Robustness and Edge Addition Strategy of Air Transport Networks: A Case Study of "the Belt and Road"

LU ZHANG [1,2,3,4,7], **HONGRU DU**[1,2], **XIAOLEI ZHANG**[1,2], **PHILIPPE DE MAEYER**[3,4,7],
BART DESSEIN[6], **AND YANNAN ZHAO**[2,5]

[1]Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Department of Geography, Ghent University, 9000 Ghent, Belgium
[4]Sino-Belgian Joint Laboratory of Geo-information, Urumqi 830011, China
[5]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[6]Faculty of Arts and Philosophy, Ghent University, 9000 Ghent, Belgium
[7]Sino-Belgian Joint Laboratory of Geo-information, 9000 Ghent, Belgium

Corresponding authors: Yannan Zhao (zhaoyn.16b@igsnrr.ac.cn) and Hongru Du (duhongru@sina.com)

ABSTRACT Air transportation is of great importance in "the Belt and Road" (the B&R) region. The achievement of the B&R initiative relies on the availability, reliability, and safety of air transport infrastructure. A fundamental step is to find the critical elements in network performance. Considering the uneven distributions of population and economy, the current literature focusing on centrality measures in unweighted networks is not sufficient in the B&R region. By differentiating power and centrality in the B&R region, our analysis leads to two conclusions: (1) Deactivating powerful nodes causes a larger decrease in efficiency than deactivating central nodes. This indicates that powerful nodes in the B&R region are more critical than central nodes for network robustness. (2) Strategically adding edges between high powerful and low powerful nodes can enhance the network's ability to exchange resources efficiently. These findings can be used to adjust government policies for air transport configuration to achieve the best network performance and the most cost effective.

INDEX TERMS Power, robustness, network performance, air transport, "the Belt and Road".

I. INTRODUCTION

Many studies use simulations to explore various transportation networks and complex systems to understand the relational structures in real networks as diverse as airlines [1], [2], maritime [3]–[5] and railway networks [6], [7]. Network structure plays a critical role in fostering network functions and values. Network robustness and performance, the two most important properties of a network, have attracted increasing attention [8]. Network robustness is particularly important in the case of random node failure or targeted attack [8]. In the analysis of complex networks, it is critical to identify those components that may lead to network vulnerabilities or that allow the network to be appropriately managed [9]. A review of the literature suggests that network robustness

The associate editor coordinating the review of this manuscript and approving it for publication was Jianyong Yao.

may play out at both node and edge levels [10], [11]. Nodes are basic for exchanging resources, so protecting them from targeted attacks is often the first concern of a national policy [12]. Therefore, the major problem in network design is to identify critical nodes in order to get the best network performance [13].

Most travel and commercial behaviors depend on the efficient operation of large-scale networks [14]. Therefore, understanding how to improve network performance is important for network design. The most efficient strategy for enhancing network performance is increasing the capacity of nodes and links [8], [15], while the primary strategy to improve network capacity has been the edge addition strategy [16]. However, not all routing strategies have the same effect on network performance [17]. Prioritizing routes has been necessary for controlling costs, and studies show that high-centrality-first has proved to be an efficient strategy

in this regard [18], [19]. Moreover, network efficiency has been identified as an appropriate parameter for describing a network's ability to propagate information and exchange resources [20], [21]. Thus, efficiency may be a better way to describe and characterize complex network than other commonly used indicators, such as path length and clustering coefficient [22], [23].

This analysis focuses on network robustness at node level and performance at link level in "the Belt and Road" (the B&R) region. Interest in the B&R initiative has grown since 2013. The B&R concept is based on the Old Silk Road, a trade route that contributed to cultural, economic, social and political interactions among Eurasian countries. Infrastructure connectivity is one of the five priority areas in the implementation process of B&R initiative. (The other four are policy coordination, unimpeded trade, financial integration and people-to-people bonds.) [24]. The B&R initiative can be seen as a configuration to reduce spatial barriers, particularly through the development of transport infrastructure to facilitate flows across city nodes [25], [26]. Air transportation is not only the fuel of economic growth, it is also a major way that societies prosper [27], [28] and regions achieve economic integration [29], [30]. However, modern states and societies can enjoy the benefits of this configuration only when air transport is available continuously. In other words, air transport infrastructure is critical for actors whose failure to exchange resources could result in shortages, and thus have a negative impact on regional development [31]–[33].

Previous studies of network robustness have focused on various centralities, which measure the importance of each node [34]. However, because of the imbalance of population and economic development in the B&R region [35], passenger flows at both node and link levels are quite uneven. Thus, it is noteworthy that the central positions of nodes are not consistent with their actual importance. For instance, nodes in East Asia, such as Guangzhou, Chengdu and Kunming, have a high level of passenger flow, and thus occupy a high central position in the B&R aviation network. Other nodes, such as Abu Dhabi, Istanbul, Dubai and Kuala Lumpur, which do not have as much passenger flows as the East Asian nodes, still have high importance, based on their position and status, rather than because of their power and centrality in the network system [36], [37]. This is because they are the main entries into their domestic hinterlands. These actors exercise power because they have weak neighbors with no alternative exchange partners. Consequently, if these powerful nodes fail, their weak neighbors fail, too.

Because of the difference between centrality and power in a network system, the question arises whether powerful nodes are more critical than central nodes for network robustness in the B&R region. Therefore, this analysis has two objectives. The first is to examine the performance of powerful nodes on network robustness in the B&R region. The second, inspired by findings about network performance at link level, is to propose a general method of enhancing network performance by configuring routes among these powerful nodes.

The remainder of this paper consists of four sections. Section II focuses on methodologies. Section III provides the results of the analysis. Section IV presents implications from our analysis, as well as avenues for further research. Section V is an overview of major findings, with policy and theoretical implications.

II. METHODOLOGY
A. CASE STUDY OF "THE BELT AND ROAD"
A case study of the B&R region must recognize that economic, political, geographical and national security considerations are interrelated [24], [25], [38], [39]. First, there is strong interest in developing a modern, comprehensive transport system, even though the B&R countries have raised certain doubts [40]–[42]. Second, natural disasters in the B&R region increase the susceptibility to accidents and can reduce transport network serviceability – sometimes considerably. Third, there are not many studies of transport infrastructure in the B&R region. One of the most important reasons for this is that the sheer size and diversity of city nodes make it an enormous challenge to describe and capture the region. However, because of its city density and diversity, the B&R region is a good lens to consider how different kinds of cross-border transport networks are affected by political geography and regional studies. It is important to identify those critical nodes in air transport networks beforehand in order to guarantee the performance in air transport systems.
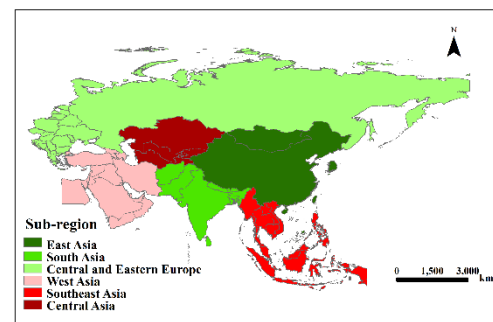

FIGURE 1. The scope of "the Belt and Road".

The study area covered six sub-regions in Eurasia (East Asia, South Asia, Central and Eastern Europe, West Asia, Southeast Asia and Central Asia) (see Figure 1), as well as 66 countries (see Figure 2). Nodes in the network selected for this study meet the following criteria: (1) any city with an airport having more than 25 airlines; (2) all capitals in the 66 countries. To construct the weighted network for our analysis, we chose cities – not airports – as the nodes, since some of the cities have more than one airport. As a result, 198 nodes were included in our analysis. The strength of connection is based on direct flights per week. The airline data were obtained from Google flight search (https://www.google.com/flights).
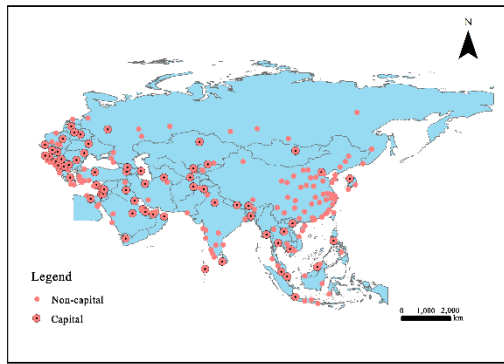
FIGURE 2. The distribution of selected nodes in "the Belt and Road".

FIGURE 3. Targeted attack in descending order.

B. CALCULATION OF POWER AND CENTRALITY

The measures to differentiate power and centrality in our weighted network were developed by .Neal [36]. According to his comments, the recursive centrality (RC_i) and recursive power (RP_i) of node i can be computed as:

$$RC_i = \sum_{j=1}^{n} R_{ij} * DC_j \qquad (1)$$

$$RP_i = \sum_{j=1}^{n} \frac{R_{ij}}{DC_j} \qquad (2)$$

where DC_j refers to the degree of centrality of node j. R_{ij} refers to strength of the connection, based on weekly flights between nodes i and j. Accordingly, recursive centrality refers to the strength of node i, which is calculated by the degree of centrality of the node to which it is connected. The recursive power of node i weights each connection by the contact's inverse degree of centrality. Thus, the recursive power captures the extent to which node i is dominating node j.

C. ATTACK STRATEGIES

Both random and targeted attacks have been widely considered in previous studies. Random attacks attack nodes which are sorted in a random sequence while targeted attacks attack nodes which are sorted in a certain sequence. The sequence of attack strategies can result in various results, but the method of attacking nodes sorted by centrality degree is the one most commonly applied. Based on the aims of our analysis, the sequences used to evaluate targeted attacks were sorted by centrality degree, power and random failure, respectively. Network efficiency is calculated to present the decline in network function from random and targeted attacking. The formula to calculate global efficiency of a network is

$$E(G) = \frac{1}{n(n-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \qquad (3)$$

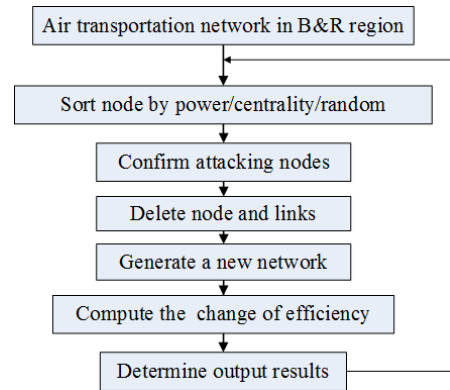where d_{ij} refers to the shortest path between node i and node j.

The procedure for a targeted attack is to delete one node and its adjacent edges in each sequence, then calculating the network efficiency of the new network matrix. Thus, under the targeted attack approach, the nodes with the highest degrees of power and centrality were removed sequentially. Figure 3 shows the flowchart for this approach.

D. EDGE ADDITION STRATEGIES

Edge addition strategies should be implemented following precise guidelines. This analysis examines how powerful nodes can provide useful guidelines for improving network efficiency. To accurately reflect the distribution characteristics of power neither being too detailed nor general, after repeated trials, all nodes in the B&R aviation network were divided into five categories, based on the Jenks Natural Breaks algorithm: high, medium-high, medium, medium-low and low. We performed five edge addition strategies and did the corresponding analysis.

The initial network is G = {n, f}, where n refers to the number of nodes and f refers to the number of routes in the B&R region. We applied five edge addition strategies to the 198 nodes in our study. The edge addition strategies can be represented as: A = {$0, a$}, where a refers to the edge added during each of the five edge addition strategies.

Strategy A-high power first (HPF): Add 100 edges between high powerful nodes and high powerful nodes.

Strategy B-medium-high power first (MHPF): Add 100 edges between medium-high powerful nodes and powerful nodes in high and medium-high categories, respectively.

Strategy C-medium power first (MPF): Add 100 edges between medium powerful nodes and powerful nodes in high, medium-high and medium categories, respectively.

Strategy D-medium-low power first (MLPF): Add 100 edges between medium-low powerful nodes and powerful nodes in high, medium-high, medium and medium-low categories, respectively.

Strategy E-low power first (LPF): Add 100 edges between low powerful nodes and powerful nodes in high, medium-high, medium and medium-low and low categories, respectively.

The new network G' is calculated as:

$$G' = G + A = \{n, f + 100\} \qquad (4)$$

III. RESULTS

A. IDENTIFICATION OF POWERFUL AND CENTRAL NODES

Figure 4 illustrates the distinct characteristics between recursive centrality and power for the 198 nodes in our study. Our analysis indicates that cities in the B&R aviation network were not always ranked from highly powerful and central nodes to powerless and peripheral cities.

Beijing, Shanghai and Guangzhou, for example, are in the lower-right corner, indicating that they have high recursive centrality and relatively low recursive power. Their high recursive centrality means that these cities are connected more densely across the network than other cities are. These cities exchange more resources with other cities because they can benefit from the high concentrations of passenger flows. This gives actors in these central nodes, such as companies and organizations, more opportunities to strategize and innovate.

By contrast, the positions of Istanbul, Moscow and Dubai in Figure 4 indicate that they are very powerful but occupy insignificant central positions. These cities are more likely to be influential by connecting to cities which have few aviation connections. They are likely to be instrumental by facilitating central nodes even though they do not represent much flow in the network. The most powerful nodes are frequently located at the periphery of the network, and thus serve as the principal entry hubs for their respective hinterlands.
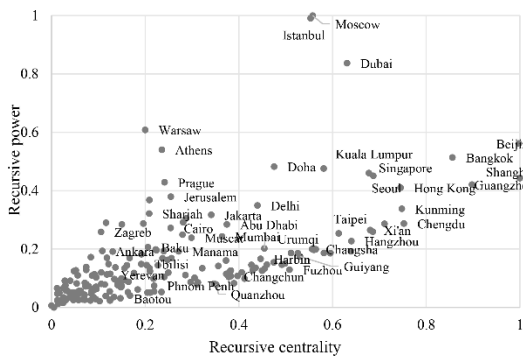

FIGURE 4. Comparison of recursive centrality and power in the transport network.

Finally, cities such as Kuwait, Manama and Saint Petersburg are in the lower-left corner of Figure 4, indicating that they have low central positions and insignificant powerful positions.

B. EVALUATION OF ROBUSTNESS

This section shows the effects of powerful nodes on network robustness by (1) comparing the decline of network efficiency caused by deactivating individual powerful and central nodes or by random failure, and (2) comparing the change

of tendency when attacking powerful and central nodes, and nodes in random sequence.

In Table 1 shows the 10 most critical nodes ranked by power, centrality and random failure. By deactivating each of the 30 nodes, we can calculate the impact of a node's deactivation on network robustness. Column 1 of Table 1 shows that the 10 most powerful nodes were the most critical nodes because together they reduce the efficiency across the transport network by 0.083. This is was 9.2% higher than the effect of central nodes (0.076) and 51% higher than the effect of random failure (0.055).

TABLE 1. Effect of the deactivation of individual nodes in the transport network.

Top ten powerful nodes	ΔE	Top ten central nodes	ΔE	Random failure nodes	ΔE
Moscow	-0.014	Shanghai	-0.007	Shijiazhuang	-0.005
Istanbul	-0.009	Beijing	-0.010	Dhaka	-0.006
Dubai	-0.007	Guangzhou	-0.007	Jinan	-0.008
Warsaw	-0.007	Bangkok	-0.010	Ho Chi Minh	-0.006
Beijing	-0.010	Chengdu	-0.007	Bandar Seri Begawan	-0.005
Athens	-0.006	Kunming	-0.007	Sanaa	-0.004
Bangkok	-0.010	Hong Kong	-0.007	Wenzhou	-0.005
Doha	-0.006	Chongqing	-0.006	Podgorica	-0.004
Kuala Lumpur	-0.007	Singapore	-0.009	Jakarta	-0.006
Seoul	-0.007	Shenzhen	-0.006	Erbil	-0.005
Total	-0.083	Total	-0.076	Total	0.055

Note: the efficiency of the original network is 0.526. The removed of nodes listed in the first and third columns are the ranking powerful and central nodes, respectively. The declines of efficiency are listed in the second and fourth column, respectively.

Before we made a comparison, we conducted an F test to calculate the significance of the variances in the three sequences. Table 2 shows that the P-value is 0.00 and F (437.87) > F crit (3.02), indicating that network inefficiencies caused by deactivation in three sequences have significant variances.

TABLE 2. F-Test for variances.

	Central	Power	Random failure
Mean	0.129	0.106	0.168
df	198	198	198
F	437.87		
P-value	0.00		
F crit	3.02		

Under targeted attack, powerful nodes seem to reduce the network robustness significantly. In Figure 5, the x-coordinate represents the 198 nodes in the B&R region
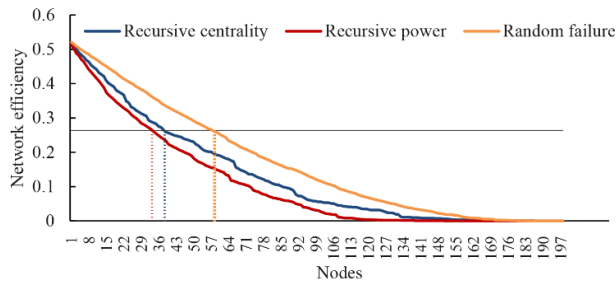
FIGURE 5. Decline of efficiency under targeted and random attacking in the transport network.

TABLE 3. Increment of efficiency in the network per added link (%).

Strategy	Category	High	Medium-high	Medium	Medium-low	Low
HPF	High	-				
MHPF	Medium-high	0.068	0.009			
MPF	Medium	0.103	0.063	0.058		
MLPF	Medium-low	0.159	0.093	0.077	0.051	
LPF	Low	0.232	0.200	0.114	0.114	0.084

while the y-coordinate represents network efficiency in the new network matrix, as the powerful, central and random failure nodes were cumulatively reduced. Results show that a targeted attack on a network leads to lower robustness than does a random attack. The declining rate of network efficiency is sorted as power > centrality > random. For instance, after conducting targeted attacks on the 33 most powerful nodes, the network efficiency dropped to 0.263, which is half of the initial value. The connectivity in the B&R aviation network becomes quite poor and the service capability becomes quite weak. Results for central nodes show that network efficiency dropped to 0.263 after conducting targeted attacks on the 38 nodes with the most centrality. In comparison, network efficiency dropped to 0.263 while attacking 58 nodes.

C. EDGE ADDITION STRATEGIES

Given our finding that powerful nodes have greater effects on network robustness than central nodes, we can now explore the most effective ways to configure extra links among powerful nodes. Figure 6 shows the powerful nodes in the B&R region based on Jenks Natural Breaks algorithm. We used the categories of powerful nodes to analyze how adding limited links among powerful nodes could improve network efficiency. Then, we calculated the average increment of efficiency by adding randomly chosen links among the five categories. There is no need to configure additional edges in the high power first (HPF) strategy, since cities were fully connected. As a result, we identified 15 kinds of undirected connections among the five categories (see Table III.).
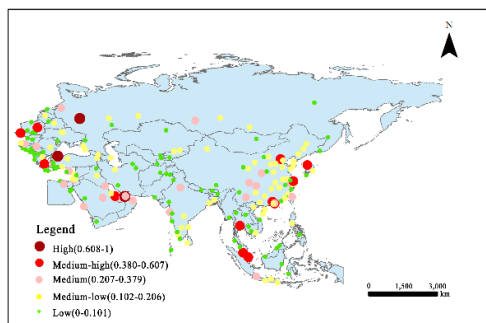
There are two initial observations about connecting powerful nodes. First, of all categories, the improvement rate of efficiency with the low power first (LPF) strategy is higher than any other edge addition strategy, as shown in the last row in Table III. For instance, the increment of efficiency is 0.232%, 0.200%, 0.114%, 0.114% and 0.084%, when each link is added under the combination of high, medium-high, medium, medium-low and low, respectively. Second, of all LPF strategies, the most efficient way to improve network efficiency involves links between high and low powerful nodes. For instance, the average increment of efficiency is 0.232% while connecting high and low powerful nodes, which is the highest rate. Therefore, of all categories, efficiency is improved the most by connecting high with low powerful nodes.

By adding the randomly chosen 100 links between the high and low powerful nodes, the efficiency rises to 0.549, with the highest average increment of efficiency per link. Figure 7 shows the 100 links between the high and low powerful nodes.
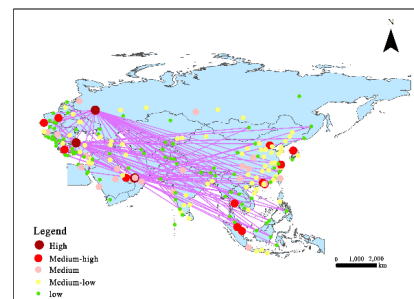

FIGURE 7. The 100 randomly chosen links connecting high and low powerful nodes.

D. EXPLORATION OF CONFIGURING MECHANISM

Table 4 shows the change of centrality and power among configured and non-configured cities when the 100 randomly chosen links were configured. As a result, we offer three observations.

(1) While looking at the whole network, configuring routes can improve recursive centrality and decrease

FIGURE 6. The powerful nodes in "the Belt and Road".

TABLE 4. The change of centrality and power among types of cities.

Type of city	Powerful city	Centrality	Power
Configured nodes	High powerful	0.05	-13.99
df	Low powerful	2.39	108.32
Non-configured nodes		2.33	-110.82
Total		4.76	-16.49

recursive power. When 100 randomly chosen links between high and low powerful nodes were configured, the value of recursive centrality in the whole network increased by 4.76, which occupies 2.31% of the original network. Moreover, the value of recursive power in the network decreased by 16.49, which occupies 0.04% of the original network.

(2) Configured low powerful nodes and non-configured nodes have increased their centrality most. After configuring 100 routes, the centrality of configured low powerful nodes increased by 2.39, accounting for 50.2% of the total centrality value. Cities with non-configured routes also increased the centrality value 2.33, accounting for 48.9% of the total value, indicating that such configuring strategy has also significantly improved the centrality of the non-configured route.

(3) The configuration strategy can increase the recursive power of low powerful nodes. By configuring 100 randomly chosen links between high powerful and low powerful nodes, the power of configured low powerful nodes increased 108.32, which is 757% of the total value.

IV. DISCUSSION

We showed that powerful nodes are critical for network robustness by comparing the decline of network efficiency caused by deactivating powerful and central nodes, respectively. The critical value of powerful nodes for network robustness lies in that their failure may cause their weak neighbors to be disconnected. Consistent with previous studies [15], our analysis shows that a proper edge addition strategy can enhance network performance. What is different is that our analysis indicates that route connections between high and low powerful nodes can enhance the network's efficiency in exchanging resources. By constructing connections, the low powerful nodes get access to high powerful nodes instead of depending on limited cities.

The route configuration is rational and practical. In general, low powerful nodes are weakly connected and marginalized. They lack the ability to achieve self-development and have to attach to other high value cities. Furthermore, the power in the B&R network is mainly concentrated in a few nodes, such as Moscow, Istanbul and Dubai. Those nodes are influential in exchanging resources, and thus their aviation services are more capable than other nodes. It is clear, then, that low powerful nodes benefit more by establishing links with high powerful destinations.

Our analysis shows that network robustness is lower under targeted attacking than under random attacks, which is consistent with previous studies [43], [44]. Our analysis also confirms that a network is understandable from multiple perspectives in which power and centrality are independent and can be used to sort cities into distinct types [36], [45]. By differentiating the centrality and power in transport networks, we have identified powerful cites in the B&R region. For instance, Moscow, which is located at the geographical periphery, is connected by few domestic cities and thus fails to be the central node in the B&R network. However, Moscow can disrupt other Russian cities' access to cities in the B&R network, and thus offers structural opportunities for resources flowing through the network. Moreover, the route configuration strategy developed in our analysis is consistent with the disassortativity in complex networks, a concept which. Newman [46] used to describe the observation that high-degree nodes in a network associate preferentially with other low-degree vertices. Here we find the same tendency of disassortativity among powerful nodes in configuring physical links. The value of configuration lies in the fact that it allows less powerful nodes to "borrow power" by being well connected to powerful nodes.

The application of power in network robustness can also be generalized and applied in other transportation networks such as metro and railway, which has been explored in previous studies [47], [48]. In addition, our analysis indicates two concerns about route configuration, which may be the subject of future research. One limitation involves the cost of route configuration. While constructing random links, our study focused only on the power of cities, whereas it is clear that some links involved long distances and were likely to be more costly. The costs for construction at the nodes and the cost of low passenger flows between configured links have not been discussed in our study. Thus, determining which links are the most rational means considering both construction costs and the level of passenger flow. A final consideration may be the political benefit of constructing specific links. These factors may need to be examined through further research.

V. CONCLUSIONS

Based on the examination of the existence and distinct characteristics of centrality and power in the transport network in the B&R region, the exploratory study in our analysis has confirmed that (1) deactivating powerful nodes can cause greater reductions in efficiency than deactivating central nodes or random failure, indicating that powerful nodes in the B&R region are more critical than central nodes in the performance of network robustness; (2) network efficiency is improved most by configuring proper physical links between high and low powerful nodes.

One policy implication is that constructing air transport infrastructure in the B&R region can be more rationally directed, Enhancing network efficiency requires edge addition strategies. By contrast, the "sprawl investment" on infrastructure is not wise since resources are limited.

Given the findings about powerful nodes, our analysis suggests that linking the key performance edges to increase network performance is both more practical and more economical. The theoretical implication of our analysis is to introduce the power concept into studies of network robustness. Even though the power concept has been well-identified in previous studies [36], [49], relatively limited attention has been paid to its application to network robustness.

Studies cited in the current literature related robustness to measures of centrality, such as betweenness and closeness, and thus were limited in unweighted networks [50], [51]. While the sophisticated properties in networks were detected, empirical studies call for mathematical properties accounting for strength of intercity linkages [45]. In this context, our analysis is an exploration of robustness in weighted networks by introducing recursive power and centrality. The identification of the powerful nodes in air transport networks is a further step toward identifying additional node properties.

REFERENCES

[1] G. Bagler, "Analysis of the airport network of India as a complex weighted network," *Phys. A, Stat. Mech. Appl.*, vol. 387, no. 12, pp. 2972–2980, 2008.

[2] D. P. Cheung and M. H. Gunes, "A complex network analysis of the United States air transportation," in *Proc. Int. Conf. Adv. Social Netw. Anal. Mining (ASONAM)*, Aug. 2012, pp. 699–701.

[3] Y. Hu and D. Zhu, "Empirical analysis of the worldwide maritime transportation network," *Phys. A, Stat. Mech. Appl.*, vol. 388, no. 10, pp. 2061–2071, 2009.

[4] P. Kaluza, A. Kölzsch, M. T. Gastner, and B. Blasius, "The complex network of global cargo ship movements," *J. Roy. Soc. Interface*, vol. 7, no. 48, pp. 1093–1103, 2010.

[5] D. Chen and Z. Yang, "Systematic optimization of port clusters along the maritime silk road in the context of industry transfer and production capacity constraints," *Transp. Res. E, Logistics Transp. Rev.*, vol. 109, pp. 174–189, Jan. 2018.

[6] Y. Zhao, J. Guo, X. Zhao, L. Tang, and Y. Wang, "The characteristics of city network along belt and road in China based on railway and aviation passenger transport," *J. Arid Land Resour. Environ.*, vol. 31, no. 1, pp. 51–57, 2017.

[7] L. Sun, Y. Huang, Y. Chen, and L. Yao, "Vulnerability assessment of urban rail transit based on multi-static weighted method in Beijing, China," *Transp. Res. A, Policy Pract.*, vol. 108, pp. 12–24, Feb. 2018.

[8] Z. Jiang, M. Liang, and D. Guo, "Enhancing network performance by edge addition," *Int. J. Mod. Phys. C*, vol. 22, no. 11, pp. 1211–1226, 2011.

[9] A. Nagurney and Q. Qiang, "A network efficiency measure with application to critical infrastructure networks," *J. Global Optim.*, vol. 40, nos. 1–3, pp. 261–275, 2008.

[10] R. Criado, A. G. del Amo, B. Hernández-Bermejo, and M. Romance, "New results on computable efficiency and its stability for complex networks," *J. Comput. Appl. Math.*, vol. 192, no. 1, pp. 59–74, 2006.

[11] M. Ventresca and D. Aleman, "A derandomized approximation algorithm for the critical node detection problem," *Comput. Oper. Res.*, vol. 43, pp. 261–270, Mar. 2014.

[12] V. Latora and M. Marchiori, "How the science of complex networks can help developing strategies against terrorism," *Chaos, Solitons Fractals*, vol. 20, no. 1, pp. 69–75, 2004.

[13] R. Criado, J. Pello, M. Romance, and M. Vela-Pérez, "Structural analysis and optimality of vulnerability and efficiency in artificial networks," *New Trends Tools Complex Netw.*, vol. 23, no. 3, pp. 31–37, 2007.

[14] V. H. Louzada, F. Daolio, H. J. Herrmann, and M. Tomassini, "Generating robust and efficient networks under targeted attacks," in *Propagation Phenomena in Real World Networks*. Cham, Switzerland: Springer, 2015, pp. 215–224.

[15] W. Huang and T. W. S. Chow, "Effective strategy of adding nodes and links for maximizing the traffic capacity of scale-free network," *Chaos, Interdiscip. J. Nonlinear Sci.*, vol. 20, no. 3, 2010, Art. no. 033123.

[16] A. I. Eirola, "Improving packet transport network efficiency using capacity aware routing," M.S. thesis, Dept. Comput. Sci. Eng., Aalto Univ., Espoo, Finland, 2012.

[17] Z.-Y. Jiang, M.-G. Liang, and W.-J. An, "Effects of efficient edge rewiring strategies on network transport efficiency," *Phys. A, Stat. Mech. Appl.*, vol. 394, pp. 379–385, Jan. 2014.

[18] J. Ma, W. Han, Q. Guo, and S. Zhang, "Enhancing traffic capacity of scale-free networks by link-directed strategy," *Int. J. Mod. Phys. C*, vol. 27, no. 3, 2016, Art. no. 1650028.

[19] G. Zhang, D. Wang, and G. Li, "Enhancing the transmission efficiency by edge deletion in scale-free networks," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 76, no. 1, 2007, Art. no. 017101.

[20] Y. Zhou and J. Wang, "Efficiency of complex networks under failures and attacks: A percolation approach," *Phys. A, Stat. Mech. Appl.*, vol. 512, pp. 658–664, Dec. 2018.

[21] Y. Yu, X. Zhou, H. Wang, X. Hu, X. Zhu, L. Xu, C. Zhang, and Z. Sun, "Small-world brain network and dynamic functional distribution in patients with subcortical vascular cognitive impairment," *PLoS ONE*, vol. 10, no. 7, 2015, Art. no. e0131893.

[22] P. Crucitti, V. Latora, M. Marchiori, and A. Rapisarda, "Efficiency of scale-free networks: Error and attack tolerance," *Phys. A, Stat. Mech. Appl.*, vol. 320, pp. 622–642, Mar. 2012.

[23] V. Latora and M. Marchiori, "Efficient behavior of small-world networks," *Phys. Rev. Lett.*, vol. 87, no. 19, Oct. 2001, Art. no. 198701.

[24] L. K. Cheng, "Three questions on China's 'belt and road initiative,'" *China Econ. Rev.*, vol. 40, pp. 309–313, Sep. 2016.

[25] T. Summers, "China's 'new silk roads': Sub-national regions and networks of global political economy," *Third World Quart.*, vol. 37, no. 9, pp. 1628–1643, 2016.

[26] W. A. Callahan, "China's belt and road initiative and the new eurasian order," Norwegian Inst. Int. Affairs, Policy Brief., Oslo, Norway, Tech. Rep. 2016-22, 2016. [Online]. Available: https://nupi.brage.unit.no/nupi-xmlui/handle/11250/2401876

[27] M. Beine, S. Bertoli, and J. F.-H. Moraga, "A practitioners' guide to gravity models of international migration," *World Econ.*, vol. 39, no. 4, pp. 496–512, 2016.

[28] R. P. Pradhan and T. P. Bagchi, "Effect of transportation infrastructure on economic growth in India: The VECM approach," *Res. Transp. Econ.*, vol. 38, no. 1, pp. 139–148, 2013.

[29] M. A. Shoukat, K. Ahmad, and M. Abdullah, "Does infrastructure development promote regional economic integration? CPEC's implications for Pakistan," *Pak. Dev. Rev.*, vol. 56, pp. 455–468, Dec. 2017.

[30] H. Kuroda, M. Kawai, and R. Nangia, "Infrastructure and regional cooperation," in *Global: Rethinking Infrastructure for Development*, vol. 2, F. Bourguignon and B. Pleskovic, Eds. Washington, DC, USA: World Bank, 2008, pp. 235–259.

[31] S. Arianos, E. Bompard, A. Carbone, and F. Xue, "Power grid vulnerability: A complex network approach," *Chaos, Interdiscip. J. Nonlinear Sci.*, vol. 19, no. 1, 2009, Art. no. 013119.

[32] M. Zanin and F. Lillo, "Modelling the air transport with complex networks: A short review," *Eur. Phys. J. Special Topics*, vol. 215, no. 1, pp. 5–21, Jan. 2013.

[33] O. Lordan, J. M. Sallan, and P. Simo, "Study of the topology and robustness of airline route networks from the complex network approach: A survey and research agenda," *J. Transport Geogr.*, vol. 37, pp. 112–120, May 2014.

[34] D. T. Nguyen, Y. Shen, and M. T. Thai, "Detecting critical nodes in interdependent power networks for vulnerability assessment," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 151–159, Mar. 2013.

[35] H. Liu, C. Fang, Y. Miao, H. Ma, Q. Zhang, and Q. Zhou, "Spatio-temporal evolution of population and urbanization in the countries along the Belt and Road 1950–2050," *J. Geograph. Sci.*, vol. 28, no. 7, pp. 919–936, 2018.

[36] Z. Neal, "Differentiating centrality and power in the world city network," *Urban Stud.*, vol. 48, no. 13, pp. 2733–2748, 2011.

[37] K. S. Cook, R. M. Emerson, M. R. Gillmore, and T. Yamagishi, "The distribution of power in exchange networks: Theory and experimental results," *Amer. J. Sociol.*, vol. 89, no. 2, pp. 275–305, 1983.

[38] W. H. Overholt, "One belt, one road, one pivot," *Global Asia*, vol. 10, no. 3, pp. 1–8, 2015.

[39] W. Liu, M. Dunford, and B. Gao, "A discursive construction of the belt and road Initiative: From neo-liberal to inclusive globalization," *J. Geograph. Sci.*, vol. 28, no. 9, pp. 1199–1214, 2018.

[40] M. D. Swaine, "Chinese views and commentary on the 'one belt, one road' initiative," *China Leadership Monitor*, vol. 47, no. 2, p. 3, 2015.

[41] J. D. Sidaway and C. Y. Woon, "Chinese narratives on 'one belt, one road' in geopolitical and imperial contexts," *Prof. Geographer*, vol. 69, no. 4, pp. 591–603, 2017.

[42] (2015). *Vision and Actions on Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road*. [Online]. Available: http://en.ndrc.gov.cn/newsrelease/201503/t20150330_669367.html

[43] C. Yu, W. Jiao'e, and J. Fengjun, "Robustness and fragility of Chinese air transport network," *Geogr. Geo-Inf. Sci.*, vol. 31, no. 3, pp. 59–64, 2015.

[44] E. Estrada, "Virtual identification of essential proteins within the protein interaction network of yeast," *Proteomics*, vol. 6, no. 1, pp. 35–40, 2006.

[45] Z. Neal, "Does world city network research need eigenvectors?" *Urban Stud.*, vol. 50, no. 8, pp. 1648–1659, 2013.

[46] M. E. J. Newman, "The structure and function of complex networks," *SIAM Rev.*, vol. 45, no. 2, pp. 167–256, 2003.

[47] S. Derrible, "Network centrality of metro systems," *PLoS ONE*, vol. 7, no. 7, 2012, Art. no. e40575.

[48] M. Jafari and S. M. Fakhar, "Network centrality analysis of Tehran urban and suburban railway system," 2018, *arXiv:1802.06219*. [Online]. Available: https://arxiv.org/abs/

[49] P. Bonacich, "Power and centrality: A family of measures," *Amer. J. Sociol.*, vol. 92, no. 5, pp. 1170–1182, 1987.

[50] H.-L. Liu, C. Ma, B.-B. Xiang, M. Tang, and H.-F. Zhang, "Identifying multiple influential spreaders based on generalized closeness centrality," *Phys. A, Stat. Mech. Appl.*, vol. 492, pp. 2237–2248, Feb. 2018.

[51] L.-L. Ma, C. Ma, H.-F. Zhang, and B.-H. Wang, "Identifying influential spreaders in complex networks based on gravity formula," *Phys. A, Stat. Mech. Appl.*, vol. 451, pp. 205–212, Jul. 2016.

LU ZHANG received the B.Sc. degree in geography science from the Shandong Normal University, Jinan, China, in 2013. She is currently pursuing the Ph.D. degree with the Geography Department, University of Chinese Academy of Sciences, and Ghent University. Her research interests include urban development and transportation network security.

HONGRU DU received the B.S. degree from Xinjiang Normal University, Urumqi, China. She received the M.S. and Ph.D. degrees in human geography from the Chinese Academy of Sciences (now the University of Chinese Academy of Sciences), in 2000 and 2006, respectively. She is currently the Director and a Research Fellow with the Department of Human–Earth System and Regional Development, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Her research interests include urbanization and the coordinated development model in arid zone, regional development strategy, resource and environment carrying capacity, and main functional area in arid zone.

XIAOLEI ZHANG received the B.Sc. degree from the Geography Department of Shaanxi Normal University, in 1986, and, the M.S. degree from Xinjiang Institute of Geography(now Xinjiang Institute of Ecology and Geography) in 1992, and after graduation began to work at the Institute. In 1997, he received the Ph.D. degree from the Institute of Geography under the CAS (now Institute of Geographic Science and Resource Research) and Postdoctoral Fellow from the School of Urban and Environmental Sciences of Peking University. He is currently the President of Xinjiang Branch of the CAS, Research Fellow, member of academic/degree evaluation committee, and doctoral/master' tutor. His research interests include urban geography, economic geography, tourism geography, political geography, development and utilization of resources, and regional sustainable development.

PHILIPPE DE MAEYER received the master's degree in geography, the Postgraduate Diploma in geology and marine applications, the Doctorate in sciences and the Postgraduate certificate in business economy. He is a Senior Full Professor in cartography and GIS at Ghent University, Belgium. His research interests include applied GIS, esp.: use of GIS and remote sensing in archaeology, risk and land-use issues including risks of climate change (esp. Central-Asia), use of GIS for risk modelling of floods and other natural hazards, use of GIS for accessibility to health care, etc.

BART DESSEIN received the M.A. degree in sinology from Ghent University and Liaoning University, in 1987–1989 and the Ph.D. degree from Ghent University, in 1994. He is also a Honorary Professor at Liaoning University, China and Guest Professor at Shanghai University, China. He is a Full Professor with the Department of Chinese Language and Culture of Ghent University. He is a former Director of the Section of Humanities of the Royal Academy for Overseas Sciences, Belgium, Board Member of the Belgian Institute for Higher Chinese Studies, Brussels, Vice-President of the School for Comparative Philosophy, Antwerp, Vice-President of the European Association for Chinese Philosophy, President of the European Association for Chinese Studies, and Senior Associate of the European Institute of Asian Studies, Brussels.
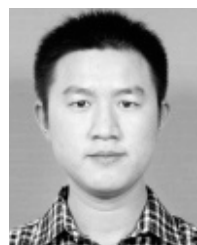
YANNAN ZHAO received the B.Sc. degree in resources environment and the management of urban and rural planning from Henan Polytechnic University, Jiaozuo, China, in 2013. In the same year, he was recommended for admission as a master with an excellent grade, and received the Master Diploma in human geography from Xinjiang Institute of Ecology and Geography, University of Chinese Academy of Sciences, in 2016 and the Ph.D. degree in human geography from Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences in 2019. His research interests include spatial planning, sustainable livelihood in the context of national park, and business geography.

● ● ●