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An analysis of the Chinese scheduled freighter network during the first year of the COVID-19 pandemic

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ABSTRACT
COVID-19 caused the vast majority of passenger flights to be grounded, but the crisis raised the importance of the network of dedicated cargo flights and, therefore, interest in its development. This paper aims to evaluate the Chinese scheduled freighter network (CSFN) via its topological properties and to explore its changes following the COVID-19 pandemic. Using spatial analysis with the complex network theory (CNT), the paper found that the CSFN displays small-world and scale-free network properties, similar to that of air passenger network. Hangzhou, Shenzhen and Nanjing are the dominant national hubs in the CSFN because they host the headquarters of many e-commerce giant enterprises and have relatively underutilized airport capacities. The CSFN has improved since the COVID-19 pandemic, with increased network average degree, clustering coefficient, and closeness, and reduced average path. These improvements were mainly driven by major hub cities whose centralities had been strengthened with more route connections. Since China’s air passenger traffic had quickly restored in the second half of 2020, we argue that the changes in the CSFN during COVID-19 were unlikely to be a result of the substitution effect between freighter and passenger aircraft. It was more likely a result of the higher air cargo demand during the pandemic and airlines’ realisation of the importance of freighter operations in China.

1. Introduction
The development of China’s air freight market commenced a few decades ago in conjunction with the country’s rapid economic growth. This increase is attributed to the development of global manufacturing supply chains, especially after China’s entry into the World Trade Organisation (WTO) in November 2001 (Hui et al., 2004). In recent years, China has become the largest e-commerce market, selling US$1.5 trillion worth of goods in 2019 (Boeing, 2020). Shopping online became the primary driver for China’s air cargo volume and revenue. From 2012 to 2017, the increase in the number of parcels and turnover was 48% and 33%, respectively (Boeing, 2018). According to Boeing’s World Air Cargo Forecast (Boeing, 2020), as a key participant in this market, China is expected to have the fastest growing regional air cargo market with an expected average 4.3% annual growth in the coming 20 years by 2039.

The years of rapid economic growth created a severe imbalance in regional development: more than 70% of the air cargo and mail volume is still concentrated in the eastern part of the country (CAAC, 2019). However, recent increases in labour costs in the eastern coastal area and foreign capital investment moving to inland China, with support from the Chinese government, have accelerated the infrastructure development of the air freight industry and network in inland cities such as Zhengzhou (Walcott and Fan, 2017). Also, Chinese cargo airlines lack dedicated freighter aircraft whereas in the USA, for example, UPS and FedEx operate more than 1000 dedicated freighter aircraft (Fang et al., 2009). Therefore, Chinese airlines rely on passenger aircraft carrying cargo in their ‘belly’ compartment (i.e., the cargo hold).

While a large amount of the domestic air cargo is transported via the belly capacity in passenger flights, the geographic pattern of the air cargo network depends on the nature of aircraft and the passenger flight timetable (Jiang et al., 2003). The top 20 mail and cargo airports are almost the same as the top 20 passenger airports. The air corridors linking the three main international gateway airports – Beijing, Shanghai and Guangzhou – contain the largest market share with more than 40% of the total cargo and mail traffic. The unbalanced air route network and the intensive traffic in the east coast means the ‘golden triangle’ of air routes connecting these three mega-cities is almost saturated, with the main airports in this area nearing maximum capacity (Zhang and Zhang, 2016; Ma et al., 2019).

In early 2020, the vast majority of passenger flights were grounded.
as a possible measure to control COVID-19 spreading (Zhang et al., 2020; Tisdal et al., 2021). This resulted in a significant shrinkage of the overall cargo capacity initially because of the reliance on the carrying capacity of passenger flights. The COVID-19 pandemic reinforced the desperate need for specialised freight aircraft and airport infrastructure to increase air cargo capacity (Li, 2020a). Amid the crisis, the authorities recognised a deficiency in emergency logistics caused by an inadequate dedicated air cargo transport system with restricted services such as a scarcity of specialised cargo airports and the absence of very large logistics companies with international standardisation. The virus outbreak exposed the crucial role of logistics in tackling public health emergencies. A seamless air cargo service is critical for fulfilling the prompt delivery of supplies when reacting rapidly to public health events (MERICS, 2020). The obstacles in air cargo capacity thus should be removed (Li, 2020b).

Therefore, how the air cargo industry meets the e-commerce boom and responds quickly to public health hazards has received extensive attention from Chinese authorities. In August 2020 the National Development and Reform Commission and the Civil Aviation Administration of China (CAAC) issued a memorandum with opinions on how to develop China’s air cargo transport facilities. The memorandum pointed out that cargo airlines should expand their fleets and develop dedicated aircraft transport. Specifically, it gave explicit directions on developing specialised air cargo enterprises. It encouraged the current air freight operators, which are broadly speaking state-owned passenger airlines’ subsidiaries or their cargo business divisions, to establish dedicated cargo airlines by breaking state ownership restrictions and attracting more investment from the private sector. Private logistics companies were welcome to build their cargo capacity with in-house fleets and lead the planning, construction and operation of professional cargo hub airports. With large express logistics enterprises as the main body, Chinese cargo airlines were expected to be the primary entity to construct and operate the air freight network.

Despite the recognised significance of dedicated air cargo capacity in the foreseeable growth of China’s air transport industry, the literature on Chinese cargo airlines and their network is scarce when compared with that for all-passenger airlines in China. The collapse of the air passenger network in the initial stage of the COVID-19 pandemic implies an insufficient cargo capacity and thus a disruption in the just-in-time global supply chains. With the high demand for medical and essential items, and the encouragement of government policies, operating dedicated cargo flights has been a significant source of revenue for many airlines and saved them from bankruptcy. China’s air freight sector has been developing very fast in the last two decades and the pandemic provides it with another growth opportunity. However, little attention has been paid to China’s air freight operators and their network development. This research aims to address this topic and fill the literature gap. Specifically, first, this paper will review the development of the dedicated cargo carriers in China. Second, we will conduct a spatial analysis using the complex network theory (CNT) to examine their network properties before and after the outbreak of the pandemic. Third, this study will identify the significant nodes and assess the performance of the CSFN during the pandemic period. This paper has seven sections. Section 1 introduces the study. The literature on dedicated air freight services and their networks is reviewed in Section 2. The background of Chinese cargo airlines is given in Section 3. Section 4 introduces the methodology and the data collection procedure. An overview of the current status of the CSFN is presented in Section 5. Section 6 examines the changes in key indicators of the CSFN during the pandemic period. Section 7 concludes.

2. Literature review

The belly compartment’s capacity in combination with passenger services was the initial entrant in the air cargo market, with air freight providing an income supplement (Van Asch et al., 2020). In the latter half of the twentieth century, dedicated freight-only airlines and specialist air freighter services began to emerge (Van Asch et al., 2020; Budd and Ison, 2017). Even though both types of traffic require identical airport-to-airport transport services, they operate in different modes in terms of cost structures, management features and spatial supply-demand patterns (Budd and Ison, 2017). Fundamentally, the requirements for human beings and cargo being transported on board are different. Zhang and Zhang (2002) compared the different characteristics of air cargo and passenger services. First, the preference for flight take-off time and route choice (to travel directly or to pass through two or more airports) is distinctive and not harmonious. Second, travellers commute between two destinations, while shippers often pass cargos to others. Finally, manufacturing and logistics centres can be located in sparsely populated areas, not locations that will attract tourism traffic. These factors influence dedicated air freight services and give them distinct characteristics from that of the passenger flights with belly cargo which generally considers passenger customers ahead of freight requirements (Scholz and Cossel, 2011; Lange, 2019).

The network patterns of passenger flights are different to those of dedicated air freight services (Zhang and Zhang, 2002; Scholz and Cossel, 2011). The dedicated cargo operations often show “big circle” routes connecting a few destinations, while passenger carriers often utilise hub and spoke services (Zhang and Zhang, 2002). Since cargo traffic has a unique routing pattern and different requirements to passenger traffic, the flight schedules and routes of passenger services are not suited to cargo operations. Moreover, Lange (2019) found an increasing risk of departure delays because of the more complicated operation when handling passengers and cargo at the one time. As a result, passenger flights need to consider how the volume of cargo being shipped impacts on passenger service quality. In contrast, dedicated cargo airlines fly aircraft to airports with networks and schedules that suit air freight requests (Merkert et al., 2017). Hence, dedicated cargo carriers provide better control of take-off and landing time, shipping amounts and journey, utilisation of specialised cargo airports and the disposition of hazardous and outsized shipments that cannot be loaded on passenger aircraft. These advantages are favourable for shippers and cargo airlines (Budd and Ison, 2017; Van Asch et al., 2020).

Despite this essential role for dedicated air cargo carriers in the air freight services sector, the academic literature on dedicated cargo airline scheduled networks is scarce. In studies about the passenger business, air cargo sometimes exists simply as a counterpart or auxiliary service (Zhang and Zhang, 2002; Zhang et al., 2004; Hong and Zhang, 2010). The literature focuses on the choice of airport and the network centrality of individual carriers (Gardiner et al., 2005; Gardiner and Ison, 2008; Scholz and Cossel, 2011; Kupfer et al., 2016), rather than evaluating the whole network with comprehensive topological indices to reflect the overall structure. Some studies have evaluated the air cargo network containing combined and dedicated cargo routes together (Scholz and Cossel, 2011; Bombelli et al., 2020), while Boonekamp and Burghouwt (2017) apply a connectivity model to analyse the networks of seven European airports with the main cargo volume shipped in the region. Lin and Chen (2003) investigated mainland China’s air cargo network, but their study focused on the air cargo flows to and from China’s gateway airports, with no mentioning of the air cargo network in the domestic market.

Some studies have provided a network analysis of global and regional air cargo markets using an international cargo traffic dataset (Bombelli et al., 2020; Malighetti et al., 2019a; Bowen Jr, 2012). The air-cargo service network literature primarily focuses on global logistics companies, the US and the international trade market (Bowen Jr, 2012; Malighetti et al., 2019a). Malighetti et al. (2019a) Bowen Jr (2012) pointed out the important roles of Chinese airports as the main hubs in Asia for global logistics companies. However, no reference is made to the air freight network patterns of the dedicated cargo carriers in China. Therefore, it is worth taking a closer look at Chinese cargo carriers and the trend of their development in the world’s biggest e-commerce and
3. Dedicated air freight services in China

At the end of 2020, there were nine carriers operating scheduled dedicated air cargo flights in China. Table 1 shows general information about these cargo carriers, including the size of their own fleet (all carriers are using Boeing aircraft), ownership and hub airports. The scheduled freighter networks they have built are the focus of this paper.

The International Air Transportation Association (IATA) considers e-commerce growth to be one of the primary drivers of air cargo industry developments (IATA, 2018). China Postal Airlines, SF Airlines and YTO Cargo Airlines are the cargo-only carriers of three local logistics companies, respectively: China Post Group, SF Express and YTO Express. Founded in 1996, China Postal Airlines is wholly state-owned. SF Airlines and YTO Cargo Airlines are owned by private investors.

According to the State Post Bureau (2020), in 2019 China’s express delivery volume reached 63.52 billion orders and the total industry revenue reached RMB749.78 billion (approximate US$110 billion). The sub-total market share of delivery orders of the top six express logistics companies, which are all listed private sector firms, reached 80.37%. Only two of them, SF Express and YTO Express, operate self-owned air cargo fleets and scheduled flights within these top six express logistics companies. SF Express is a leading logistics company in China with an annual revenue of RMB112.19 billion (approximate US$16.74 billion) as of 2019, which was far higher than other top players, while YTO Express’s annual revenue was RMB31.15 billion (approximate US$4.65 billion) (Fig. 1).

Air China Cargo was established in March 2003 by Air China based in Beijing Capital International Airport. By the end of 2020, Air China Cargo’s freighter fleet comprises three B747–400s, eight B777Fs and four 757-200SFs. The wide-body aircraft are mainly deployed in the international market. In 2010, Air China Cargo became a joint venture between Air China and Cathay Pacific Airways. Currently China National Aviation Holding owns 45% of its shares with Cathay Pacific Cargo and Langxing being the second and third largest stake holders, respectively.

Suparna Airlines and Tianjin Air Cargo are both majority-owned by the Hainan Airlines Group. It was formerly known as Yangtze River Airlines, which had developed from Yangtze River Express which was founded as a cargo-only airline in January 2003. The airline was rebranded as Suparna Airlines on 7 July 2017. Yangtze River Express had offered a dedicated air cargo service to SF Express, FedEx and UPS in the Chinese domestic market. From 2003 and before SF Express set up its own aircraft fleet in 2009, Yangtze River Express was the contractor used by SF Express to make it the first private parcel express company using dedicated cargo flights in China. In 2010, Yangtze River Express operated three B737Fs for FedEx at Hangzhou Xiaoshan International Airport, while UPS worked with the airline to build a hub for its domestic express services network at Pudong International Airport in Shanghai (Bowen Jr, 2012). Using Pudong as its hub, Suparna Airlines’ dedicated air cargo network now covers the main corridors of Shanghai–Beijing–Tianjin and Shanghai–Guangzhou on the east coast.

Tianjin Air Cargo launched its maiden flight in 2018. The airline was founded in 2016 as a joint venture between the Tianjin municipal government and Hainan Airlines. The carrier chose Tianjin as its only hub with an expectation of taking advantage of its proximity to the capital city Beijing. Using Tianjin Air Cargo, the Tianjin municipal government intended to develop an air cargo hub in north China at Tianjin International Airport to alleviate congestion at Beijing Capital International Airport. However, it is operating at a small scale compared with the competing full-freighter airlines. The network is not yet formed, with the only regular domestic all-cargo flights being on the Zhengzhou–Nanchang and Tianjin–Weihai routes.

Recently, as the result of increasing labour costs in the eastern part in China, some foreign capital investment moved to inland China (Walcott and Fan, 2017). An experimental Zhengzhou Airport Economic Zone was created, with a purpose to develop a logistics-based economy in the capital of Henan Province. The Henan local authority is enthusiastic about introducing air freight services, and to base dedicated cargo carriers at Zhengzhou Xinzheng International Airport. The airport, which is also the hub of Cargolux in China, is now the base for two cargo airlines – Longhao Airlines and Central Airlines – serving the domestic market.

Longhao Airlines is a private and dedicated cargo carrier which has been expanding rapidly. In 2015 it was founded by the Longhao Group which is based in Guangdong Province. The Longhao Group transferred its majority stake in the airline to Hainan Civil Aviation Development and

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**Table 1**
The Chinese carriers operating with a local freighter timetable in 2020.a

| Carriers                  | CAAC approval (year) | Freighter Fleet | Ownership                | Hub                |
|---------------------------|----------------------|-----------------|--------------------------|--------------------|
| China Postal Airlines     | 1996                 | 28 (B737F, B757F) | China Post Group Corporation | Nanjing            |
| Suparna Airlines          | 2002                 | 14 (B737F, B747F) | Hainan Airlines           | Shanghai           |
| Air China Cargo           | 2003                 | 15 (B737F, B747F, B777F, B757F) | China National Aviation Holding, Cathay Pacific | Beijing Capital, Shanghai |
| SF Airlines               | 2009                 | 61 (B737F, B747F, B757F, B767F) | SF Express | Guangzhou |
| Loong Air                 | 2012                 | 3 (B737F)       | Zhejiang Loong Airlines | Hangzhou           |
| YTO Cargo Airlines        | 2015                 | 10 (B737F, B757F) | YTO Express | Hangzhou |
| Longhao Airlines          | 2016                 | 6 (B737F)       | Henan Civil Aviation Development and Investment | Zhengzhou, Guangzhou |
| Tianjin Air Cargo         | 2018                 | 4 (B737F)       | Hainan Airlines           | Tianjin            |
| Central Airlines          | 2020                 | 3 (B737F)       | Central Airlines         | Zhengzhou          |

a Related information was updated to the end of 2020 from CAAC reports, the latest financial reports and company publications.

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1 The express delivery volume is measured by the number of letters and parcels delivered with the fastest form of shipping and delivery.
Investment Company Ltd. in May 2019. The airline’s full company name was then changed from Guangdong Longhao Airlines to China Central Longhao Airlines. It plans to build up a double hub system including Zhengzhou and Guangzhou Airports. In 2020 the airline aggressively doubled its network of cities by opening five new domestic destinations. Except for Shenzhen, Guangzhou, Lianyungang and Quanzhou, all of its destinations are provincial and regional cities in the middle of China.

Central Airlines is the first dedicated cargo carrier in Henan Province. Its main operating base is Zhengzhou Xinzhexing International Airport. Formerly known as Zhongzhou Airlines, the airline is majority-owned by a local freight agent, Henan Zhongzhou Tengfei International Freight Forwarding Co. Ltd. The joint venture was founded in 2016 but only started air freight operations in May 2020. It managed to put all three aircraft into operation within six months of its first flight. Operating its own fleet of three B737-300Fs, the carrier maintains a scheduled all-cargo flight network covering seven cities and seven city-pair routes.

Founded in 2011, Loong Air, like Suparna Airlines, is a local carrier operating scheduled passenger and cargo services. Previously known as CDI Cargo Airlines, the airline launched scheduled passenger flights in December 2013 with narrow-body aircraft, Airbus’s A320s. Loong Air is based in Hangzhou, the capital city of Zhejiang Province in eastern China. Taking advantage of Hangzhou’s position as the headquarters of an e-commerce giant and an important national logistics hub in the Yangtze River delta area, Loong Air focuses on the potential volume of cargo in the province. Loong Air has not increased its all-cargo fleet of three freighters in recent years, but its passenger fleet continues to proliferate. Compared with its aggressive cargo competitors, it may no longer consider all-cargo flights to be its core business.

4. Methodology and data collection

4.1. Complex network theory (CNT)

To understand Chinese domestic freighter network structure and the impact of COVID-19, we adopt the CNT approach and compare the results before and after the COVID-19 pandemic. The CNT has been widely applied to analyse a country’s overall air passenger network (e.g., Wang et al., 2011; Hossain and Alam, 2017) and an individual airline’s network to understand the strategy and competitiveness of the airlines (e.g., Jiao and Wang, 2014; Jiang et al., 2017; Wu et al., 2020). A recent paper by Bombelli et al. (2020) used the CNT to evaluate a worldwide air cargo network.

This paper uses centrality measures – degree, closeness and betweenness – to evaluate the role that hubs and spoke cities play within the networks. It also applies the structure measures to analyse the networks through indices, including degree distribution, the average path length and the clustering coefficient. We list all these variables and the indices used to analyse the networks in Table 2.

4.2. Data collection

The data were collected from the CAAC in 2020 (Civil Aviation Administration of China (CAAC), 2020a, 2020b). Normally, the CAAC issues two seasonal flight plans a year – the summer timetable (effective from late March to late October) and the winter timetable (effective from late October to late March of the next year) (Wu et al., 2020). The flight plan separates passengers and all-cargo flights. Due to the COVID-19 outbreak, the summer timetable was revised in May 2020. The study area includes cities in mainland China (excluding Hong Kong, Macao and Taiwan) with airports operating scheduled all-cargo flights from 28 October, 2019 to 29 March 2021. The routes in the network are operated by the dedicated cargo carriers discussed previously as listed in Table 1.

A node in this study represents a city rather than an airport. Most cities in the data set have a single airport. For mega-cities like Beijing and Shanghai which have more than one airport, the data from the same cities are combined. The data were only obtained for regular all-cargo flights. Passenger and charter flights are not included.

5. An overview of the Chinese scheduled freighter network (CSFN) in 2020

5.1. The CSFN in 2020

Unlike other countries’ cargo networks reported in the literature where a cargo flight tends to have multiple destinations, and may or may not return to its departure airport, it is found that about 90% of the city-pair routes in China are operated by return cargo flights. Therefore, to assess the network structure of the CSFN, we simplify it as a connected vertices and undirected lines graph $G = (V, E)$, where $V = \{v_i : i = 1, 2, \ldots, n\}$ is the number of nodes (navigable cities) and $E = \{e_i : i = 1, 2, \ldots, m\}$ the number of edges (routes). The network is described as a connectivity (adjacency) symmetric matrix $A_{n \times n}$ where an element $a_{ij} = 1$ if a flight route exists between node $i$ and $j$, otherwise $a_{ij} = 0$. When $a_{ij} = 1$, connected two nodes are considered as neighbours. The CSFN is composed of 45 cities and 132 unique air routes as at the end of 2020 (Fig. 2). Table A1 in the appendix lists the cities in the CSFN in the 2019 winter and the 2020 winter schedules, respectively, with indices including degree $(k)$, clustering coefficient $(C)$, closeness and betweenness.
5.2. Centrality measures

This subsection is dedicated to the analysis of the centrality of different cities in the CSFN, measured by the closeness and betweenness indices using the 2020 winter data. Such centrality measures illustrate the importance of each city (i.e., node) in the network. The degree is also a useful measurement of the node’s centrality and is thus discussed in this subsection for different cities. The indices of the top 20 cities in the 2020 winter are listed in Table 3. The top three positions in each of the centrality measurements are filled by the cities with national level freighter airline hubs in the CSFN. Hangzhou with its Xiaoshan International Airport is in first place on all indicators, followed by Shenzhen/Bao’an and Nanjing/Lukou. Guangzhou, Beijing and Tianjin can be classified as regional level freighter hubs in the CSFN, ranking in the 4th to 7th places. Interestingly, China’s gateways cities, Beijing, Shanghai and Guangzhou are not the top-ranking cities in the CSFN, although these cities are the top three air passenger markets in China. This suggests that the country’s freighter network does not necessarily align well with its air passenger network. In addition, Hangzhou and Shenzhen are the headquarters of China’s internet and e-commerce giant enterprises, Alibaba and Tencent, respectively, which obviously influences the outcome here.

Eastern and southern cities play key roles in the CSFN. Beijing and Tianjin are important regional hubs in the north, while Wuhan and Zhengzhou are ones in the central region. Like the passenger-oriented network, the CSFN relies on the east coast area. Other outstanding cities are Chengdu, Shijiazhuang, Fuzhou and Nanchang. Chengdu is the core city in the west. Shijiazhuang is the important node after Beijing and Tianjin in the Jing-Jin-Ji Metropolitan Region, which is also known as the Beijing-Tianjin-Hebei Economic Zone. Zhengzhou in central China has been developing rapidly in recent years (Walcott and Fan, 2017). Interestingly, according to the 2020 winter timetable, Nanchang has good degree and betweenness with connections to the main hubs in China such as Hangzhou, Shenzhen, Shanghai and Zhengzhou, and to key international hubs such as Hong Kong, Liege, Anchorage, Osaka and Moscow.

Clearly, the ranks for degree, closeness and betweenness are similar in the top 20 cities: fifteen cities appear repeatedly in all three centrality assessments. Providing more insight, the cities’ rankings on betweenness can be far less than their performances on degree and closeness (Wang et al., 2011). Cities with higher values of degree and closeness tend to have better connectivity in the network with relatively more scheduled dedicated cargo flights and more convenient access with shorter paths. However, some cities with fewer connections can act as important transit nodes. For example, Xi’an and Nanchang rank fourth and seventh for betweenness, respectively, but they have much lower ranks for degree or closeness. These two cities are both connected with important hubs, such as Nanjing and Hangzhou. They play roles as “bridge” airports, which Bombelli et al. (2020) defined as connecting two or more hub-and-spoke sub-structures in the whole network.

Overall, cities along the east coast and in the central area have the best connectivity in the CSFN with higher degree and closeness (Fig. 3). In terms of betweenness, with the fourth highest value, Xi’an serves as an important transfer hub for north western and inland cities. In terms of degree and closeness, cities in peripheral areas such as Guiyang, Haikou, Weihai, Yinchuan, Xuzhou, Yunlin and Jieyang have only one degree, and one freight flight to hub cities. Almost all these cities have the lowest value of accessibility. Several stopovers are needed before a shipment arrives at its destination in the network. Given the single contact with one hub city, their betweenness value is zero, which implies that they are not in the middle of the shortest paths between any city-pairs.

So far, our betweenness measure treats the edges equally as long as there are direct freighter flights operating on it. This ignores the capacity of each route, which may not capture the differences in importance between routes. Thus, we can weight each edge in the network by its freight capacity to differentiate their importance for the nodes and the entire network. Following Opsahl et al. (2010) and Bombelli et al. (2020), the weighted betweenness is calculated with a consideration of the number of weekly cargo flights. The weighted and the unweighted betweenness are compared in Table 4.

The weighted betweenness centrality measure does not change the ranking significantly. However, the results computed with weighted edges show that the betweenness scores of a few highly ranked cities record a substantial increase. This is because the number of shortest paths between two cities will decrease after the frequency is used as weight. For example, the shortest paths from city A to B can be A-C-D-B and A-E-F-B with no consideration of the edge weighting. However, when the edges are weighted based on flight frequencies, there will be only one route counted as the pair’s shortest path.

5.3. Correlation analysis

Correlation analysis in the CNT evaluates the nodes’ neighbours’ connectivity to reflect the function of the same degree nodes in the network. A correlation assessment summarises the average degree and clustering coefficient of their direct connection points to all nodes with the same k-degree. These indices reflect how connected nodes depend on each other (Hossain and Alam, 2017). A neighbour node with higher degree and clustering coefficient provides more support than the rest of the nodes in the direct connection graphs. If strong connectivity nodes with high degree connect with strong ones, the pattern of the network is assortativity (Wang et al., 2011; Hossain and Alam, 2017). Otherwise, it is disassortative and means that the low-degree nodes rely on the high-degree ones as their transit stops.

Fig. 4 was created using the 2020 winter timetable data. It shows that the nodes can be clearly grouped into three clusters. The degree correlation illustrates a negative tendency, implying that high-degree nodes tend to run direct flights with low-degree ones. It implies that the CSFN is disassortative. In the first group where the node degree values are over 20 including national level hubs such as Hangzhou, Shenzhen and Nanjing (see Table A1), the highest k degree values (29 and 23) correspond to the lowest values of average degree of connected cities (5.97 and 7.26). Cities in the range of 12-degree to 8-degree (the second

| Rank | City          | Degree | Closeness | Betweenness |
|------|---------------|--------|-----------|-------------|
| 1    | Hangzhou      | 9.76   | 8.65      | 8.49        |
| 2    | Nanjing       | 9.70   | 8.38      | 8.03        |
| 3    | Shenzhen      | 9.52   | 8.32      | 7.69        |
| 4    | Beijing       | 9.50   | 8.24      | 7.54        |
| 5    | Guangzhou     | 9.17   | 8.11      | 7.34        |
| 6    | Tianjin       | 8.91   | 7.99      | 7.01        |
| 7    | Chengdu       | 8.82   | 7.86      | 6.97        |
| 8    | Shijiazhuang  | 8.80   | 7.83      | 6.95        |
| 9    | Taiyuan       | 8.73   | 7.76      | 6.86        |
| 10   | Nanchang      | 8.64   | 7.69      | 6.78        |
| 11   | Xi’an         | 8.62   | 7.65      | 6.74        |
| 12   | Shenyang      | 8.54   | 7.61      | 6.68        |
| 13   | Zhenjiang     | 8.48   | 7.56      | 6.62        |
| 14   | Shanghai      | 8.46   | 7.55      | 6.60        |
| 15   | Wuhan         | 8.32   | 7.43      | 6.49        |
| 16   | Dalian        | 8.20   | 7.36      | 6.37        |
| 17   | Weihai        | 8.16   | 7.30      | 6.36        |
| 18   | Harbin        | 8.16   | 7.31      | 6.35        |
| 19   | Xiamen        | 8.07   | 7.23      | 6.28        |
| 20   | Quanzhou      | 8.01   | 7.18      | 6.23        |

Table 3 The top 20 cities/airports in China by degree, closeness and betweenness.
group) are mainly regional sub-hubs in the CSFN and their degree generally follows a negative correlation with $K(k)$. The 9-degree city, Shanghai, is an exception. Unlike other sub-hubs, Shanghai is in the Yangtze River delta region adjacent to the high degree hubs of Hangzhou and Nanjing and does not connect to them with direct cargo flights. Within the lowest degree group (the third group), the 2-degree nodes have the largest $K(k)$ value of 20.42, followed by 4- and 3-degree cities with 16.6 and 15.67, respectively. Among the individual cities, the 2-degree cities of Kunming and Lanzhou have the equal value of $K(i)$ (the average neighbour nodes’ degree of the city), 26. Both cities are connected with Hangzhou and Nanjing which have the high degree values in the CSFN. The $K(k)$ value for 1-degree nodes shrunk to 14. Most 1-degree cities directly connect with sub-hubs with small-scale dedicated cargo carriers such as Yulin (which connects to Xi’an by YTO Cargo) and Xuzhou (which is connected to Xi’an by Longhao Airlines). This dis-assortative mixing with lower degree cities surrounding higher degree cities in the CSFN demonstrates that the national level hubs and the regional sub-hubs support the connectivity to remote cities.

The clustering degree correlation provides more evidence on how national and regional level hub nodes provide connectivity to peripheral nodes in the CSFN (Fig. 5). The relationship between the clustering coefficients and degrees tend to be negative linear. In this negative linear correlation, higher degree hubs tend to directly support lower

As shown in section 5.2, Hangzhou, Shenzhen and Nanjing can be classified as national logistics hubs. Here we call other provincial capital cities intermediate regional sub-hubs.

| Rank | Unweighted network          | Weighted network       |
|------|----------------------------|------------------------|
| Node | $C_B$                      | $C_{Bw}(i)$            |
| 1    | Hangzhou/Xiaoshan          | 0.374                  | Hangzhou/Xiaoshan          | 0.615                  |
| 2    | Shenzhen/Bao’an            | 0.211                  | Shenzhen/Bao’an            | 0.430                  |
| 3    | Nanjing/Lukou              | 0.176                  | Nanjing/Lukou              | 0.095                  |
| 4    | Xi’an/Xianning             | 0.099                  | Xi’an/Xianning             | 0.090                  |
| 5    | Beijing/Capital-Daxing     | 0.069                  | Wuxi/Shuangdi              | 0.087                  |
| 6    | Tianjin/Binhai             | 0.066                  | Beijing/Capital-Daxing     | 0.086                  |
| 7    | Nanchang/Changsha          | 0.059                  | Nanchang/Changsha          | 0.047                  |
| 8    | Guangzhou/Baiyun           | 0.046                  | Tianjin/Binhai             | 0.046                  |
| 9    | Shijiazhuang/Zhengding     | 0.022                  | Guangzhou/Baiyun           | 0.041                  |
| 10   | Zhengzhou/Zhengdong        | 0.020                  | Shanghai/Pudong            | 0.004                  |
| 11   | Shanghai/Pudong            | 0.016                  | Shijiazhuang/Zhengdong     | 0.001                  |
| 12   | Wuhan/Tianhe               | 0.013                  | Zhengzhou/Zhengdong        | 0.001                  |
| 13   | Fuzhou/Changle             | 0.012                  | Wuhan/Tianhe               | 0.000                  |
| 14   | Chengdu/Shanxi              | 0.011                  | Fuzhou/Changle             | 0.000                  |
| 15   | Quanzhou/Jinqiang          | 0.005                  | Chengdu/Shanxi             | 0.000                  |
| 16   | Wuxi/Shuangdi              | 0.005                  | Quanzhou/Jinqiang          | 0.000                  |
| 17   | Shenyang/Taoxian           | 0.004                  | Shenyang/Taoxian           | 0.000                  |
| 18   | Xiamen/Gaoji               | 0.004                  | Xiamen/Gaoji               | 0.000                  |
| 19   | Harbin/taiping             | 0.002                  | Harbin/taiping             | 0.000                  |
| 20   | Dalian/Zhoushuizhi         | 0.001                  | Dalian/Zhoushuizhi         | 0.000                  |

Fig. 3. Spatial distributions of degree, closeness and betweenness in the CSFN.
clustering coefficient cities. In contrast, lower degree cities are inclined to connect with higher clustering coefficient hubs.

6. Analysis of network development during the COVID-19 pandemic

Table 5 shows the overall network structure measures by the different timetable schedules. Overall, during the COVID-19 pandemic, the number of nodes reduced by one (2019 Winter vs. 2020 Winter), but the number of edges (i.e., the number of routes) increased by nearly 30%, which reflects the high demand for dedicated cargo services during the pandemic. The average degree and the clustering coefficient also increased, while the average path length fell. The average path length measures the convenience of navigation in a related network. The clustering coefficient is a ratio that measures the degree of connection density around a node: a higher cohesiveness in the node’s neighbourhood provides a more efficient pathway with fewer transit points (Wang et al., 2011; Hossain and Alam, 2017). The model shows the growth of the CSFN with more origin-destination (OD) flights between the navigable cities in 2020 since the outbreak of COVID-19. It also shows that the overall structure of the CSFN improved from 2019 to 2020. More detailed analyses by different indices are presented in the following subsections.

6.1. Degree distribution

As shown in Table 5, in the 2019 winter, the average degree was 4.52 in the CSFN with a maximum value of 28. The CSFN’s cumulative degree distribution follows an exponential or a power function also as \( P(k) = 0.7055e^{-0.133k} \) \((R^2 = 0.9071)\), \( P(k) = 1.659 \times 10^{-0.8949} \) \((R^2 = 0.9518)\), respectively, as shown in the upper panel of Fig. 3. It means that a small number of the busiest cities/airports in the CSFN constitute the nodes of most of the all-cargo routes. They linked to a small number of hubs, and resembled the characteristics of a scale-free network. In late 2020 the exponential function was updated to \( P(k) = 0.7871e^{-0.133k} \) \((R^2 = 0.8949)\) or the power function became \( y = 2.0108x^{-1.133} \) \((R^2 = 0.8899)\), as shown in the lower panel of Fig. 6. The average degree increased to 5.87 (Table 5), as more cities launched new all-cargo routes, which can be seen in Fig. 7. Table 6 and Table A1 of the appendix suggest that some provincial capital cities, or intermediate regional sub-hubs, such as Chengdu, Wuhan and Zhengzhou operated more direct routes between each other in the CSFN in 2020. They also play roles as transit points between the central hub and peripheral cities in the network. It appears that during the pandemic, the distribution pattern of the CSFN developed into a network with more small-world properties. This will become clearer as we look at the changes in clustering coefficient and average path length next.

Based on the degree rankings in the 2019 Winter, Chinese cities are further grouped into categories of "top 10", "top 110" and "others", such that the heterogeneous impacts of COVID-19 on different groups of airports can be investigated with a paired t-test. The results have been collated in Table A2. As can be seen, the increases in the network degree were mainly driven by the top 20 cities. More direct air freight routes were added to larger airports, further enhancing the small-world nature of the CSFN in China. This reflected the booming air cargo demand during the COVID-19 period for e-commerce goods and essential medical supplies which were mainly produced and consumed in key economic centers in China. On the other hand, we did not see a reduction in the degree of nodes in smaller airports, suggesting little or no impact of COVID-19 on smaller airports’ air freight network.

6.2. Average path length and clustering coefficient

The CSFN’s average path length was 2.17 in the 2020 winter, which was slightly smaller than in 2019 for the same period (Table 6). This value is less than that of the air passenger network of China, 2.23, measured by Wang et al. (2011). Compared with the passenger flights that are still subject to a certain degree of regulation, the dedicated cargo carriers have more freedom to enter and exit a route. They could design a more efficient network with smaller average path length to minimise the transit times based on the historical cargo flow data. Table 6 summarises the distribution of the shortest paths among all city-pairs in the CSFN for 2019 and 2020. In 2019 about 11% of the city-pairs were connected by direct flights. About 67% of the city-pairs were connected with more than one stop. About 96% of the city-pairs were connected with no more than two stops. In 2020 the figures show an apparent improvement given the shorter average path length value, and fewer transit points needed for a consignment to reach its destination in China’s air freighter network. As shown in Tables 6, 72% of the city-pairs were connected by direct all-cargo flights or one transit in 2020.

In the 2020 winter, the value of the clustering coefficient was 0.434 (Table 7), representing an increase of almost 50% from the same period in 2019. This implies that the topological distance for shipping a parcel from one airport to another became much shorter during the pandemic. To the best of our knowledge, there are no other studies on a nation’s scheduled freighter network that allow us to compare this value. Therefore, to understand the transitivity and cohesiveness of the CSFN, we compare its clustering coefficient with air passenger transport networks (Table 7), including China’s full-service (FSC) and low-cost carrier (LCC) networks (Table 8). Considering that there are fewer nodes and edges, it is not surprising that the CSFN is less cohesive than most of
Table 5
Changes of the CSFN structure by the scheduled timetable periods.

| Schedule       | Effective period    | No. nodes (n) | No. edges (m) | Average degree < K> | Average path length (L) | Clustering coefficient |
|----------------|---------------------|---------------|---------------|---------------------|-------------------------|------------------------|
| 2019 Winter    | Oct 2019-Mar 2020   | 46            | 104           | 4.52                | 2.26                    | 0.293                  |
| 2020 Summer    | Mar–May 2020        | 47            | 108           | 4.60                | 2.26                    | 0.317                  |
| 2020 Summer revised | May–Oct 2020    | 45            | 123           | 5.47                | 2.18                    | 0.415                  |
| 2020 Winter    | Oct 2020-Mar 2021   | 45            | 132           | 5.87                | 2.17                    | 0.434                  |

Fig. 6. The cumulative degree distribution for the 2019 and 2020 winter timetables.

Fig. 7. A comparison of the k degree by the number of nodes for the winter schedules of 2019 and 2020.
As shown in Table 6, the increase in clustering coefficient since the COVID-19 pandemic was mainly driven by the small airport cohort. This paper has evaluated the current CSFN via topological properties and has explored how this system changed after the COVID-19 pandemic. Using spatial analysis with the CNT, the paper found that the CSFN displayed small-world and scale-free network properties amid the COVID-19 pandemic. It showed a cumulative degree distribution that aligned more with an exponential function, with an average path length of 2.17 and an increased clustering coefficient of 0.434 by the end of 2020. In terms of network patterns, the CSFN almost duplicates the air passenger traffic imbalance in relying on three eastern mega-city clusters. However, the national hubs for dedicated cargo carriers are Shenzhen in the Pearl River delta, and Hangzhou and Nanjing in the Yangtze River delta for the CSFN, instead of Guangzhou and Shanghai as in the case of China’s air passenger network. The CNT analysis suggests that the CSFN is not a randomly formed network and has offered a good coverage of the country. The network appears to have a clear layering feature consisting of national and intermediate level hubs as well as many small nodes (peripheral cities). Most peripheral cities with low degree airports are directly linked to the national hubs that have the best centrality. Intermediate airports function as regional sub-hubs in the CSFN through developing direct routes between each other and playing roles as transit points between the central hub and peripheral cities. In particular, intermediate airports such as Beijing, Tianjin, Xi’ an and Nanchang play roles as transit points between the national level hubs and the peripheral cities in the network. The increase in the direct freighter routes among the cities such as Wuhan, Beijing, Tianjin and Guangzhou in the first year of the COVID-19 pandemic had enhanced the density and transitivity of the CSFN.

Many researchers have studied the performance of China’s passenger market in the COVID-19 pandemic. For example, Xue et al. (2021) reported that one month after the reopening of Wuhan, a fast and strong recovery rate of air travel was observed. This was also the case for Beijing after its reopening in July 2020 (it went into lockdown in June 2020). The authors claimed that China’s successful control of COVID-19 in 2020 led to an almost full recovery of the domestic air demand by the end of 2020. Therefore, we can argue with confidence that the COVID-19 pandemic has not had a damaging impact on the CSFN. On the contrary, the CSFN has improved since the COVID-19 pandemic, with increased network average degree, clustering coefficient, closeness and reduced average path. Such improvement is mainly driven by major hub cities whose centralities have been strengthened with more route connections. Since China’s air passenger traffic had resumed quite quickly in the second half of 2020, the CSFN’s better performance amid the COVID-19 pandemic was not likely due to the substitution effect from a reduction in belly cargo on passenger aircraft. Rather, it was more likely a result of the higher air cargo demand during the pandemic and airlines’ realisation of the importance of freighter operations in China.

China’s big three gateway cities (Beijing, Shanghai and Guangzhou) are important passenger and cargo markets. However, they are not the top-ranking cities in the CSFN, probably because there have been a large number of passenger flights with belly cargo to and from these cities. This paper only considers the dedicated cargo carriers and excludes the passenger flights, which may underestimate the role of these cities in the domestic air freight market. This constitutes a limitation of this study. It is worth noting that the international all-cargo routes to/from China...
could have had an impact on the domestic freighter network. The national level hubs and most regional sub-hubs identified in the Chinese scheduled freighter network (CSFN) have hosted international all-cargo flights. However, studying the international dedicated cargo carriers and flights is beyond the scope of this research, and can be a future research area. The next-step research should give a closer look at the individual cargo carriers’ network developments and compare them with those of the world-class dedicated cargo carriers in the EU and US. It is also necessary to establish the link between China’s cargo carriers’ network development and the e-commerce evolution patterns, which can generate important policy implications for both carriers and government agencies.

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**Appendix A**

**Table A1**

The comparison of navigable cities in China’s scheduled freighter network at the end of 2019 and in 2020.

| City          | 2019 Winter | 2020 Winter | CAAC Regional Admin | Airspace Class |
|--------------|-------------|-------------|---------------------|----------------|
| Hangzhou     | 28          | 29          | East China          | 4F             |
| Nanjing      | 22          | 23          | East China          | 4F             |
| Shenzhen     | 17          | 23          | Centre and Southern | 4F             |
| Shanghai     | 8           | 9           | East China          | 4F             |
| Xi’an        | 8           | 8           | Northwest           | 4F             |
| Beijing      | 7           | 12          | North China         | 4F             |
| Guangzhou    | 7           | 11          | Centre and Southern | 4F             |
| Tianjin      | 7           | 10          | North China         | 4E             |
| Chengdu      | 5           | 9           | Centre and Southern | 4F             |
| Shenyang     | 5           | 7           | East China          | 4E             |
| Chengdu      | 5           | 7           | Southwest           | 4F             |
| Fuzhou       | 5           | 7           | East China          | 4E             |
| Wuxi         | 5           | 6           | East China          | 4E             |
| Xiamen       | 5           | 5           | East China          | 4E             |
| Wuhan        | 4           | 9           | Centre and Southern | 4F             |
| Dalian       | 4           | 6           | Northeast           | 4E             |
| Wenzhou      | 4           | 4           | East China          | 4E             |
| Quanzhou     | 4           | 4           | East China          | 4D             |
| Qingdao      | 4           | 3           | East China          | 4E             |
| Nantong      | 4           | 3           | East China          | 4E             |
| Nanchang     | 3           | 8           | East China          | 4E             |
| Shijiazhuang | 3           | 7           | North China         | 4E             |
| Harbin       | 3           | 5           | Northeast           | 4E             |
| Changsha     | 3           | 4           | West China          | 4E             |
| Changchun    | 3           | 4           | Northeast           | 4E             |
| Ji’nan       | 3           | 3           | East China          | 4E             |
| Chongqing    | 3           | 3           | Southwest           | 4F             |
| Lanzhou      | 3           | 2           | East China          | 4E             |
| Sanya        | 3           | 2           | Southwest           | 4E             |
| Weifang      | 2           | 4           | East China          | 4F             |
| Taiyuan      | 2           | 3           | North China         | 4E             |
| Ningbo       | 2           | 3           | East China          | 4E             |
| Nanning      | 2           | 2           | Centre and Southern | 4F             |
| Kunming      | 2           | 2           | Southwest           | 4F             |
| Hohhot       | 2           | 2           | North China         | 4E             |
| Huai’an      | 1           | 3           | East China          | 4D             |
| Urumqi       | 1           | 2           | Xinjiang            | 4E             |
| Hefei        | 1           | 2           | East China          | 4E             |
| Guizhou      | 1           | 1           | Southwest           | 4E             |
| Haikou       | 1           | 1           | Centre and Southern | 4E             |
| Yinxiang     | 1           | 1           | Centre and Southern | 4F             |
| Guanli       | 1           | 0           | North China         | 4E             |
| Luoyang      | 1           | 0           | North China         | 4E             |
| Xining       | 1           | 0           | North China         | 4E             |
| Xingyi       | 1           | 0           | Southwest           | 4D             |
| Zunyi        | 1           | 0           | Southwest           | 4C             |
| Lianyungang  | 0           | 3           | East China          | 4D             |
| Weihai       | 0           | 1           | East China          | 4C             |
| Xuzhou       | 0           | 1           | East China          | 4D             |
| Yulin        | 0           | 1           | Northwest           | 4D             |

CAAC Regional Admin. and Airspace Class source: Civil Aviation Administration of China (CAAC) (2020a, 2020b).

**Notes**

1) CAAC organizes its administration through seven regional divisions based on the economic development level and geographic zoning. The ‘region’ column displays which regional authority the airport reports to (Jiang et al., 2017).

2) According to Civil Aviation Administration of China (CAAC) (2015), basically, the Chinese Airfield Area Class is aligned to the ICAO Aerodrome Reference Code included in ICAO Annex 14. The standards reflect the maximum space capacity that the airport can allow aircraft for takeoff and landing. The standard codes consist of...
numeric and letter parts. Generally, 4F is the highest class for the maximum with B747s, A380s and equivalent size aircraft. 4E is up to B777s and A330s, and 4D is for B767s and A310s.

Table A2
The paired t-test for several network indices for 2020 Winter and 2019 Winter network.

| Category       | Degree | Clustering coefficient | Closeness | Betweenness |
|----------------|--------|------------------------|-----------|-------------|
| all            | 1.12***| 0.1346***              | 0.0424**  | 0.001       |
| (0.261)        | (0.0433)|                       | (0.018)   | (0.0034)    |
| top 10         | 3.00***| 0.04                   | 0.061***  | 0.005       |
| (0.667)        | (0.03) |                       | (0.008)   | (0.014)     |
| top 11–20      | 2.00***| –0.001                 | 0.056**   | 0.009       |
| (0.494)        | (0.038) |                       | (0.0075)  | (0.006)     |
| others         | 0.200  | 0.2113***              | 0.0317    | –0.003      |
| (0.205)        | (0.067) |                       | (0.0034)  | (0.0027)    |

Note:
1. The category of the cities are based on the ranking of degree in 2019 Winter network.
2. The paired-t-test shows the difference of index (the change of 2020 Winter relative to 2019 Winter), and the number in the parenthesis is the standard deviation.
3. ***, **, * stand for significant level at 1%, 5% and 10%, respectively.

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