stage, which is

$$\mathrm{TAPL} = \frac{\int_{t_d}^{t_r} \left(\mathrm{MOP}\left(t_0\right) - \mathrm{MOP}(t)\mathrm{d}t\right)}{t_r - t_d}. \tag{7}$$

RA is the recovering capacity of the system, which is

$$\mathrm{RA} = \left|\frac{\mathrm{MOP}\left(t_{ns}\right) - \mathrm{MOP}\left(t_r\right)}{\mathrm{MOP}\left(t_0\right) - \mathrm{MOP}\left(t_r\right)}\right|, \tag{8}$$

where MOPs focus on different KPIs of the airport networks, and this paper mainly considers two KPAs, which is capacity area and safety area, during the pandemic of COVID-19. To allow for comparison, the MOPs of airport networks are normalized in the range $[0, 1]$:

$$\begin{aligned} \mathrm{MOP}_{\mathrm{KPI}_j^{A_i}}(t) &= \frac{\log_{10}\mathrm{KPI}_j^{A_i}(t)}{\log_{10}\max\left[\mathrm{KPI}_j^{A_i}(t)\right]} \in [0, 1], \\ t &= 1, \ldots, m, \\ i &= 1, \ldots, k, \\ j &= 1, \ldots, n. \end{aligned} \tag{9}$$

Overall, the modeling framework that examines a single indicator affecting airports network resilience metrics can be expressed as follows:

$$\mathrm{GR}_{\mathrm{KPI}_j^{A_i}} = R_{\mathrm{KPI}_j^{A_i}} \times \left(\frac{\mathrm{RAPI}^{\mathrm{RP}}_{\mathrm{KPI}_j^{A_i}}}{\mathrm{RAPI}^{\mathrm{DP}}_{\mathrm{KPI}_j^{A_i}}} \right) \times \left(\mathrm{TAPL}_{\mathrm{KPI}_j^{A_i}} \right)^{-1} \times R_{\mathrm{KPI}_j^{A_i}}, \tag{10}$$

where $\mathrm{GR}_{\mathrm{KPI}}^{\mathrm{AJ}}$ denotes the resilience metrics of key performance indicator j of key performance area A_i about impacting airport network operation.

Based on the entropy weight method [31], index entropy weight can be obtained by the following formula:

$$\mathrm{MOP} = \left\{ b_{tj} \right\}_{m\times n}, \tag{11}$$

where MOP is the normalized matrix.

The entropy of the j evaluation index is

$$E_j = (-\ln m)^{-1} \sum_{n=1}^{m} P_{tj} \ln P_{tj}, \tag{12}$$

where $P_{tj} = (b_{tj}/\sum_{t=1}^{m} b_{ij})$.

After the entropy of the index is defined, the entropy weight of the index can be obtained:

$$W_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \quad \left(0 \le W_j \le 1, \sum_{j=1}^{n} 1 \right). \tag{13}$$

Combining the weights of each index, the airport network resilience metrics in a key performance area A_i can be obtained:

$$\mathrm{GP}_{\mathrm{KPA}_i} = \sum_{j=1}^{n} W_j \mathrm{GR}^{A_i}_{\mathrm{KPI}_j}. \tag{14}$$

3. Case Study

The proposed method was applied to evaluating the airport's resilience during the COVID-19 spread. VariFlight [32] reported that aircraft movements handled by airports in mainland China reached a YoY drop of 75% in the first half of 2020, which was about the level of 2001. With more business travel encouraged by the effective prevention and control of the COVID-19, aircraft movements in June have returned to the level close to 2016. And the trends of aviation operation have been highly correlated with COVID-19 development, especially the confirmed cases of United State and European countries are in the particular fast rise, and civil aviation in those countries will get worse and may take longer to recover (see Figure 4).

3.1. Data. The data of this study was obtained from various resources; the detailed airport production operational data of Mainland China was obtained from the Civil Aviation Administration of China (CAAC) and VarFlight; this paper mainly discusses the COVID-19 impact on China and European Airports. Therefore, according to the airport production statistics data of four regions released by CAAC released, which are East region, Middle (MID) region, West region, and Northeast (NE) region, we analyze resilience recovery of the mainland airports in China during the COVID-19 epidemic (see Table 1). Figure 5 shows the data of aircraft movements, passenger throughput, and freight throughput sharply in February because of COVID-19 outbreak from Wuhan; then, the government of China posted the lockdown city ban. From March, the COVID-19 epidemic is gradually being effectively controlled in China, and the domestic flights resumed gradually until more than 70% of Chinese mainland airport flights resumed in June. Domestic passenger traffic in China already bottomed out in mid-February, and the capacity offered in June was recovered to around 76% of last year [32]. As can be seen from the curves, the airport production indicators in the eastern region recovered better than the other three regions.

3.2. Economic Losses of Aviation due to COVID-19. The socio-technical system consists of two parts: the social system and the technical system. The social system includes personnel at different organizational levels (employees, managers, contractors, etc.). The support of the social system is inseparable during the operation of the civil aviation system. Human-caused disruptions are often unpredictable and inevitable in all the systems, such as accidents, weather-induced hazards, and virus pandemic. With the COVID-19 outbreak, the aviation system was also hit hard, the traffic of 18 airports in major aviation markets in Asia-Pacific and the Middle East plummeted by 95% by the middle of April [34]. The COVID-19 pandemic has had a dramatic impact on airport traffic: passenger volumes reduced 60% in 2020 vis-à-vis the projected baseline and cargo traffic also declined by −17.5% in the first six months of 2020 year-over-year. Airports Council International (ACI) World projects a revenue shortfall for the year 2020 exceeding \$100 billion for the airport industry at a global level [35]. Under the "recession" scenario, the COVID-19 may cause a loss of US \$ 82 trillion in the global economy within five years from the University of Cambridge Judges Business School Risk Research Center data, and it is having a huge impact on the aviation and air travel industry [36]. The impact of COVID-19 has already surpassed the 2003 SARS outbreak which had resulted in a reduction of annual RPKs by 8% and US \$6 billion revenues for Asia/Pacific airlines (see Figure 6) [37].

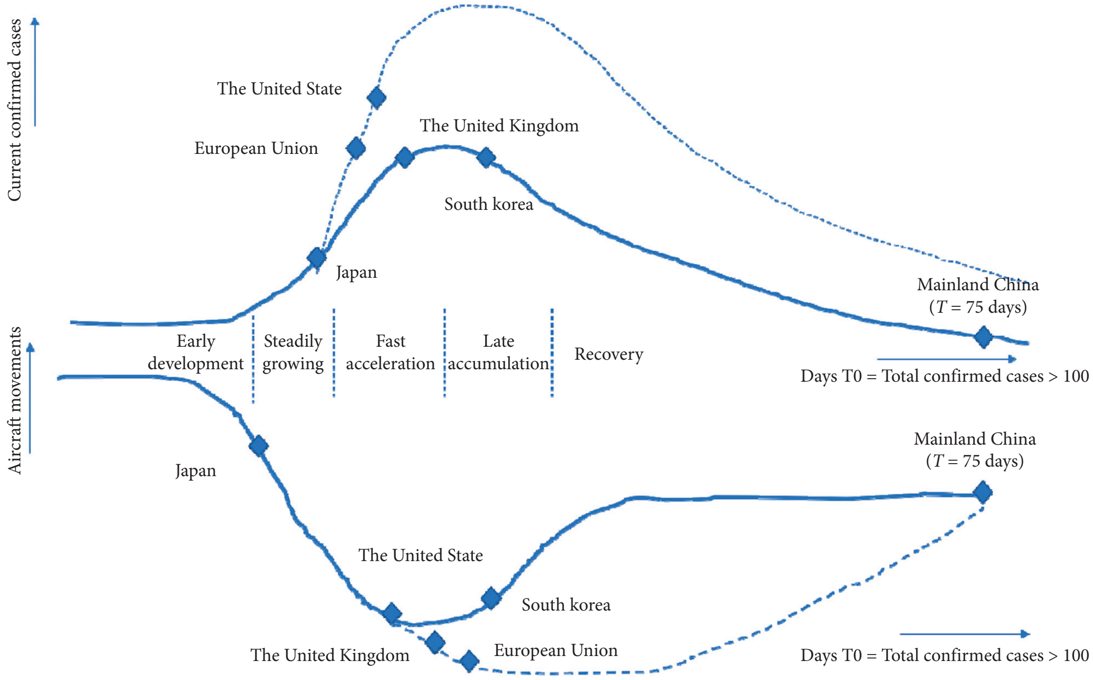


Figure 4: COVID-19 confirmed cases and aircraft movements compared chart [33].

Table 1: Airport production data of four regions in China.

Time	Aircraft movements (en thousand)				Passengers throughput (million people)				Freight throughput (en thousand KG)			
	Et	Mid	W	NE	E	Mid	W	NE	E	Mid	W	NE
Jan	42.8	11.5	27.7	5.8	5511.4	1150	2988.9	675.9	97.4	9.7	22.2	5.5
Feb	13	2.5	7.4	1.7	914.8	146.3	517.3	126.3	53.2	3.5	8.6	2.3
Mar	18.7	4.2	16	2.1	1442.7	303.7	1165.8	177.9	85.6	8.3	16.8	3.4
Apr	21	6.3	19.2	2	1603	372.4	1283.5	189.8	90.5	9.4	17.2	3.6
May	28.6	10.2	25.7	3	2542.8	601.2	1944.4	206.2	101.3	11.3	20.2	3.6
June	31.8	11.8	28	4.4	3016	748.3	2246.3	303.2	98.4	11.8	21.5	4.2
July	36.1	13.4	30.3	5.5	3864	993.3	2712	452.3	95.3	11.4	21.6	3.8

In the past eight months, the COVID-19 directly caused a loss of US $74 trillion in the international and domestic region of whole world airports from the ICAO data (see Figure 7). ICAO [38] developed interactive dashboards to monitor the impact of COVID-19 on civil aviation based on data-driven, mainly about operational impact, economic impact, aircraft utilization, and country-pair traffic. As mentioned in the International Air Transport Association (IATA), restoring air connectivity will be a key contribution to a successful and rapid recovery of the global economy post-COVID-19. The ICAO Council Aviation Recovery Task Force (CART) [39] proposed 10 key principles to restart and recover the aviation operations in a safe, secure, sustainable, and orderly manner. And states and the civil aviation industry will need to commit towards building a more resilient aviation system in the longer term.

Meanwhile, EUROCONTROL [30] has produced two scenarios to illustrate the possible impact of COVID-19 for airlines and airports in all European States, which are coordinated measures and uncoordinated measures scenario. According to the prediction data, the coordinated measures scenario envisages a loss of 45% of flights (5 million) in 2020, while the uncoordinated measures scenario would result in the loss of 57% of flights (6.2 million). Also, according to the China Aviation Daily reported [41], among the Top 150 global airports, the number of airports in mainland China, which have reduced flights by more than 50% year-on-year, is below 20 since March 16, while the number of airports in other countries and territories has been rising rapidly close to 110, which is the highest ever been.

With the effective execution of antiepidemic measures, the global outbreak is under control gradually. Since February 20, the number of confirmed cases in China has continued to reduce, and operated flights have started to rise steadily after experiencing a sustained fall. The domestic flight of China started to revive and increase from April 2020, and Europe as well as the US have also gradually reopened the domestic flight from May 2020.

3.3. Result and Discussion. According to equations (10) and (14), the airports' resilience index of these four regions in the disruption scenario can be computed. The results are shown

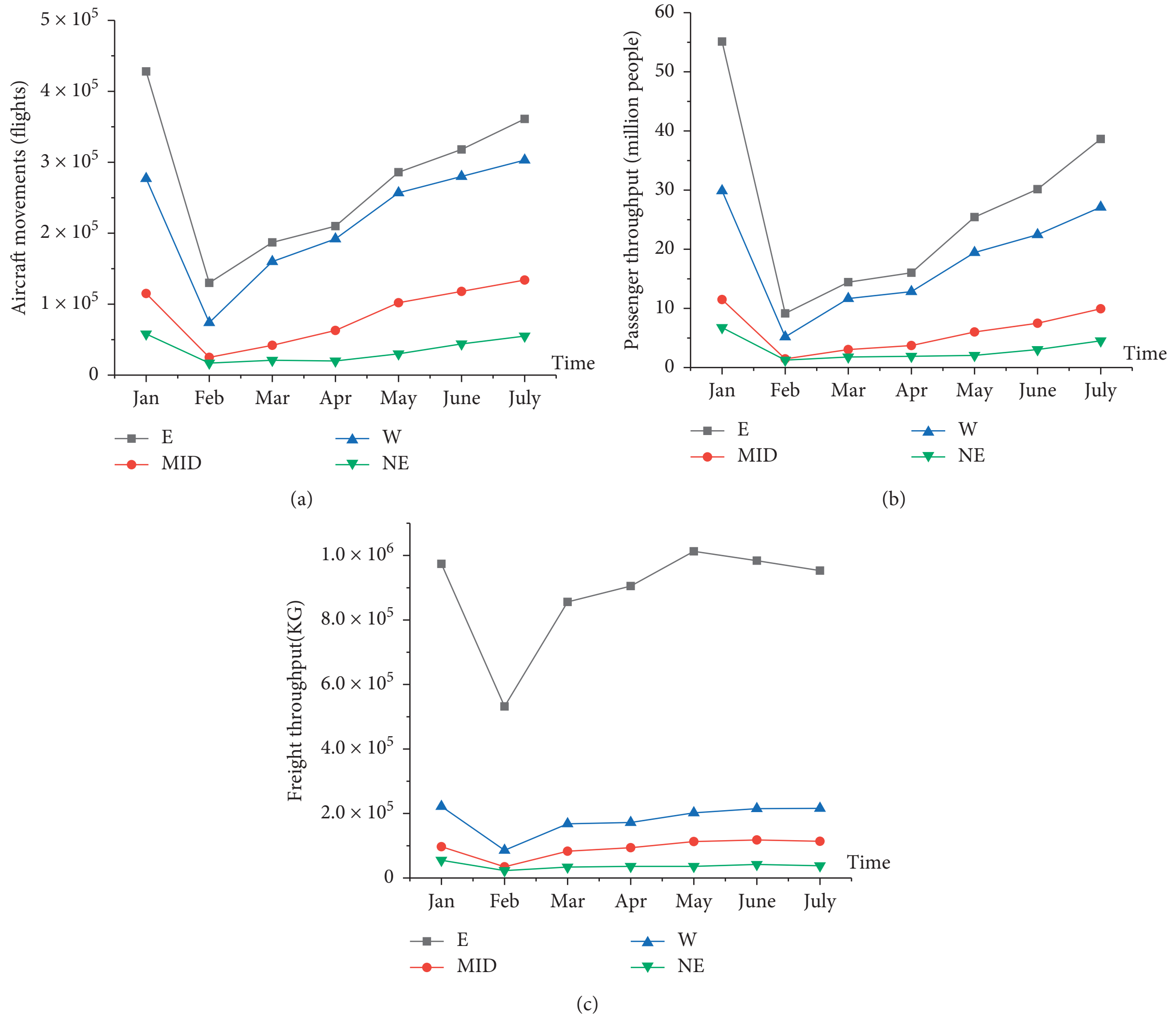


FIGURE 5: Airport production data of China in the first-seven month of 2020. (a) Aircraft movements. (b) Passenger throughput. (c) Freight throughput.

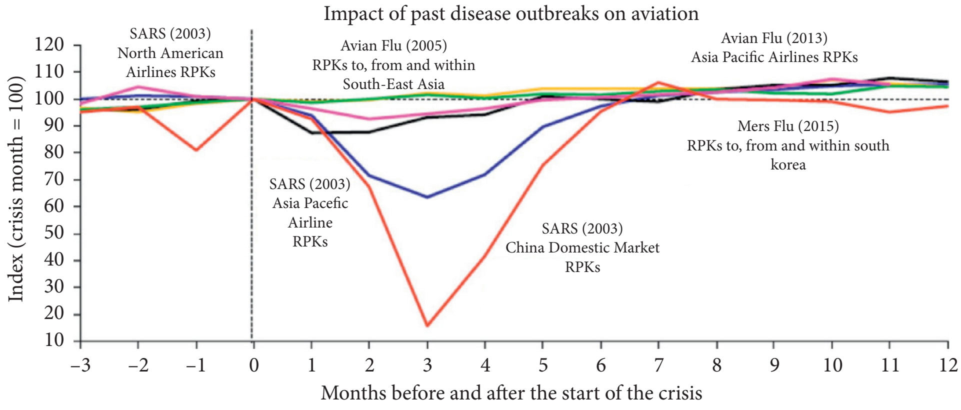
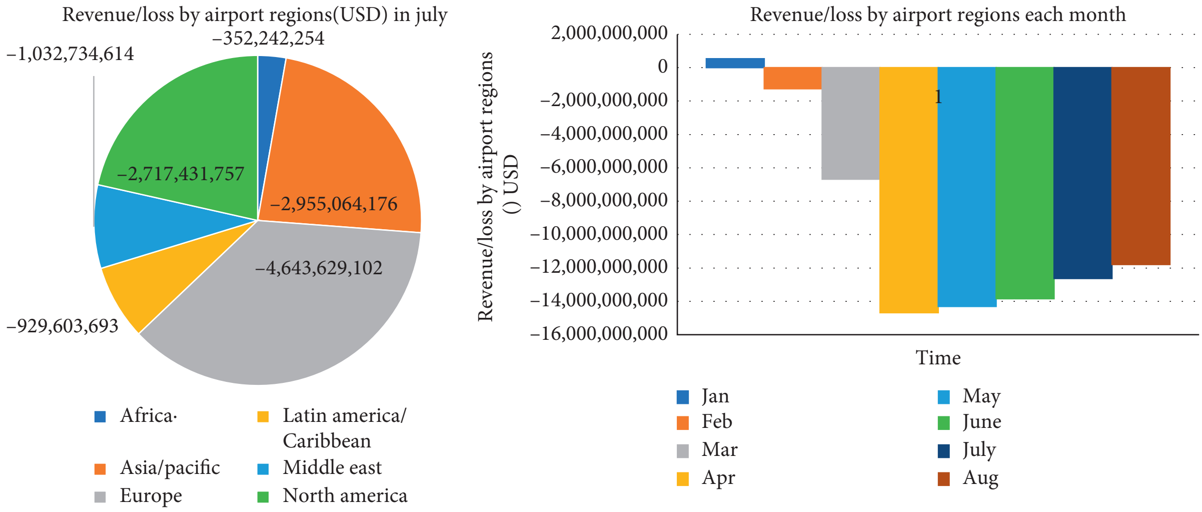


FIGURE 6: Impact of past disease outbreaks on the aviation chart [37].

in Table 2. Figures 8(a)–8(c) show the capacity recovery of the four regional airports in terms of aircraft movements, passenger throughput, and freight throughput, respectively. West region airports recover better than the other three regions according to the resilience index of aircraft movements, passenger throughput, and freight throughput.



(a) (b)

Figure 7: Airport revenue/losses of the whole world in half of 2020 (data from [40]). (a) Revenue/loss in July. (b) Revenue/loss in each month.

However, considering the weight of each indicator, overall recovery in the eastern region airports is best during the COVID-19 epidemic (see Figure 8(d)). Due to the difficulty of obtaining all production index data of the airport, this paper only analyzes the take-off and landing index. Airports in mainland China have classified three types by passenger throughput, which are above 30 million, 10 million to 30 million, and 2 million to 10 million. We choose eleven 30 million level airports of China to study the resilience and recovery of the airport during the COVID-19 pandemic, which is SHA (ZSSS), PVG (ZSPD), PEK (ZBAA), CAN (ZGGG), CTU (ZUUU), CKG (ZUCK), KMG (ZPPP), XIY (ZLXY), SZX (ZGSZ), HGH (ZSHC), and NKG (ZSHJ) [42].

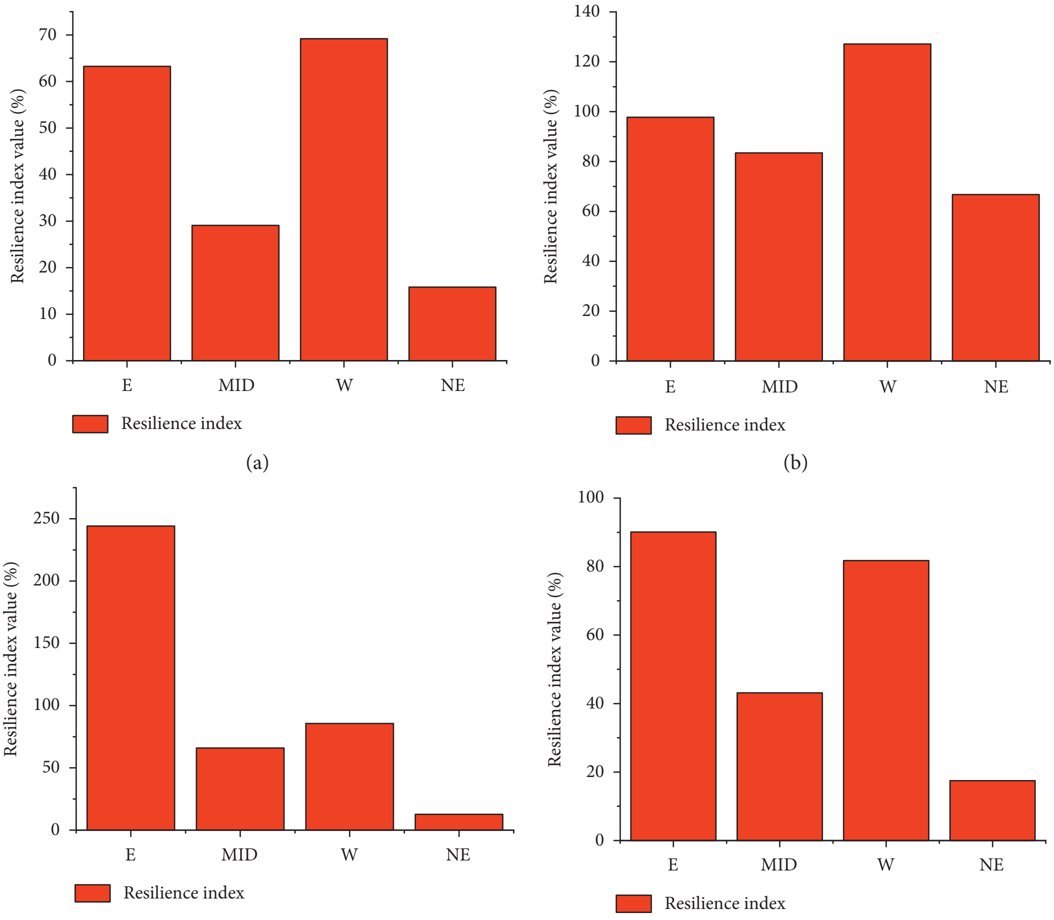
Besides, we choose eight European airports among the top 50 airports globally in 2019, that is, LHR (EGLL), CDG (LFPG), AMS (EHAM), FRA (EDDF), MAD (LEMD), MUC (EDDM), BCN (LEBL), and LGW (EGKK). The overseas epidemic continued to break out in March, and the European continent entered a "state of emergency." In Figure 9(a), the red box shows the aircraft movements trends of China mainland airports. And the blue box shows that the aircraft movement numbers have sharply decreased, due to Europe starting to post the travel restriction in April. Therefore, the traffic in Europe dropped to a freezing point from April. According to equation (10), the resilience matric about aircraft movements of airports can be computed. Tables 3 and 4 show the results.

Since the COVID-19 outbreak in Wuhan, different epidemic prevention strategies have been adopted in each country of the world. Based on SARS's epidemic prevention experience in 2003, China quickly established an epidemic prevention strategy (denotes strategy 1), and the Chinese authorities introduced exceptional measures to stem the virus rapid spread, from quarantines and shop closures to putting entire cities of millions on lockdown. Therefore, the aircraft movements of large airports that above 30 million levels of China have recovered to around 70% of the same period last year in June [32]. As shown in Figure 9(b), the resilience index value of aircraft movements at 11 major airports of China was above 2.0, except for Beijing airport. The aircraft movements of ZGSZ and ZUUU airports have returned to near pre-COVID-19 levels. Besides, ZSSS, ZUCK, and ZSHC airports also have returned to near pre-COVID-19 levels. Due to the special geographical location and strict prevention measures of Beijing Airport (ZBAA) [43], CAAC has implemented a very strict epidemic prevention policy, and the flight volume recovery is relatively low.

However, some countries such as Europe and the United States initially lacked awareness of COVID-19, so they took prevention and control measures slowly. When the epidemic outbreaks happened globally at the end of March 2020, the number of confirmed cases in European countries rose frequently. European epidemic prevention measures (denotes strategy 2) are different from Chinese, which is total immunization and no wearing face mask at first. Europe experienced a resurgence in cases, as people are more relaxed about social distancing during the summer months. Therefore, there was a trend rebound in the epidemic in the second half of 2020. As shown in Figure 9(a), the aircraft movements of European major airports dropped to a minimum in April, by the end of July, the number of aircraft movements was rising, but growth speed was slow because the COVID-19 epidemic was not fully controlled and was at risk of a second outbreak. From Figure 9(b), the resilience index value of European major airport was below 1.0 and the recovery of European airports production was relatively slow. Figures 9(c) and 9(d) show different airport operational scenarios by different strategies. Facing the global public crisis, it has different results by different strategies to prevent the COVID-19 epidemic. The strategy 1 is very strict, but strategy 2 is not severe. The results of strategy 1

Table 2: The resilience index result of four regional airports in China.

Resilience index (%)	Aircraft movement	Passenger throughout	Freight throughout	$GR_{KPI_j^{A_i}}$ (%)
E	63.26	97.75	244.24	90.09
MID	29.07	83.47	65.97	43.14
W	69.18	127.14	85.59	81.76
NE	15.83	66.74	12.67	17.49



(a) (b) (c) (d)

Figure 8: The resilience index of the four regional airports in China. (a) Aircraft movements. (b) Passenger throughout. (c) Freight throughout. (d) Airports.

and strategy 2 show that the airport's ability to respond to sudden global public emergencies varies greatly. The fact to prove that social distancing measures and testing and tracing methods can help contain a large resurgence of the COVID-19.

3.4. The Preventing and Controlling Measures in Aviation on COVID-19 Epidemic. Various countries are taking corresponding measures to gradually restore normal social operations to reduce the economic losses caused by COVID-19. Internationally, in 2006, ICAO had established the Prevention and Management of Public Health Events in Civil Aviation (CAPSCA) programme to assist in preparedness planning for the public health event that might cause a public health emergency. The CAPSCA programme has developed a strategy known as the Public Health Corridor Concept. This strategy describes how to manage essential flights that allow aircraft and crew to perform with minimal additional burdens during the COVID-19 crisis [44]. From the active case surveillance, rapid case diagnosis and management, strict follow-up and quarantine of persons with close contact, and issuance of guidance to prompt and effective high-level policy decisions, China established a complete activation of the public health system [45]. China is gradually resuming domestic flight operations. To prevent imported cases, the Chinese authorities have established a set of relative comparisons complete antiepidemic measures,

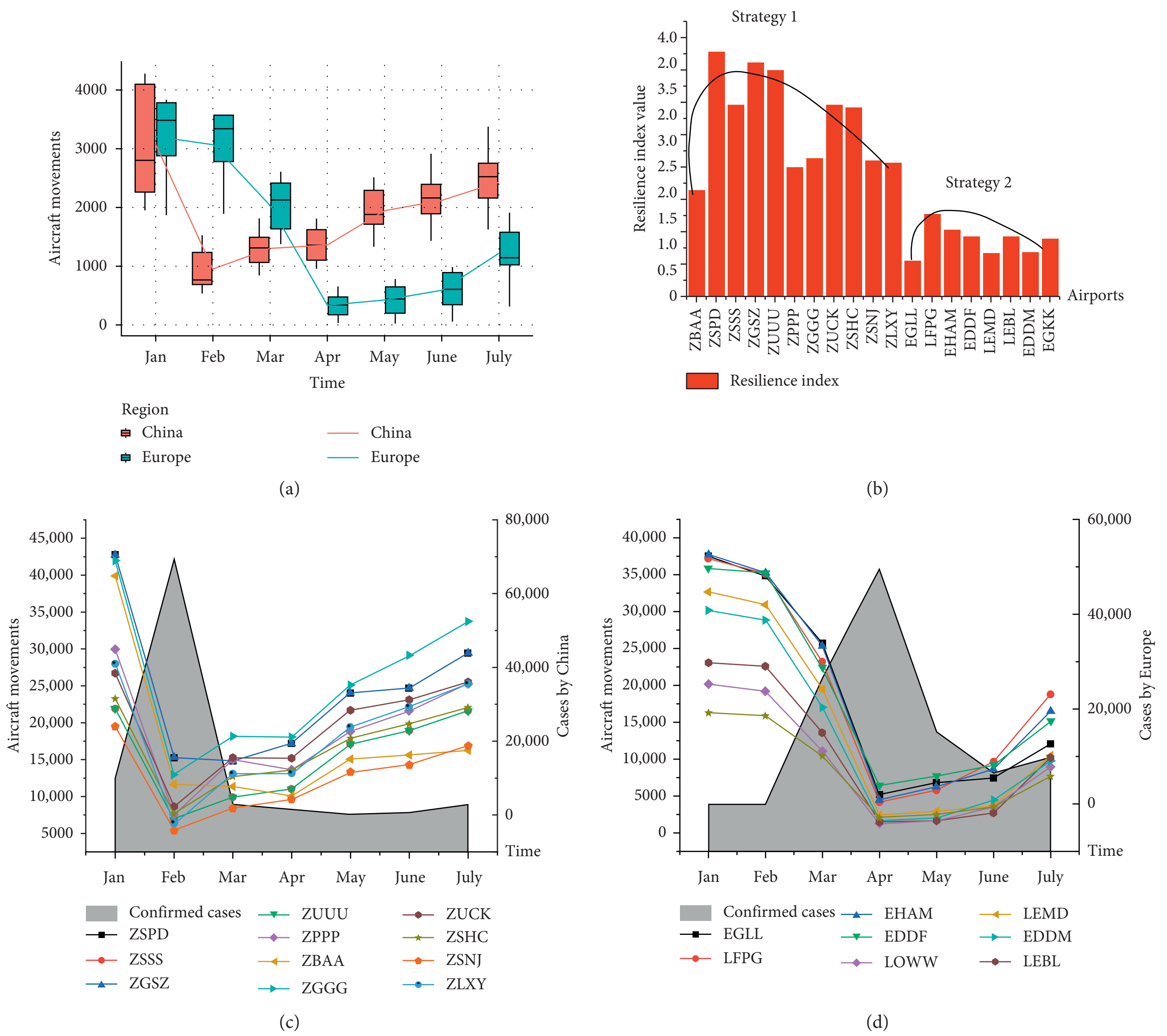


Figure 9: The aircraft movements of airports during the global public health crisis. (a) Aircraft movements of airports. (b) Resilience index value of airports. (c) Airport scenario at Strategy 1. (d) Airport scenario at Strategy 2.

such as the 14-day health code, which is an effect on the resumption of work and production [46]. To resolutely contain the increasing risks of imported COVID-19 cases, CAAC issued the Information on International Flight Plans (Phase Five) on 12 March, which all airlines shall follow. European Union Aviation Safety Agency (EASA) and European Center for Disease Prevention and Control (ECDC) have developed a serial operational guidelines on 30 June, which purpose is to serve as an Aviation Health Safety Protocol and to provide a source of best practice on how airport operators, airplane operators conducting commercial and noncommercial passenger transport operations (hereon referred to as “aircraft operators”) [47]. Furthermore, ICAO has developed this COVID-19 Recovery Platform to collate the forecasts, guidance, tools, and resources which are needed by national regulators pursuing pandemic responses and outlined a series of recommendations and measures for all levels, local, national, and international [39].

4. Conclusions

Limited studies have been carried out to assess the resilience of the airport network considering the impact of COVID-19 events on airport operations. This paper addresses one key research question using airport data in China and Europe as an example: how airport network resilience varies spatially and temporally during the COVID-19 outbreak. Based on resilience index analysis and entropy of information calculated, this study reveals that airport resilience to public health events does vary depending on factors such as public health preventive and control strategy and airport capacity.

Table 3: The resilience computations of China airport for COVID-19-Strategy 1.

Airport	GR	R	RAPI_{DP} (1/month)	RAPI_{RP} (1/month)
ZBAA	1.6307	0.8698	0.0434	0.0152
ZSPD	3.7938	0.9007	0.0497	0.0161
ZSSS	2.9680	0.8837	0.1163	0.0230
ZGSZ	3.6164	0.9086	0.0914	0.0174
ZUUU	3.4901	0.9110	0.0890	0.0164
ZPPP	1.9923	0.8662	0.1338	0.0235
ZGGG	2.1349	0.8897	0.1103	0.0179
ZUCK	2.9559	0.8891	0.1109	0.0213
ZSHC	2.9142	0.8893	0.1107	0.0211
ZSNJ	2.0974	0.8693	0.1307	0.0232
ZLXY	2.0534	0.8559	0.1441	0.0268

Note: GR: general resilience; R: robustness, RAPI_{DP}: rapidity in disruptive phase; RAPI_{RP}: rapidity in the recovery phase.

Table 4: The resilience computations of European airport for COVID-19-Strategy 2.

Airport	GR	R	RAPI_{DP} (1/month)	RAPI_{RP} (1/month)
EGLL	0.5386	0.813	0.1512	0.0264
LFPG	1.2667	0.7936	0.1618	0.0472
EHAM	1.0211	0.7982	0.1641	0.0411
EDDF	0.9164	0.8365	0.1189	0.0272
LEMD	0.6618	0.7516	0.1985	0.0465
LEBL	0.9103	0.7266	0.2208	0.0641
EDDM	0.6674	0.7261	0.2183	0.055
EGKK	0.8848	0.5615	0.2032	0.128

Note: GR: general resilience; R: robustness; RAPI_{DP} rapidity in disruptive phase; RAPI_{RP}: rapidity in the recovery phase.

In particular, the recovery of the airport network in Europe tends to be relatively longer during the COVID-19 crisis than in China, due to taking different prevention and control measures for COVID-19. The emergency response ability of the country for the public health crisis was found to have a significant positive impact on speeding up the recovery of aviation. Furthermore, we also compared the operational resilience measures with network performance indicators which were used to analyze the robustness of the airport network. Due to the strict preventing and controlling measures of the epidemic, the airport's operational production in the east and west regions of China recovered better than in other regions. The success of aviation's recovery today and future resilience is best achieved with collective efforts among different regions and sectors. The rigorous follow-up to the recommendations and measures outlined by ICAO will be required in every country.

However, one should note that this study also has several limitations, which should improve upon in future research endeavors. For example, our current analysis did not capture the factors, such as flight punctuality, COVID-19 confirm cases, passenger, and cargo throughput of airports in other countries that were implemented at the airport during the COVID-19 crisis. These aspects of airport network resilience should be further studied once such data becomes available. Future work will investigate strategies to improve the resilience of the airport network during the disruption. Using big data analytics to assess the airport network performance at the disruption, it can support the airport management agencies to take more proactive measures in emergency response and management.

Data Availability

Data can be obtained from https://ansperformance.eu/dashboard/stakeholder/airport/ and http://www.caac.gov.cn/en/SY/ Some data can be found in the manuscript (see Table 2).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported in part by the China Scholarship Council (CSC) scholarship (no. 201808515167), National Science Foundation of China (no. U1733105), special foundation for Local government Science and Technology Development of China (2020ZYD094), and Civil Aviation Authority Security Capacity Building Funding Project (TM-2018-18-1/3). National Key R&D Program of China (2018YFC0831800); Research Programs of Sichuan Science and Technology Department (17ZDYF3184).

References

[1] H. Li, S. Liu, X. Yu, S. Tang, and C. Tang, "Coronavirus disease 2019 (COVID-19): current status and future perspectives," *International Journal of Antimicrobial Agents*, vol. 55, no. 5, Article ID 105951, 2020.

[2] H. Lau, V. Khosrawipour, P. Kocbach et al., "The association between international and domestic air traffic and the coronavirus (COVID-19) outbreak," *Journal of Microbiology, Immunology and Infection*, vol. 53, no. 3, pp. 467–472, 2020.

[3] Y. Qiu, X. Chen, and W. Shi, "Impacts of social and economic factors on the transmission of coronavirus disease 2019 (COVID-19) in China," *Journal of Population Economics*, vol. 33, no. 4, pp. 1127–1172, 2020.

[4] E. Dong, H. Du, and L. Gardner, "An interactive web-based dashboard to track COVID-19 in real time," *The Lancet Infectious Diseases*, vol. 20, no. 5, pp. 533-534, 2020.

[5] R. Dandekar and G. Barbastathis, "Quantifying the effect of quarantine control in Covid-19 infectious spread using machine learning medRxiv," pp. 1–13, 2020.

[6] J. Hellewell, S. Abbott, A. Gimma et al., "Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts," *The Lancet Global Health*, vol. 8, no. 4, pp. e488–e496, 2020.

[7] Z. Ma, *Health QR Code Helps Curb Spread of Infection*, China Daily, Beijing, China, 2020, https://www.chinadailyhk.com/article/124757.

[8] Z. Wang, M. Yao, C. Meng, and C. Claramunt, "Risk assessment of the overseas imported COVID-19 of ocean-going ships based on AIS and infection data," *ISPRS International Journal of Geo-Information*, vol. 9, no. 6, p. 351, 2020.

[9] E. Jenelius and L.-G. Mattsson, "Resilience of transport systems," in *Encyclopedia of Transportation*Elsevier, Amsterdam, Netherlands, 2020.

[10] J. Rasmussen, "Human error and the problem of causality in analysis of accidents," *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, vol. 327, no. 1241, pp. 449–460, 1990.

[11] E. Hollnagel, D. D. Woods, and N. Leveson, *Resilience Engineering: Concepts and Precepts*, Ashgate Publishing, Ltd., Farnham, UK, 2006.

[12] EuroControl, *A White Paper on Resilience Engineering for ATM, Cooperative Network Design*, EuroControl, Brussels, Belgium, 2009.

[13] C. S. Holling, "Resilience and stability of ecological systems," *Annual Review of Ecology and Systematics*, vol. 4, no. 1, pp. 1–23, 1973.

[14] J. E. Muriel-Villegas, K. C. Alvarez-Uribe, C. E. Patiño-Rodríguez, and J. G. Villegas, "Analysis of transportation networks subject to natural hazards-insights from a Colombian case," *Reliability Engineering & System Safety*, vol. 152, pp. 151–165, 2016.

[15] S. A. Markolf, C. Hoehne, A. Fraser, M. V. Chester, and B. S. Underwood, "Transportation resilience to climate change and extreme weather events-beyond risk and robustness," *Transport Policy*, vol. 74, pp. 174–186, 2019.

[16] S. Hosseini, K. Barker, and J. E. Ramirez-Marquez, "A review of definitions and measures of system resilience," *Reliability Engineering & System Safety*, vol. 145, pp. 47–61, 2016.

[17] E. Filippone, F. Gargiulo, A. Errico, V. Di Vito, and D. Pascarella, "Resilience management problem in ATM systems as a shortest path problem," *Journal of Air Transport Management*, vol. 56, pp. 57–65, 2016.

[18] A. Cook, H. A. P. Blom, F. Lillo et al., "Applying complexity science to air traffic management," *Journal of Air Transport Management*, vol. 42, p. 149, 2015.

[19] R. Palumbo, A. Errico, D. Pascarella, F. Gargiulo, and E. Filippone, "Modeling approach for resilience engineering of the future ATM system," in *Proceedings of the 15th AIAA Aviation Technology, Integration, and Operations Conference*, Dallas, TX, USA, June 2015.

[20] Y. Wang, J. Zhan, X. Xu, L. Li, P. Chen, and M. Hansen, "Measuring the resilience of an airport network," *Chinese Journal of Aeronautics*, vol. 32, no. 12, pp. 2694–2705, 2019.

[21] L. Zhou and Z. Chen, "Measuring the performance of airport resilience to severe weather events," *Transportation Research Part D: Transport and Environment*, vol. 83, Article ID 102362, 2020.

[22] M. Janić, "Modelling the resilience, friability and costs of an air transport network affected by a large-scale disruptive event," *Transportation Research Part A: Policy and Practice*, vol. 71, pp. 1–16, 2015.

[23] ICAO, *Manual on Global Performance of the Air Navigation System*, International Civil Aviation Organization, Montréal, Canada, 2009.

[24] M. Bruneau, S. E. Chang, R. T. Eguchi et al., "A framework to quantitatively assess and enhance the seismic resilience of communities," *Earthquake Spectra*, vol. 19, no. 4, pp. 733–752, 2003.

[25] E. D. Vugrin, M. A. Turnquist, and N. J. K. Brown, "Optimal recovery sequencing for enhanced resilience and service restoration in transportation networks," *International Journal of Critical Infrastructures*, vol. 10, no. 3, pp. 218–246, 2014.

[26] Z. Jakšić and M. Janić, "Modeling resilience of the ATC (air traffic control) sectors," *Journal of Air Transport Management*, vol. 89, pp. 1–20, 2020.

[27] F. Ren, T. Zhao, J. Jiao, and Y. Hu, "Resilience optimization for complex engineered systems based on the multi-dimensional resilience concept," *IEEE Access*, vol. 5, pp. 19352–19362, 2017.

[28] D. Henry and J. Emmanuel Ramirez-Marquez, "Generic metrics and quantitative approaches for system resilience as a function of time," *Reliability Engineering & System Safety*, vol. 99, pp. 114–122, 2012.

[29] C. Nan and G. Sansavini, "A quantitative method for assessing resilience of interdependent infrastructures," *Reliability Engineering & System Safety*, vol. 157, pp. 35–53, 2017.

[30] EuroControl, *Aviation Recovery–Importance of a Coordinated approach*, EuroControl, Brussels, Belgium, 2020.

[31] Y. Liu and J. Cui, "Identification of hazard sources in prefabricated building construction by entropy weight method," *IOP Conference Series: Earth and Environmental Science*, vol. 560, no. 1, Article ID 012073, 2020.

[32] VariFlight, *VariFlight Civil Aviation Report*, VariFlight, Hefei, China, 2020.

[33] VariFlight, *COVID-19 Outbreak: Analysis of Global Aviation Operation*, VariFlight, Hefei, China, 2020.

[34] Flightglobal, "Traffic at Asia-Pacific airports hits "rock bottom": ACI," 2020, https://www.flightglobal.com/air-transport/traffic-at-asia-pacific-airports-hits-rock-bottom-aci/138010.article.

[35] P. Villard, "COVID-19: Tailoring airport charges to support the economic recovery of airports, ACI," 2020, https://blog.aci.aero/covid-19-tailoring-airport-charges-to-support-the-economic-recovery-of-airports/.

[36] S. Nagarajan, "$82 trillion over 5 years? Cambridge study counts the cost of cornavirus, the World economic forum COVID action platform," 2020, https://www.weforum.org/agenda/2020/05/coronavirus-covid19-pandemic-econamy-money-depression-recession/.

[37] B. Pearce, *COVID-19 Updated Impact Assessment*, IATA Economics, Montreal, Canada, 2020.

[38] ICAO, "Economic development," International Civil Aviation Organization, Montréal, Canada, 2020, https://www.icao.int/sustainability/Pages/COVID-19-Air-Traffic-Dashboard.aspx.

[39] ICAO, *Council Aviation Recovery Task Force (CART) Report*, International Civil Aviation Organization, Montréal, Canada, 2020.

[40] ICAO, "Statement on the second meeting of the International Health Regulations (2005) Emergency Committee regarding the outbreak of novel coronavirus (2019-nCoV)," 2020, https://www.who.int/news/item/30-01-2020-statement-on-the-second-meeting-of-the-international-health-regulations-(2005)-emergency-committee-regarding-the-outbreak-of-novel-coronavirus-(2019-ncov).

[41] China Aviation Daily, "Impacts of the epidemic on global civil aviation industry," Aviation Daily, Beijing, China, 2020, http://www.chinaaviationdaily.com/news/77/77851.html.

[42] VariFlight, "Global airport and airline punctuality report for the first half of 2020," VariFlight, Hefei, China, 2020.

[43] Beijing CDPC, *Prevention and Control Measures of Covid-19 in Beijing, China*, Beijing Centers for Disease Control and Prevention, Beijing, China, 2020.

[44] ICAO, "Collaborative arrangement for the prevention and management of public health events in civil aviation-CAPSCA," International Civil Aviation Organization, Montréal, Canada, 2020, https://www.icao.int/safety/CAPSCA/Pages/About-CAPSCA.aspx.

[45] T.-L. Xu, M.-Y. Ao, X. Zhou et al., "China's practice to prevent and control COVID-19 in the context of large population

movement," *Infectious Diseases of Poverty*, vol. 9, no. 1, pp. 1–14, 2020.

[46] China Center for Disease Control, *Technical Guidance for Prevention and Control of COVID-19*, China Center for Disease Control, Beijing, China, 2020.

[47] EASA, *COVID-19 Aviation Health Safety Protocol Operational Guidelines for the Management of Air Passengers and Aviation Personnel*, European Union Aviation Safety Agency, Cologne, Germany, 2020.