Comparison on Vulnerability of European and Chinese Air Transport Networks under Spatial Hazards

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(Received 3 March 2020; revised 18 April 2020; accepted 20 April 2020)

Abstract: European air transport network (EATN) and Chinese air transport network (CATN), as two important air transport systems in the world, are facing increasingly spatial hazards, such as extreme weathers and natural disasters. In order to reflect and compare impact of spatial hazards on the two networks in a practical way, a new spatial vulnerability model (SVM) is proposed in this paper, which analyzes vulnerability of a network system under spatial hazards from the perspectives of network topology and characteristics of hazards. Before introduction of the SVM, two abstract networks for EATN and CATN are established with a simple topological analysis by traditional vulnerability method. Then, the process to study vulnerability of an air transport network under spatial hazards by SVM is presented. Based on it, a comparative case study on EATN and CATN under two representative spatial hazard scenarios, one with an even spatial distribution, named as spatially uniform hazard, and the other with an uneven spatial distribution that takes rainstorm hazard as an example, is conducted. The simulation results show that both of EATN and CATN are robust to spatially uniform hazard, but vulnerable to rainstorm hazard. In the comparison of the results of the two networks that only stands from the points of network topology and characteristics of hazard without considering certain unequal factors, including airspace openness and flight safety importance in Europe and China, EATN is more vulnerable than CATN under rainstorm hazard. This suggests that when the two networks grow to a similar developed level in future, EATN needs to pay more attention to the impact of rainstorm hazard.

Key words: vulnerability; spatial vulnerability model (SVM); air transport networks; spatial hazards

CLC number: U8 **Document code:** A **Article ID:** 1005-1120(2020)02-0300-11

0 Introduction

Air transport, as one of the most important transportation modes, is not only closely linked with our daily life, but also contributes to the world economy[1-2]. In 2018, approximate 4.3 billion passengers and 5 million tones of freight were carried by airplanes, which totally brought 814 billion USD revenues for the whole world[3]. European air transport network (EATN) and Chinese air transport network (CATN), as two large air transport systems, play significant roles in the worldwide air transportation business. However, in recent years, air transport system has been suffering severe challenges when facing increasingly spatial hazards, such as extreme weathers and natural disasters. Negative effects of the hazards could become global along flight routes between airports. Usually these hazards may have severe global impacts when happen to large air transport systems. For example, the

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How to cite this article: LI Hang, LIU Xinying, ZHANG Yingfei, et al. Comparison on vulnerability of European and Chinese air transport networks under spatial hazards[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(2): 300-310.

http://dx.doi.org/10.16356/j.1005-1120.2020.02.011

2008 snowstorm disaster in southern China led to a large scale of airport closures and thousands of stranded passengers[4]; the 2010 eruption of the Eyjafjallajokull Volcano in Iceland had blocked European air transport system, causing more than 10 million passengers delayed and leading to almost 1.7 billion USD loss in airline industry[5]. The motivation to choose EATN and CATN can be further clarified from two aspects. First, in order to reduce impact of spatial hazards on air transport network, it is important to analyze the impact on large air transport systems like EATN and CATN, as they may suffer more. Second, EATN and CATN have their own features: EATN is a relative stable and advanced system with an annual air traffic demand increased by less than 1% from 2015 to 2021 in Europe forecast[6]; CATN is a rising and developing system, with over 6% forecasted annual traffic demand increase from 2018 to 2022[7]. It may be helpful to explore experience and inspiration by comparing impacts of spatial hazard on different systems, especially between an advanced system and a rising system, because the advanced systems have developed for a long time and may be apt at reducing hazard impact and maintaining resilience. Therefore, this paper focuses on analyzing and comparing impact of spatial hazards on EATN and CATN.

Vulnerability is an important concept to assess the performance of a system in the presence of hazards. In recent decades, relevant studies on vulnerability of air transport systems have grown rapidly[8-11]. At present, two distinct traditions are widely recognized and used among researchers[12]. The first one is topological vulnerability analysis[13-15]. In this category, air transport systems are described as abstract networks, in which nodes represent airports and edges represent air routes, and then the vulnerability of an air transport system can be calculated as decrease of some important network properties by removing nodes or edges randomly or according to some attack strategies. These properties include maximal flow[16], shortest path[17], connectivity[18], system flow[19], etc. The second is network attribute-based vulnerability analysis[20-21]. It also regards air transport systems as abstract networks, but considers more actual transportation information on the networks to analyze its vulnerability, such as travel time[22], travel cost[23], etc. However, both directions could hardly help us to obtain a general idea on vulnerability of air transport networks like EATN and CATN under spatial hazards. First, the two kinds reveal vulnerability of air transport networks by identifying some key components, and lacks a system viewpoint that analysis on impact of spatial hazards needs, given that a spatial hazard influence could become global through network topology. Second, both of them ignore characteristics of hazards that happen to be crucial to assess vulnerability, as a system may have different performances under hazards with different spatial distributions. The proposed spatial vulnerability model (SVM)[24] may bring some light to the problem. This model studies vulnerability of a network system by considering both its network topology and characteristics of hazards, emphasizing the global impact of spatial hazards, including direct and indirect ones, on network systems.

1 Establishment of EATN and CATN

In this section, two abstract networks for EATN and CATN are established. Then a simple topological analysis of the two networks is conducted and some conclusions about vulnerability of EATN and CATN are drawn.

1.1 Data processing

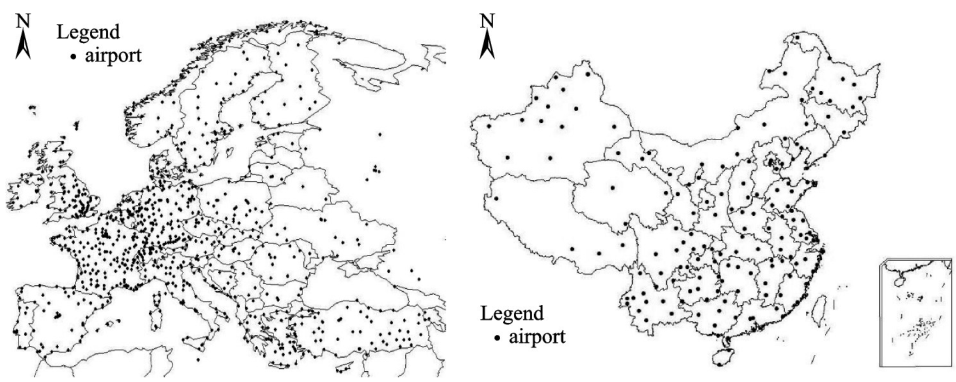
In this paper, we establish EATN and CATN based on internal flights, i.e., internal flights of Europe in EATN and internal flights of China in CATN. Although globalization leads to more and more airports running both internal and external (international) flights, internal air transport demand still dominates within a country or a region.

For EATN, we firstly collect one week European flights data from DDR2 dataset of EUROCONTROL database from 1 January 2016 to 7 January 2016. As one of the most important air traffic management data repositories in the world, EUROCONTROL database stores enormous European air traffic data. And its DDR2 dataset records detailed historical air traffic data, including each flight's ID, origin (ICAO code, latitude, longitude), destination (ICAO code, latitude, longitude), date, aircraft type and length. Secondly, we remove data of the airports outside of Europe, as well as data of external flights of all European airports. Finally, we obtain 906 airports, 14 462 air routes and over one hundred thousand flights for EATN, as shown in Fig. 1(a).

For CATN, we collect data of Chinese airport flights, from 1 January 2016 to 7 January, 2016 from the biggest Chinese travel website, Qunaer that contains detailed flights information, such as each flight's number, origin (IATA), destination (IATA), date, aircraft type, and so on. Finally, we obtain 172 airports, 4 295 air routes and 107 222 flights for CATN, as shown in Fig. 1(b).

1.2 Establishment of two directed-weighted networks for EATN and CATN

In order to better capture the topological characteristics of EATN and CATN, we describe them by directed-weighted networks, in which nodes represent airports, and edges represent nonstop flights. Take EATN as an example. Mathematically, we establish a 906×906 directed-weighted matrix $\boldsymbol{E}$. In $\boldsymbol{E}$, any element in the ith row and jth column is denoted as E_{ij}, which is weighted by the amount of flights on this edge, i.e., flights originated from airport i and ended at airport j. In addition, we regard any pair of E_{ij} and E_{ji} as different elements, i.e., any flight is directed. This is reasonable because the quantity of flights originated from airport i may be different from that ended at airport i, especially after removing external flights from original European airports. Similarly, we build a directed-weighted matrix $\boldsymbol{C}$ based on Chinese domestic flights.



(a) Spatial distribution of European airports (b) Chinese airports

Fig.1 Spatial distribution of European airports and Chinese airports

Considering traditional studies that usually analyze important properties of network topology to find vulnerability of air transport networks, we conduct a simple topological analysis on EATN and CATN based on two classical concepts, degree centrality and betweenness centrality. Degree centrality[25] is to identify certain nodes from a system that are connected by the most number of other nodes in the system. Betweenness centrality[26] aims to measure the extent to which a particular node lies on the shortest paths between any pairs of nodes. In this paper, given the two directed-weighted networks, the definitions of degree and betweenness become directed-weighted ones accordingly.

Next, we simulate and obtain the degree centrality and betweenness centrality results of EATN and CATN, as shown in Fig. 2. In Fig.2, cumulative degree/betweenness distributions of both of the networks follow a power law, showing scale-free network properties. Such networks have been proven to be resilient to random hazards but vulnerable to intended attacks[27]. However, this method may be not able to reveal the vulnerability of EATN and CATN under spatial hazards because of its drawbacks discussed in Introduction. To study vulnerability of an air transport network under spatial hazards,

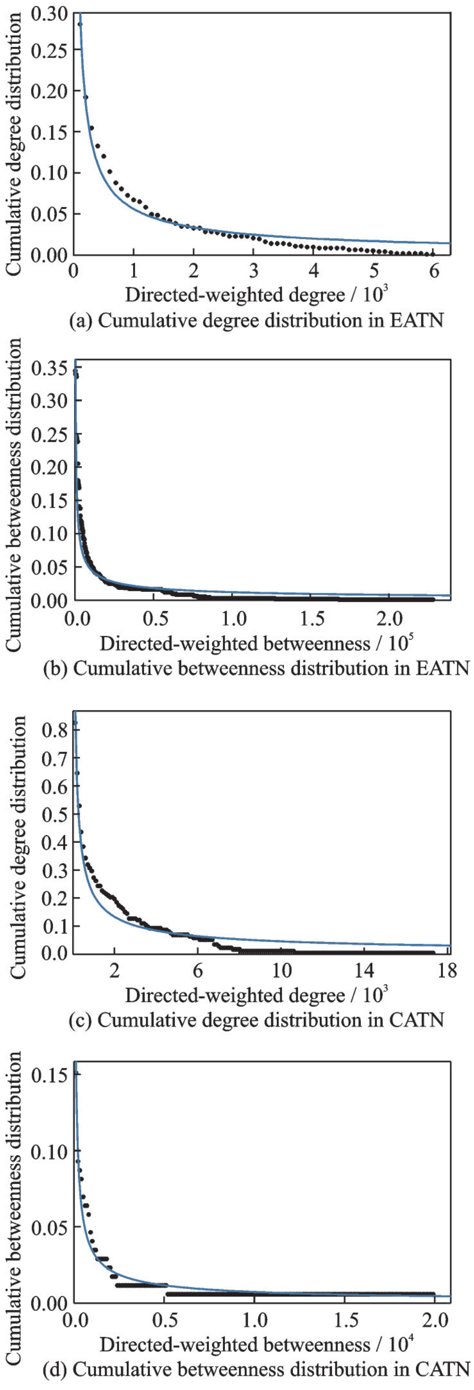


Fig.2 Cumulative degree and betweenness distribution of EATN and CATN

a new method, SVM, is introduced.

2 Method

In SVM[24], the spatial vulnerability of a network system is defined as the degree of the system as a whole to be likely harmed due to its exposure to spatial hazards. Then, SVM introduces two important curves, the impact curve and the neutral curve, to qualitatively study spatial vulnerability of a network. Further, SVM proposes two quantitative indexes, absolute spatial vulnerability index (ASVI) and relative spatial vulnerability index (RSVI), to quantitatively analyze the spatial vulnerability of a network system. This model emphasizes the global impact of spatial hazards on a network system, including direct impact and indirect impact causing by link relations among network nodes.

Specifically, in the qualitative method, the impact curve is defined by measuring the global impact of hazards on a network system against the area covered by hazards. Here we simply replace the area covered by hazards with the percentage of hazard covered area. It should be noted that the definition of global impact is highly problem dependent. Take air transport network as an example, we can use the number of impacted airports to quantify the global impact of hazards. Meanwhile, we can use impacted air routes or impacted passengers to calculate the global impact of hazards. In this paper, we mainly concern about impacted airports of EATN and CATN under spatial hazards. Therefore, we simply use impacted airports to define global impact of a spatial hazard on the two networks, i.e., the percentage of impacted airports. In addition, considering the impact of a hazard may be still different because of different hazard locations, even for the same hazard covered area, we further calculate the average percentage of impacted airports under a specific percentage of hazard covered area by hazard simulations. For the neutral curve, it usually reflects an expectation on the resistance capacity of a network system at the face of a spatial hazard, and is a crucial standard that we can use to judge whether or not a network system is vulnerable to the hazard. The definition of neutral curve is also problem dependent, which can be defined according to problem characteristics or common senses. In this paper, we simply define it according to a common sense, i.e., the percentage of impacted airports is proportional to the percentage of hazard covered area. Therefore, the neutral line should be a 45° straight line from the point (0%, 0%) to the point (100%, 100%), as shown in Fig. 3. After that, we can qualitatively determine whether EATN or CATN is vulnerable to a spatially localized hazard. If its impact curve is mainly above/ below the neutral line, the system is vulnerable/ robust to the hazard.

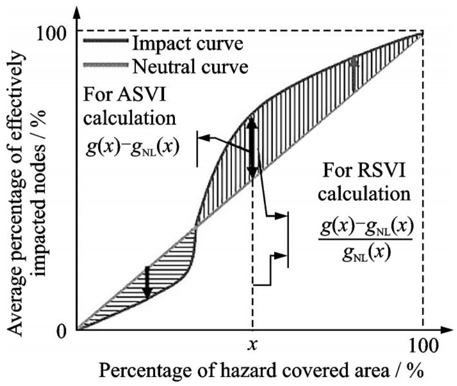


Fig.3 Spatial vulnerability model

In the quantitative method, based on the two important curves, the SVM further defines two spatial vulnerability indexes, ASVI and RSVI. Their mathematical descriptions are as follows

$$V_{\text{ASVI}}=\int_0^1 (g(x)-g_{\text{NL}}(x))\mathrm{d}x \tag{1}$$

$$V_{\text{RSVI}}=\int_0^1 \frac{g(x)-g_{\text{NL}}(x)}{g_{\text{NL}}(x)}\mathrm{d}x \tag{2}$$

where x is the percentage of hazard covered area, $g(x)$ the average percentage of impacted nodes for a given x value, and $g_{\text{NL}}(x)$ the associated neutral curve value.

According to the definition of the neutral curve in this section, one has

$$g_{\text{NL}}(x)=x \tag{3}$$

Then, we can quantitatively analyze the spatial vulnerability of EATN and CATN under spatial hazards. Specifically, if its ASVI/RSVI is positive/ negative, the system is vulnerable/robust to the hazard. A larger value of ASVI/RSVI means a higher spatial vulnerability level.

3 Case Study

In this case study, two hazard scenarios are chosen to analyze and compare vulnerability of EATN and CATN under spatial hazards. In hazard scenario 1, a hazard is evenly distributed in space. The spatially uniform hazard is usually regarded as a basic simulation scenario for network vulnerability analysis. In hazard scenario 2, the spatial distribution of a hazard is uneven, depending on the characteristics of a specific hazard, which is also common in real world. Here, we take rainstorm hazard as an example, asit usually has severe impact on air transport industry. Then, for each hazard scenario, we set up two test cases with different impact considerations.

Test Case 1: Only the airports within hazard covered area are considered, that is, only direct impacted airports.

Test Case 2: Airports that are within hazard covered area and that are outside the area but have flights to or from the airports within the area are considered, that is, both direct impacted airports and indirect impacted airports.

Under spatially uniform hazards, the occurrence probability of a hazard is equal everywhere within EATN and CATN, that is, a hazard follows a uniform spatial distribution. Under rainstorm hazard, we determine the occurrence probability of a hazard in different areas based on the actual spatial distribution of rainstorm hazards in Europe and China. Specifically, the spatial distribution of rainstorm hazards in EATN and CATN is obtained as follows. Firstly, we collect 10-year European and Chinese rainstorm occurrence data from 2004 to 2013. The European rainstorm data are collected from Wikipedia and the Chinese rainstorm data from the Chinese Meteorological Data Services. Secondly, using the inverse distance weighted (IDW) method in ArcGIS, we obtain the spatial distribution surfaces of rainstorms in EATN and CATN. Thirdly, we use the Jenks method in ArcGIS to divide the spatial distribution of rainstorms into four levels: Low, relatively low, relatively high, and high (as shown in Fig. 4). These four levels are used to determine the hazard occurrence probability within a given hazard area. For example, in hazard simulation, if an area has a low, a relatively low, a relatively high, or a high level of rainstorm, the hazard probability in this area is 0.2, 0.4, 0.6, or 0.8, respectively.

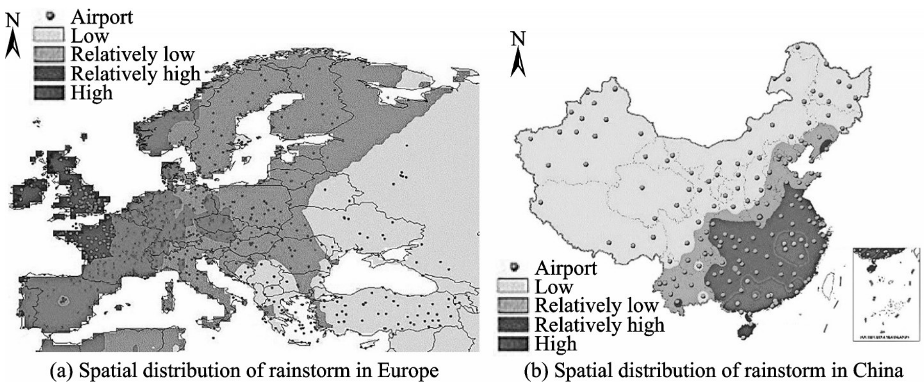


Fig.4 Spatial distribution of rainstorm in Europe and China

In this simulation study, firstly, we divided the map of China and Europe into regular grids. Europe is 22 grid×28 grid and China is 20 grid×25 grid. Each grid size is assigned a 0/1 value depending on covered area in EATN or CATN. The total area size of EATN or CATN are obtained by summing up all grid size values. Secondly, the hazard occurrence probability of each grid in EATN or CATN is determined based on the distribution of spatially uniform hazard or rainstorm hazard. Then, for a specific percentage of hazard covered area, we calculate the number of grids needed for such percentage, and choose corresponding quantity grids based on hazard occurrence probability of them. Finally, we calculate the percentage of impacted airports in EATN or CATN by counting the number of airports within the hazard covered grids, and use Eqs. (1), (2) to calculate its ASVI and RSVI values. In each test case, we change the percentage of hazard covered area from 0% to 100% by a step of 0.5%. For each given percentage of hazard covered area, we conduct 1 000 hazard simulation tests. The results of this case study are given in Table 1 and Figs.5, 6.

Table 1 Simulation results on vulnerability of EATN and CATN

Parameter	EATN				CATN			
	Test Case 1		Test Case 2		Test Case 1		Test Case 2	
	ASVI	RSVI	ASVI	RSVI	ASVI	RSVI	ASVI	RSVI
Spatially uniform hazard	−0.191 2	−0.425 9	60.240 9	266.530 3	−0.796 4	−1.606 2	50.707 4	250.049 8
Rainstorm hazard	10.947 3	29.276 2	66.096 6	304.496 6	6.412 0	18.615 7	52.960 0	272.785 0

In Test Case 1 of EATN under spatially uniform hazard, both ASVI and RSVI are negative, which indicates that EATN is robust to spatially uniform hazard. This is consistent with topological analysis of EATN in Section 1. In Test Case 2, both ASVI and RSVI values of EATN become positive, and the impact curve become above the neutral curve see Table 1 and Fig. 5(b), implying that EATN become vulnerable to spatially uniform hazard. This result is reasonable. As we all know, European airports have complicated flights relations with each other. If we take indirect impacted airports into account, the hazard would obviously have more severe impact on EATN, which is also consistent with reality. Under rainstorm hazards, we can see all results of EATN in the two test cases are positive, which means that EATN is vulnerable to rainstorm hazard. This result is also explainable. As well known, Europe has plenty of rains all a year around, especially in western of Europe which is also developed with more airports. A rainstorm in an area with dense airports usually has severe impact

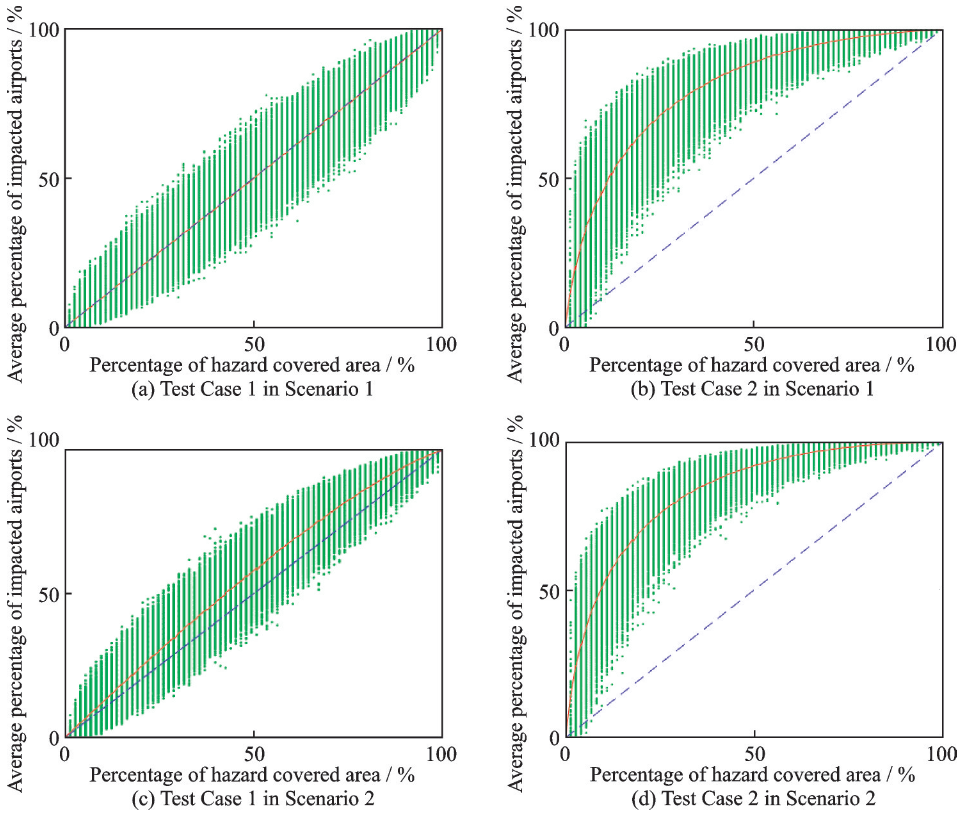


Fig.5 Simulation results on vulnerability of EATN under two hazard scenarios

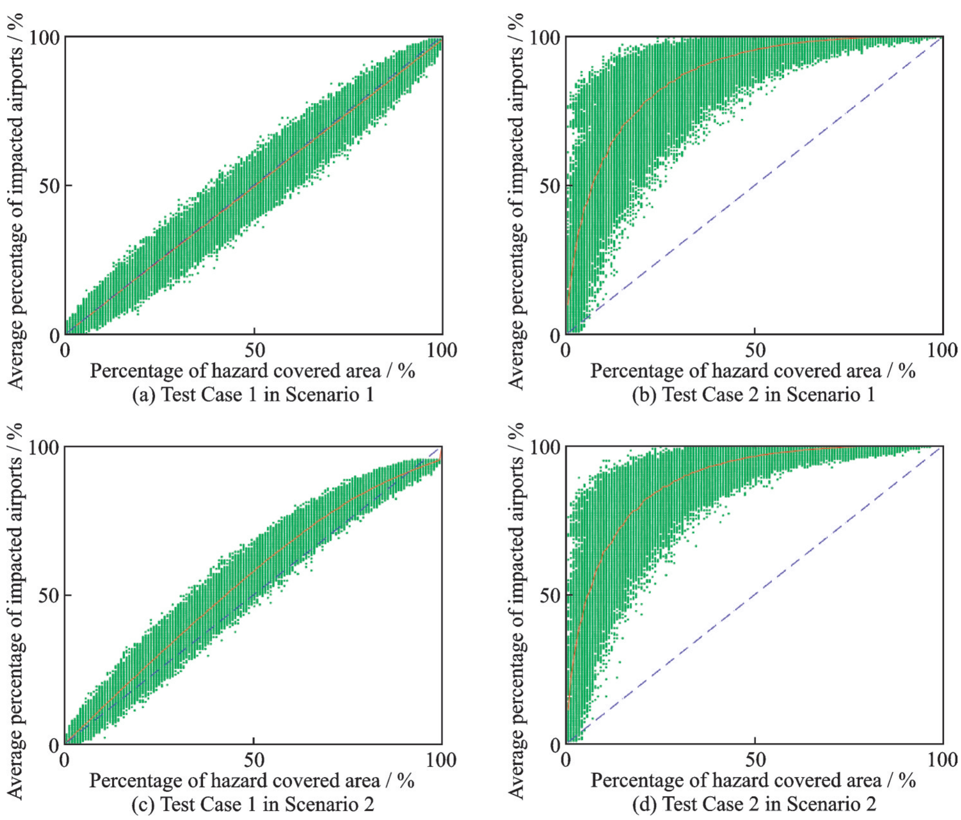


Fig.6 Simulation results on vulnerability of CATN under two hazard scenarios

on the whole system.

For CATN, according to the associated results shown in Table 1 and Fig. 6, we can obtain similar conclusions as those of EATN. Firstly, CATN is vulnerable to spatially uniform hazard when indirect impacted airports are considered. This result is consistent with the analysis of CATN in Section 1. Under rainstorm hazard, whether indirect hazard impact is considered or not, all the simulation results of CATN are positive, which means that CATN is vulnerable to rainstorm hazards. This is because most Chinese rainstorms and airports occur in eastern of China. More heavy rains that occur to more airports certainly have more bad impact on CATN.

Further, when comparing the simulation results of EATN and CATN, we can see that both of the two networks are robust under a spatially uniform hazard, which is consistent with topological analysis of EATN and CATN in Section 1. However, under rainstorm hazards, all ASVIs and RSVIs of EATN are positive and a little larger than those of CATN, which means that EATN is more vulnerable than CATN. This seems contradictory to the conclusion obtained by related statistic data[28-29] that CATN is more vulnerable than EATN as Chinese flights are more easily impacted by rainstorm hazard. This is because the traditional cognition may be misled by some unequal factors. Firstly, the airspace openness of Europe and China is different. European airspace is highly open, while China's airspace is relatively close: Only about 30% of airspace in China is available to civil aviation. This is why Chinese flights are more unpunctual than European flights even if under normal circumstances. Rainstorm hazards' impact on flights may be intensified in such limited airspace. This study analyzes the vulnerability of EATN and CATN only based on their topologies and hazard characteristics and without considering other factors like airspace openness. Therefore, it is possible that Chinese flights may be less impacted than European flights under this hazard, i.e., CATN is less vulnerable than EATN under rainstorm hazards. Secondly, flight safety importance in Europe and China may be different. In China, air safety is usually with top priority. Chinese government may require airlines to sacrifice efficiency and some benefits to ensure air safety under adverse flight conditions like rainstorm hazards that may be far from European flight restrictions. This factor is also not considered in our study. Therefore, when we analyze the results of EATN and CATN only from their topologies and characteristics of rainstorm hazard, according to some statistical data about distribution of airports in Europe and China, it is easily to obtain that EATN has more unevenly distributed dense airports than CATN, although the two networks hold similar area sizes, which can also be shown roughly in Fig. 1. Furthermore, from Fig. 4, we can see that the spatial distribution of airports is more overlapped with that of rainstorm hazards in Europe than that in China. Usually, highly frequent rainstorms occur in areas with more dense airports will have more severe impact on the system, i.e., EATN is more vulnerable than CATN under rainstorm hazards. Therefore, without considering some unequal factors, such as airspace openness and flight safety importance in Europe and China, and from the perspectives of network topology and characteristics of rainstorm hazards, EATN is more vulnerable than CATN under rainstorm hazards.

Although these unequal factors exist at present because of different levels of development in these two regions, there are many evidences to show that these factors may reduce, and even disappear in future, such as rapid economic development and increasingly air traffic demand in China in recent decades and forecasted future. EATN then need to be more careful to rainstorm hazards to improve its robustness.

4 Conclusions

To study and compare the vulnerability of EATN and CATN under spatial hazards, we establish two abstract networks for EATN and CATN with a simple topological analysis by two traditional network properties, degree centrality and betweenness centrality. To reflect vulnerability of the two networks more realistically and comprehensively, a new spatial vulnerability model (SVM) is introduced, which analyzes vulnerability of a network system under spatial hazards from network topology and characteristics of hazards simultaneously. Global impact of spatial hazards on network systems is emphasized. Then, based on SVM, we conduct a comparative case study on EATN and CATN under two spatial hazard scenarios: Hazards with even spatial distribution, named as spatially uniform hazard, and hazards with uneven spatial distribution, rainstorm hazards. The simulation results show that the two networks are robust to spatially uniform hazard and vulnerable to rainstorm hazards. Further, when comparing the results of EATN and CATN, we obtain an interesting conclusion that EATN is more vulnerable than CATN under rainstorm hazards, which may be contradictory to some statistic conclusions but can be well explained. We may be misled by some unequal factors like airspace openness and flight safety importance in Europe and China. Without considering such factors, only from the perspectives of network topology and characteristics of hazards, EATN is actually more vulnerable than CATN under rainstorm hazards.

It should be noted that this is just a preliminary application work of SVM. One main purpose is to verify the effectiveness of SVM to study vulnerability of air transport networks under spatial hazards. The main simulation results under two spatial hazard scenarios, spatially uniform hazard and rainstorm hazard, have been well explained with traditional vulnerability conclusions or deep analysis of the two networks' topology and hazard characteristics in Section 3. For its application potential in hazard risk management, analyzing vulnerability of a system is usually the first step, which is of great significance. Then, for a more vulnerable system, related managers need to pay more attention and take mitigation measures to reduce the hazard impact. In this paper, without considering some unequal factors, like airspace openness and flight safety importance in Europe and China, and from the aspects of network topology and characteristics of rainstorm hazards, we conclude that EATN is more vulnerable than CATN to rainstorm hazards. In this case, EATN needs to pay more attention to hazards and should take mitigation measures.

In future, more efforts will be needed to obtain more precise results on vulnerability of EATN and CATN under spatial hazards. Some directions for future work include further theoretical extension of SVM, like preparedness of components and more realistical indirect impact of hazards, application to more spatial hazard scenarios such as hurricane, snowstorm, with more adequate data.

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Acknowledgements This work was supported in part by the National Key Research and Development Program of China (No. 2018YFC0823706-02), and the Fundamental Research Funds for the Central Universities of China (No. 3122019057). The flight data of EATN and CATN are collected from the database of EUROCNTROL and Qunar, respectively. Some preliminary results have been presented on 2017 Risk Analysis and Crisis Response Conference.

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artificial intelligence, air traffic management, and integrated risk governance.

Author contributions Dr. LI Hang designed the study, proposed the method, interpreted the results and wrote the manuscript. Ms. LIU Xinying contributed data and program for the case study. Ms. ZHANG Yingfei contributed data and analysis for the case study. Prof. HU Xiaobing contributed to the background and discussion of the study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Bei)

空间灾害下中欧航空运输网络的脆弱性比较研究

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摘要：欧洲航空运输网络(EATN)和中国航空运输网络(CATN)作为世界上两个重要的航空运输系统，正遭受着日益严重的空间灾害，例如极端天气和自然灾害。为了更真实地反映并比较空间灾害对这两类网络的影响，本文介绍了一种新的空间脆弱性模型(Spatial vulnerability model, SVM)，该模型同时考虑网络拓扑结构和灾害特点两个方面因素研究网络系统的空间脆弱性。在引入SVM之前，本文先建立了EATN和CATN的两个抽象网络，并用传统脆弱性方法对其进行了简单的拓扑结构分析。之后，介绍了如何运用SVM研究空间灾害下航空运输网络脆弱性的方法。在此基础上，选取了两个代表性空间灾害情景，开展了EATN和CATN的脆弱性比较案例研究。这两种空间灾害，一种在空间上均匀分布，称为空间均匀灾害，另一种的空间分布不均匀，这里以暴雨灾害为例。仿真结果表明，EATN和CATN均对空间均匀灾害具有鲁棒性，但在暴雨情景下表现出脆弱性。在进一步比较暴雨情景下两个网络的脆弱性结果时，不考虑某些不对等因素(例如欧洲和中国的空域开放程度和飞行安全的重要性等)的影响，仅从网络拓扑结构和灾害特点来看，在暴雨情景下，EATN比CATN更加脆弱。这表明，当未来两个网络发展到同等发达水平时，EATN更需要重视暴雨灾害的影响。

关键词：脆弱性；空间脆弱性模型；航空运输网络；空间灾害