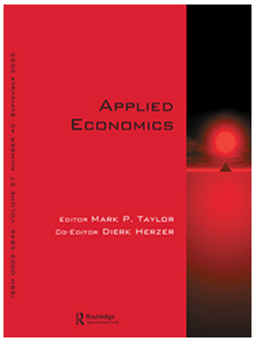

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Do trade networks among countries along the Belt and Road Initiative promote technology progress?

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ABSTRACT

The ongoing development of bilateral trade among countries participating in *the Belt and Road Initiative* (BRI) promotes the creation of trade networks and the advancement of technology in these countries. This article utilizes social network analysis to investigate the characteristics of trade networks among the BRI and how these characteristics influence technological progress. Based on bilateral trade data from 2003 to 2019, the findings of this study indicate the following key insights: First, in terms of network structure, China occupies a central position within the trade network, and the overall network density exhibits an upward trend. Notably, key players in the trade network include China, India and Singapore, which exhibit high and stable levels of centrality, connectedness, and heterogeneity. Second, empirical testing indicates that centrality, connectedness, and heterogeneity all contribute to technological advancement. Third, the varying levels of economic development among different countries significantly affect their technological progress. Lastly, the analysis suggests that increased trade liberalization enhances the impact of trade networks on technological progress in nations along the BRI.

KEYWORDS

The Belt and Road Initiative (the BRI); trade network; technological progress; social network analysis; F43; F14

JEL CLASSIFICATION

F10; F14; F15

I. Introduction

In today's global economic recovery and the strengthening of national exchanges and collaboration, regional cooperation among countries has been reinforced, leading to a more integrated world. China introduced the concepts of *the Silk Road Economic Belt* and *the 21st Century Maritime Silk Road* in September and October 2013, drawing considerable attention across the globe. Since the inception of *the Belt and Road Initiative* (BRI), China has played a pivotal role among the countries involved. The implementation of BRI not only contributes to establishing a new framework for China's international commerce but also stimulates the growth of bilateral trade with nations along the route (Zhao and Wang 2023). According to China's Ministry of Commerce website, in 2023, China's imports and exports with nations participating in BRI totalled 19.47 trillion Chinese Yuan (CNY), a 2.8% increase. These transactions accounted for 46.6% of China's total foreign trade, representing the largest scale and proportion of trade since the initiative's launch.

Technological progress is the fundamental driving force for development. By fully utilizing existing production factors and developing new ones, it promotes the rational allocation of production factors, thereby driving changes in the technological structure, product, and market structure of enterprises (Chen and Liu 2015). Actively promoting technological progress is essential for a country to inject new momentum into its economic development. However, the technological capabilities of the countries along the BRI are generally low, which limits their economic and social development. Therefore, whether bilateral trade along the BRI can foster technological progress in these countries is an important question to consider.

Following years of development, economic ties between nations have become increasingly interconnected, creating a complex web of international trade networks. There are noticeable disparities in the trading practices of various nations within the trade network, and the trade practices of nations along the route frequently change in response to those of their neighbours (Ma, Ren, and Wu 2016). Recently, several scholars have begun focusing on

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the study of trade networks as a whole. However, a review of the relevant literature reveals that few have examined the relationship between trade networks and technological advancement. This raises an important question: Does the growth of trade networks among nations participating in the BRI contribute to technological progress in those nations? What are the primary factors influencing this progress?

This article adopts a social network perspective to explicitly analyse the characteristics of the trade network among the BRI countries and then assess its impact on their technological progress. This new perspective aims to deepen our understanding of the relationship between trade networks and technological growth. Ultimately, it provides a theoretical foundation for enhancing trade cooperation among BRI countries to improve their position within these networks.

The paper is structured as follows: In the second section, this article will review the existing literature review on trade networks and technological progress. The third section will theoretically examine the mechanism through which trade networks influence technological progress and will test the relevant hypotheses. The fourth section will analyse the trade network characteristics of the countries along the BRI from 2003 to 2019 using social network methods. The fifth section will empirically examine whether the trade network promotes technology by employing a two-way fixed effects model. Finally, the conclusion section will summarize the findings and conclusions of this study.

II. Literature review

A complicated trade network is an investigation approach for developing a network system and analysing its characteristics by treating countries as nodes and the links between countries as edges, and the coarseness or fineness of these edges represents the volume of trade (Su and Li 2024). F. M. Hou et al. (2022) built the trade network system with the complex network theory as a basis, and examined its degree, structural entropy, aggregation, reciprocity, and the core edge. It resulted in a more orderly trade network structure and increased frequency of two-way exchanges between trading nations (F. M. Hou et al. 2022). Assessing the features of global trade and its development through social network analysis has become a growing area of interest among researchers (Cheng and Feng 2017). These characteristics all contribute to the complexity of the global trade network. A large portion of the network research that is currently available concentrates on particular industries or specialized sectors. Based on the interactions and trade links between industrial sectors, existing network studies have focused on energy and minerals (An et al. 2014; Q. Ji, Zhang, and Fan 2014; Li et al. 2021; J. S. Liu 2016; Yang, An, and Gao 2012), talent exchange (C. G. Hou et al. 2020), transportation (You, Yang, and Wang 2020), and agricultural patterns (G. J. Ji et al. 2024; Shutters and Muneepeerakul 2012; L. Wang et al. 2019), tourism service (Q. Liu, Liu, and Zhang 2022).

Technological innovation is a key driving force for export trade (Z. Q. Zhang and Zhang 2020). M. Y. Zhang and Wang (2023) examined how technological innovation affects the export competitiveness of digital trade. Hirsch and Bijaoui (1985) found that innovative enterprises tend to have a stronger export intention. Additionally, J. Wang and Huang (2012) empirically demonstrated that a higher intensity of technological innovation correlates with increased export propensity and export intensity among enterprises.

The volume of trade reaching a critical threshold can facilitate the formation of large-scale trade networks. This situation encourages the establishment of knowledge networks and accelerates technological advancement (Kelly 2009). By enhancing a node's centrality within the trade network, it is possible to increase the number of connected nodes. This, in turn, allows the node to achieve technological innovation through the integration of various innovation elements (Lee, Choo, and Yoon 2016; Qiu and Huang 2021). Ferrier, Reyes, and Zhu (2016) modelled the international trade system as a weighted network, quantifying both direct and indirect trade connections. Their findings highlighted that the network effects of trade are crucial for technology dissemination. Additionally, Xin (2021) argued that the primary competitiveness of Canadian domestic enterprises originates from the knowledge and technology diffusion facilitated by global networks. An increase in the centrality of a country's trade network promotes technological spillover effects (Chen 2023).

However, it has been noted that the application of social network analysis in international trade is still developing. Consequently, this paper's exploration of how trade network characteristics of countries along the BRI is particularly significant and presents ample opportunities for future research. This article provides a meaningful contribution compared to previous studies in the following ways: First, we examine how the centrality, connectivity, and heterogeneity of the trade networks of the nations among the BRI influence their technological advancement. This insight enhances existing research on the BRI and trade networks; Second, we employ social network analysis and a two-way fixed-effects model to empirically test the characteristics of trade networks and their effects on technological progress, using relevant data; Third, we explore the theoretical perspective that countries can increase their centrality within trade networks and foster technological advancement by incorporating trade liberalization as a moderating variable in our benchmark model, thus confirming its moderating effect. These findings carry important policy implications.

III. Impact mechanisms and research hypotheses

The characteristics of trade network characteristics and technological progress

Trade network centrality refers to a national's 'structural importance' within a trade network. The four primary characteristics used to describe this centrality are degree centrality, mediator centrality, eigenvector centrality, and closeness centrality. A country with higher centrality is positioned at the heart of the trade network, maintains trade relations with most other countries in the network and wields greater influence. Specifically, the centrality of trade networks can enhance a country's technological progress through competition, selection, and spillover effects.

On the other hand, trade network connectedness refers to the extent to which a node in the trade network to other nodes (Granovetter 1973). In the context of the BRI trade network, connectedness primarily reflects the strength of a country's trade relations (Lin et al. 2024). A nation's share of commerce within the trade network increases when its connections are stronger. Additionally, as a country's foreign trade volume continues to grow, so will its rate of capital accumulation and the likelihood of achieving economies of scale, which in turn will further promote that country's technical advancement (Ma, Ren, and Wu 2016).

Trade network heterogeneity refers to the presence of structural holes or weak relationships within a trade network. This heterogeneity occurs when the overall density of the trade network is low, meaning that individual nodes (trading partners) are not closely connected, or when there are redundant connections between nodes (Burt and Burt 1992). In the context of trade networks, heterogeneity can indicate the level of geographic concentration among a country's trading partners, which is inversely correlated with the number of structural holes. In other words, as more heterogeneous trade network implies that a nation's trade relationship are more geographically diverse, while a less heterogeneous network suggests a greater concentration of trading partners in specific regions. A diverse trade network can lead to varied technical risks, which may help mitigate the effects of foreign trade shocks. Furthermore, it can establish a stable domestic and international environment that supports a nation in fostering technological advancement.

Hypotheses 1, 2, and 3 are developed by the theories above.

H1: The degree of technological advancement can be increased by the centrality of trade networks.

H2: Connectivity to trade networks can enhance the level of technical advancement.

H3: The heterogeneity of trade networks can promote higher level of technical advancement.

Mechanisms of trade liberalization

As global trade has expanded, the movement of commodities, services, factors of production, and other components of international transactions has increased significantly. Trade liberalization has become the dominant trend in international trade, fostering closer relationships among nations that complement each other based on comparative advantages. It has contributed to the technological advancement of countries and regions. On one hand, trade liberalization has reduced bilateral trade costs and lower trade barriers, allowing high-quality and competitively priced goods and services from other nations to enter domestic markets, which can impact local industries. On the other hand, it can transform a country's limited domestic market into a larger, unified regional market. This shift encourages greater investment in innovative infrastructure, enhancing the environment for technological innovation and overall efficiency. Thus, trade liberalization not only helps the country's technological level but also develops sizable regional markets. Based on this rationale, we propose the following hypothesis:

H4: Increased trade liberalization can enhance the technological progress effect derived from trade networks

IV. Establishing and characterizing trade network

Construction of countries among BRI trade network

The construction of the trade network matrix utilizes social network analysis to represent, 64 countries participating in the BRI as nodes, with the trade relationship between them depicted as lines. The matrix G is defined as G = (V, E), where i and j represent the exporting and importing countries, respectively. Here, i and j range from 1 to 64, and t denotes the years from 2003 to 2019. E illustrates the commercial interaction between two nations, with each node reflecting its individual status in the network.

Using the trade network model mentioned above, this article builds the trade network based on export data from 64 countries along the BRI from the years of 2003 to 2019. However, due to the wide disparity in economic development across countries, there is also a considerable variation in the volume of bilateral export trade. To simplify calculations and create a binary 0–1 matrix, this study establishes the export trade unit at $1 million. The export trade data utilized in this article are sourced from the Gravity database within the CEPII database, while additional data is obtained from the World Bank database.

Characterization of countries along the BRI trade network

Analysis of the centrality of the trade network in the BRI countries

Network centrality is a key feature of trade networks, particularly when it comes to creating trade network indicators. The goal of centrality analysis is to identify if a node is situated in the centre of the network. A country positioned at the centre of the trade network has greater access to information and resources and exerts more influence over other nodes.

In this article, we primarily measure the centrality of the trade network among BRI countries using median centrality. The term 'mediator centrality' refers to a node's capacity to control other nodes. Specifically, the mediator centrality measures how frequently a node serves as a mediator within the network. The mediator centrality of a node is calculated by counting how many times that the node appears in all shortest pathways within the network. This indicator measures a node's ability to influence the transactions of other nodes as well as the overall connectivity of economies in the trade network. According to the study by Lv et al. (2021), the formula for the mediator centrality is as follows:

$$C_i^b = \frac{2\sum_j \sum_k \frac{q_{jk(i)}}{q_{jk}}}{(n-1)(n-2)} \quad (1)$$

In this context, j and k represent two different economies; Ci^b refers to the median centrality of economy i; the variable q_{jk} indicates the number of pathways that economies j and k have created through the trade network; $q_{jk(i)}$ denotes the number of paths created by economies j and k that have created through the trade links initiated by economy i; and n represents the total number of nodes in the network. A node with higher mediator centrality acted as a more effective intermediary within the network, granting its greater bargaining power is and making it more central to the trade network. Consequently, the greater power held by the actor at the centre of the network, the more nodes will be connected to it.

This study examines the top 15 countries along the BRI for the years 2008, 2013, and 2018, with the findings presented in Table 1. This table indicates that the mediator centrality has gradually declined over time. This decline may be contributed to several factors. First, as BRI countries have grown and various policies have been implemented, trade barriers have weakened. Moreover, the increase in international investment, collaboration, and exchanges has contributed to the annual decline in mediator centrality. As a result, trade cooperation is shifting from traditional exchange to a greater focus on the flow of talent and technology. The median centrality indicates each economy's ability to control regional resources. At the country level, India and China consistently rank the top three countries in terms of the mediator centrality. Their highest degree of centrality and stable ranking demonstrate how these two countries have strengthened the connectivity within the overall trade network, playing a crucial intermediary role in establishing extensive trade links with other economies in the region. As leading nations in the trade network, they have developed strong trade ties with varias economies, enabling them to better influence and control other economies through their manufacturing and trading capabilities. Singapore and Malaysia exhibit an increasing trend in mediator centrality, suggesting that they are becoming centre players in the trade network of the BRI countries. They serve as crucial bridges and intermediaries, within their impact on other nodes in the network steadily increasing. The UAE and Turkey also exhibit stable and consistent rankings, serving as important intermediaries and bridges within the trade network and have a significant impact on other economies. In contrast, the positions of Vietnam, Russia, Indonesia and Czechia have gradually declined over time, suggesting that their contributions to the trade network are becoming less significant.

Analysis of the connectivity of trade networks in Belt and Road countries

This article builds on Ma's, Ren, and Wu (2016) point intensity method for measuring the connectivity of trade networks. In this context, the strength of this network connectivity indicates a nation's international trade capacity and its trade relationship with other nations in the network.

Degree centrality is based on the number of connections a node has to other nodes in the network. It measures how close a node is to others, and a high centrality indicates that a node is more central in the social network. In trade networks, degree centrality primarily helps assess a country's capacity in trade with other nations. Degree centrality can be further divided into in-degree and out-degree metrics, which are calculated using the following formula.

$$\mathrm{Degree}_i^{in} = \sum\nolimits_j a_{ji} \tag{2}$$

$$\mathrm{Degree}_i^{out} = \sum\nolimits_j a_{ji} \tag{3}$$

Table 1. Top 15 countries along BRI in terms of number of intermediaries in 2008, 2013, and 2018.

Ranking	2008		2013		2018	
1	India	102.307	India	137.617	Singapore	85.52
2	Indonesia	91.071	China	78.905	China	82.67
3	China	90.395	Thailand	70.41	India	74.28
4	Vietnam	75.851	Singapore	69.344	Malaysia	72.05
5	Thailand	71.257	Malaysia	68.726	Indonesia	66.8
6	UAE	71.054	UAE	61.643	UAE	65.82
7	Turkey	66.877	Turkey	53.889	Turkey	56.63
8	Russia	62.299	Indonesia	49.846	Poland	54.16
9	Poland	58.231	Russia	44.752	Thailand	50.36
10	Malaysia	53.351	Vietnam	41.032	Vietnam	35.81
11	Czechia	48.645	Ukraine	36.917	Pakistan	34.97
12	Egypt	44.848	Czechia	36.19	Saudi Arabia	34.81
13	Singapore	42.278	Iran	34.593	Russia	33.98
14	Bangladesh	40.211	Poland	34.153	Czechia	31.09
15	Ukraine	39.492	Egypt	33.484	Philippines	24.91

In this study, we utilize Ucinet software to estimate the out-degree and in-degree of trade networks among nations along the BRI, as illustrated in Tables 2 and 3. Point degree centrality represents the influence of a node located at the centre; a higher out-degree (the number of exports) or in-degree (the number of imports) indicates that a nation has more trading partners and is more competitive. Overall, both out-degree and in-degree have remained relatively stable. This stability is evidenced by the fact that the top 15 countries in terms of out-degree and in-degree along the BRI have largely remained unchanged, likely due to the fixed nature of the countries involved in the BRI. The number of countries included in BRI is somewhat limited, which restricts the ability of these node countries to develop additional trading relationships. From the perspective of individual nations, China's trade level has consistently been high and stable, solidifying its position. Meanwhile, Singapore's trade level has been increasing, positioning it as a leading trading nation. The number of nations with a out-degree of 64 increased from four in 2008 to six in 2018. Countries such as Poland, Malaysia, Ukraine, Turkey, and Czechia have all experienced a gradual increase in their out-degree levels over time, whereas trade levels between India and Thailand tended to stabilize.

Moreover, Indonesia's trade level declined from 2008 to 2013 but saw a rise again afterwards. The decline may have been influenced by the 2008 financial crisis. Fortunately, trade levels have progressively normalized with the end of the conclusion of the financial crisis and the subsequent recovery of the country's economiy.

The top 15 countries along the BRI in terms of in-degree for the years of 2008, 2013 and 2018 are presented in Table 3. It is clear from this table that China consistently holds the top position. This not only demonstrate that China is at the centre of the trade network, but also highlights the significance of the BRI. For China, it is practically important to maintain close trade relations with the countries along the BRI and expand trade cooperation in

Table 2. Top 15 BRI countries in terms of out-degree, 2008, 2013, and 2018.

Ranking	2008		2013		2018	
1	China	64	China	64	China	64
2	Thailand	64	Singapore	64	Singapore	64
3	Indonesia	64	Thailand	64	Thailand	64
4	India	64	Malaysia	64	Malaysia	64
5	Malaysia	63	India	64	Indonesia	64
6	Russia	63	Indonesia	63	India	64
7	Vietnam	62	Turkey	62	Pakistan	63
8	UAE	62	Czechia	62	UAE	63
9	Turkey	61	Vietnam	61	Turkey	62
10	Czechia	61	UAE	61	Russia	62
11	Singapore	60	Russia	61	Poland	62
12	Pakistan	59	Poland	61	Czechia	62
13	Poland	58	Pakistan	60	Hungary	61
14	Ukraine	58	Ukraine	59	Ukraine	61
15	Sri Lanka	57	Bulgaria	59	Lithuania	61

Table 3. Top 15 BRI countries in terms of in-degree, 2008, 2013, and 2018.

Ranking	2008		2013		2018	
1	China	61	India	62	China	63
2	India	60	China	61	India	61
3	Turkey	60	UAE	61	UAE	61
4	UAE	58	Turkey	60	Turkey	61
5	Russia	57	Russia	59	Singapore	60
6	Poland	56	Ukraine	58	Poland	60
7	Egypt	55	Thailand	57	Malaysia	58
8	Czechia	55	Singapore	55	Thailand	56
9	Ukraine	55	Malaysia	55	Vietnam	56
10	Thailand	54	Indonesia	54	Indonesia	56
11	Indonesia	53	Egypt	54	Saudi Arabia	56
12	Lebanon	51	Poland	54	Russia	56
13	Romania	51	Czechia	54	Czechia	55
14	Croatia	51	Kazakhstan	53	Bulgaria	53
15	Serbia	51	Bulgaria	53	Pakistan	52

depth. China and the nations involved in the BRI are likely to continue fostering close trade relations and will aim to enhance their trade cooperation further. Notably, four nations – India, Turkey, China and the UAE – have consistently maintained their top four positional rankings in terms of in-degree, while Russia has seen a decline in its rankings. Over time, other countries may have increased their trade levels due to their enormous economic growth potential, whereas Russia's trade level has decreased due to more limited growth opportunities. Additionally, three countries – Indonesia, Singapore and Malaysia – have experienced an increase in their in-degree, while Poland's in-degree fell and then rebounded.

Analysis of the heterogeneity of trade networks in BRI countries

The adequate size of the structural hole indicator primarily measures heterogeneity indicators. The adequate size of a network is the total number of trading countries or regions involved in a trade network. An economy's actual adequate size is calculated by deducting the degree of redundancy within the network from the overall size of its networks; in other words, the adequate size represents the non-redundant portion of the network. The effectiveness of a country's trade connectivity can be assessed through its adequate size. A larger effective size indicates more trade opportunities and a broader trade market, which contributes to trade growth and economic development. An increase in the adequate size indicator suggests that a node has greater freedom to operate within the entire trade network, without being constrained by it. In this context, this article employs Ucinet software to measure the effective size indicators related to the structural holes of countries along the BRI from 2003 to 2019. It then selects the top 15 countries along the BRI in terms of their adequate size for analysis during the years 2008, 2013, and 2018, as shown in Table 4. Analysis of the data reveals that China and India consistently rank among the top three countries, reflecting their strong positions along the countries along the BRI and their dominance in trade. This suggests that the trade policies implemented by China and India are good and have the potential for long-term development. Additionally, several nations, including Singapore, Pakistan, the UAE and Poland, have increased their rankings in terms of adequate size, indicating a degree of long-term stability in their trade policy. Overall, however, the total practical scale of the nations along the BRI is trending downward, suggesting that the connected system of the trade network or the overall trade policy needs further enhancement.

V. An empirical study of the effect of trade network characteristics on technological progress

Sources of data

This article depends on the Gravity database within the CEPII database and focuses on the bilateral trade data among 64 countries along the BRI. Due to a severe lack of data for Qatar, it has been excluded from the study. The research

Table 4. Top 15 Belt and Road countries in effective size, 2008, 2013, 2018.

Ranking	2008		2013		2018	
1	China	22.912	India	21.587	China	19.827
2	India	22.798	China	21.124	Singapore	19.621
3	Thailand	22.233	Thailand	20.764	India	19.496
4	Indonesia	22.073	Malaysia	20.651	Malaysia	19.303
5	Russia	20.992	Singapore	20.643	UAE	19.173
6	Malaysia	20.841	Indonesia	19.017	Indonesia	18.992
7	Vietnam	20.696	Turkey	18.414	Thailand	18.637
8	UAE	20.471	UAE	18.016	Turkey	17.833
9	Turkey	20.029	Czechia	17.582	Poland	17.66
10	Czechia	19.392	Vietnam	17.363	Pakistan	16.996
11	Poland	19.25	Poland	17.23	Russia	16.148
12	Singapore	18.603	Russia	17.192	Czechia	15.889
13	Pakistan	16.444	Ukraine	15.842	Saudi Arabia	15.199
14	Ukraine	16.115	Egypt	15.568	Ukraine	15.15
15	Egypt	15.94	Pakistan	15.367	Vietnam	14.875

constructs a trade network using this data. According to the calculation of total factor productivity, the capital input is presented by capital stock, which is sourced from Payne's table. However, it is important to note that Payne's table is only updated to 2019, leading this article to cover the period from 2003 to 2019. This article employs Ucinet software to construct trade networks for countries along the BRI, examining the development of these networks through three perspectives: centrality, connectedness, and heterogeneity. The empirical analysis utilizes Stata16.0 to evaluate quantitative data regarding the trade network. Furthermore, the freedom is chosen as the regulating variable for the robustness of the empirical conclusions, according to Ucinet. Control variables include economic development, foreign investment, industrial structure, openness, research and development(R&D), urbanization, and patents. All data is sourced from the World Bank database.

The setting of the model

To further validate the hypotheses above, this article sets up a two-way fixed-effects model as follows in order to quantitatively examine the impact of the structural characteristics of trade networks on technological progress:

$$\mathrm{TFP_{it}} = \beta_0 + \beta_1 \mathrm{net_{it}} + \beta_2 \mathrm{X_{it}} + \delta_\mathrm{i} + \mu_\mathrm{t} + \varepsilon_\mathrm{it} \quad (4)$$

In this article, i represents countries and t represents time. The explanatory variable is technological advancement, which is indicated by total factor productivity $\mathrm{TFP_{it}}$. The core explanatory variables related to trade network features include centrality, connectivity, and heterogeneity, which are denoted as $\mathrm{net_{it}}$. And $\mathrm{X_{it}}$ denotes the control variable. Based on the relevant literature, the controlled variable includes the level of economic development, the level of foreign investment, the industrial structure, and the level of openness, the level of R&D, the level of urbanization and the number of patents. δ_i and μ_t represent individual and time-fixed effects, respectively, while ε_it is the random disturbance term. The coefficients are denoted as β_0、β_1 and β_2, respectively.

Interpretation and explanation of variables

Explained variables

This article examines technical advancement as its explanatory variable. Technological advancement is measured using total factor productivity (TFP), the primary metric used in the present literature. Two methodologies are used today to estimate TFP: parametric and nonparametric. Parametric approaches are separated into deterministic parametric production function methods and stochastic parametric production function methods, while nonparametric approaches are primarily classified into data envelopment analysis (DEA) and index methods. This research utilizes the DEA-Malmquist index approach, which combines DAE with the Malmquist productivity index for measuring TFP.

Each country along the BRI is considered as a separate decision-making unit (DMU) for evaluating TFP. The number of employed indiviuals in each nation is chosen annually as the labour input factor, while the capital input factor is measured by the capital stock. The data is sourced from the University of Pennsylvania's Payne Table 10.01, updated to 2019, and was accessed in January 2023. A key indicator of a nation's degree of economic development is its GDP, the intended output. Since economic development can lead to increase pollutants emissions, particularly carbon dioxide (a greenhouse gas that severely impacts the environment), this study identifies carbon dioxide emissions as a non-desired output based on currently available data. For the input indicators, the labour input is derived from the World Bank's calculations of the unemployment rate relative to the total population. Penn World Table 10.01 (Penn Table) provides the capital element, while the desired and non-desired outcomes are provided by the World Bank. The input-output table is shown in Table 5.

Core explanatory variables

This article uses the centrality, connectedness, and heterogeneity of trade networks as the primary explanatory variables, as explained in 4.2.1 to 4.2.3. In brief, the primary variable indicative of centrality in this article is mediator centrality. Mediator centrality quantifies a node's capacity to

Table 5. Input-output table.

variables	Metrics	unit	Source
Labor input factors	Total employment by country	number	Calculated
Capital input factors	Gross fixed capital formation	million USD	Penn World Table version10.01
Desired output	gross domestic product (GDP)	million USD	World bank
Undesired output	Emissions of carbon dioxide	kiloton	World bank

mediate, which is crucial in a social network if opinions and information are to be shared amongst nodes. This research using the point intensity method to measure connectivity. The heterogeneity of trade networks is measured in this article using effective size.

Control variables

Level of economic development (GDP_{it}): Gross Domestic Product (GDP) is a comprehensive measure of the level of economic development of a country or region and is an essential indicator of the national economy. The spillover effect of technology requires a specific economic development threshold, with both technological investment and research and development relying on a robust economy. Developed countries, being more economically developed than underdeveloped countries; therefore, generally have a better starting point for technological innovation. Therefore, this study uses GDP per capita, calculating its logarithm using data from the World Bank database.

Level of foreign direct investment (FDI_{it}): For many developing nations, FDI is a primary factor of development. In addition to providing capital, FDI introduces advanced technology and management practices, enhances the quality of the local workforce, and has other indirect effects on technological advancement. These effects increase the host nation's total factor productivity, which, in turn, advances technological progress. Consequently, this article aims to examine the impact of FDI on technological progress, utilizing the ratio of net FDI inflows to GDP, as measured by the World Bank.

Structure of industries ($STRU_{it}$): Upgrading the industrial structure shifts a nation's focus from primary industries to more advanced sectors. This process creates a 'structural dividend', resulting from resource concentration in high-productivity businesses and the reallocation of production elements from low-productivity to high-productivity sectors due to industrial structure optimization and upgrading. Economic efficiency is influenced by industrial structure, which impacts on the environment; poor environmental conditions and increased industrialization generate greenhouse gases, such as CO_2 and SO_2, that pollute the environment and can lower economic efficiency, thereby affecting TFP and technological advancement. As a result, quantifying industrial value added as a proportion of GDP is necessary to assess the influence of industrial structure on technological advancement.

Level of Openness ($OPEN_{it}$): This article also measures the degree of openness to the outside world among countries invloved in *the* BRI countries, as these countries not only participate in regional trade network but also engage in international trade with nations outside the network. To assess a nation's openness, this article uses the percentage of merchandise trade relative to GDP, as reported by the World Bank.

Level of Research and Development ($R\&D_{it}$): Every nation's scientific and technical advancement depends heavily on its R&D capability, which also serves as a gauge of its innovative input and absorption capacity. When a nation imports high-tech goods, it must educate itself about the new products and invest in learning and copying the advanced technology. However, the nation's R&D investment degree also determines whether the importing nation can fully absorb and utilize the high-tech products. To gauge each country's degree of R&D, this article employs the R&D expenditure to GDP ratio of the BRI nations, with data sourced from the World Bank database.

Level of urbanization ($URBAN_{it}$): As a nation's level of urbanization increases, its urban economy expands rapidly, and infrastructure continuously improves. According to Lewis's theory of economic growth, the population shift from agriculture to the non-agricultural sector is a significant driver of industrial prosperity and economic development, which may affect TFA. Thus, the degree of urbanization serves as a measure of a nation's civilizational advancement, stemming from increased social productivity and indicating the technological advancement. To measure it, this article uses the urban population to total population ratio, with the data obtained from the World Bank database.

Level of patent (PAT_{it}): The level of patent development is an essential indicator of technological R&D outcomes. Patents reflect the level of technical innovation within a nation or region. A strong level of patent development actively correlate with robust technological research and development, which advances the nation's technological advancement. Thus, such technological advancements can transform a nation's economic development model and foster high-quality economic growth. This study assesses the number of patent applications submitted by citizens, using data derived from calculations and the World Bank database.

Moderator variable

Trade freedom ($Tradefreedom_{it}$): This study primarily employs the Trade Freedom Index of the World Economic Freedom Index, which is a measure employed by organizations like the World Bank and the International Monetary Fund to gauge the level of global trade liberalization. It primarily manifests in two ways: first, it concerns the weighted average tariff rate of nations or regions involved in international trade; generally, the lower the tariff rate, the freer the trade; second, it considers the non-tariff trade barriers of nations or regions involved in international trade; the fewer non-tariff trade barriers that exist, the freer the trade becomes. According to the Heritage Foundation, a higher score on this index correlates with a higher the economic growth rate. The variable definitions are present in Table 6.

Analysis of empirical results

Benchmark regression analysis

This study uses Stata 16.0 to investigate the aforementioned econometric model empirically, with the regression findings presented in Table 7. Columns 1–2 of Table 7 present the findings of empirical tests on the centrality of intermediaries at each node in the BRI countries' trade network, focusing on technological advancement. Without including any empirical findings, the first column passes the significance test. Column 2 includes all of the control variables. Once these control variables are added, the results show that the coefficient for mediator centrality is 0.309, which passes the significance test at a 1% level. It implies that after adjusting for other variables, a country's centrality in the trade network considerably impacts its technological growth. Specifically, as a country's intermeditor centrality increases, its technological level also rises. While the level of R&D passes the significance test at the 5% level, the levels of openness, urbanization rate, and patent level fail at the 1% level. On the other hand, the levels of foreign investment, industrial structure, and economic development fail the test.

The empirical findings on the interconnection of between BRI countries' trade networks and technological advancement are presented in Table 8. This research utilizes point intensity to illustrate the connectivity of nations. The relationship between point intensity and technological progress is presented in Column 1, strictly controlling for time-fixed and country-fixed effects. The results

Table 6. Variable definition table.

Variable type	Variable Abbreviation	Variable Name	Data source
Explained variables	TFP_{it}	Total factor productivity	Calculated
Core explanatory variables	Cen_{it}	centrality	CEPII database and calculated via Ucinet
	Con_{it}	connectivity	CEPII database and calculated via Ucinet
	$Hete_{it}$	heterogeneity	CEPII database and calculated via Ucinet
Control variables	GDP_{it}	level of economic development	world bank database
	FDI_{it}	Level of foreign direct investment	world bank database
	$STRU_{it}$	Structure of industries	world bank database
	$OPEN_{it}$	Level of Openness	world bank database
Control variables	$R\&D_{it}$	Level of Research and Development	world bank database
	$URBAN_{it}$	Level of urbanization	world bank database
	PAT_{it}	Level of patent	world bank database
Moderator variable	$Tradefreedom_{it}$	Trade freedom	Index of World Economic Freedom

Table 7. Trade network centrality test results on technological advancement.

Variables	1 Total factor productivity	2 Total factor productivity
centrality	0.301***	0.309***
	(5.565)	(4.383)
Level of foreign direct investment		−0.00482
		(−0.248)
Structure of industries		0.176
		(1.582)
Level of Openness		−0.139***
		(−3.810)
Level of Research and Development		5.147**
		(2.217)
Level of urbanization		0.221***
		(2.739)
Level of patent		−0.00260***
		(−2.883)
Level of economic development		0.00259
		(0.387)
national fixed effects	YES	YES
time fixed effects	YES	YES
Constant	1.032***	1.024***
	(203.1)	(152.7)

Note: T-values are in parenthesis, and ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The same as below.

Table 8. Test results of trade network connectivity on technological progress.

variables	1 Total factor productivity	2 Total factor productivity
connectivity	0.186***	0.152**
	−3.373	−2.397
Level of foreign direct investment		−0.0053
		(−0.268)
Structure of industries		0.209*
		−1.807
Level of Openness		−0.128***
		(−3.345)
Leve of Research and Development		5.434**
		−2.228
Leve of urbanization		0.195**
		−2.3
Leve of patent		−0.00303***
		(−3.222)
Level of economic development		0.0140**
		−2.293
country fixed effects	YES	YES
time fixed effects	YES	YES
Constant	1.027***	1.021***
	−165.5	−137.2

demonstrate that point intensity passes the 1% significance test. The coefficient value of point intensity is 0.186, implying that point intensity positively contributes to technological progress. The empirical findings are shown in Column 2 after adding control variables. The effect of point intensity on technological progress passes the 5% significance test, and the regression coefficient is 0.152, indicating that point intensity can promote national technological progress. Among them, the level of openness and patents passed the significance test at the 1% level; the level of research and development, urbanization rate, and economic development passed the significance test at the 5% level; the industrial structure passed the significance test at the 10% level; and the level of foreign investment failed the significance test.

This article employs the effective size index in structural holes to measure trade network heterogeneity. Table 9 presents the findings from empirical tests on how trade network heterogeneity influences technological advancement, with Columns 1 and 2 controlling for country and time-fixed effects. The results in Column 1 demonstrate that, without the inclusion of control variables, trade network heterogeneity is significant at the

Table 9. Tests of trade network heterogeneity on technological progress.

variables	1 Total factor productivity	2 Total factor productivity
heterogeneity	1.161***	1.182***
	(4.954)	(3.956)
Level of foreign direct investment		−0.00122
		(−0.0625)
Structure of industries		0.179
		(1.576)
Level of Openness		−0.149***
		(−3.907)
Leve of Research and Development		4.363*
		(1.812)
Leve of urbanization		0.214***
		(2.585)
Leve of patent		−0.00301***
		(−3.272)
Level of economic development		0.00724
		(1.141)
country fixed effects	YES	YES
time fixed effects	YES	YES
Constant	1.028***	1.021***
	(188.9)	(147.1)

1% level, with a regression coefficient of 1.161. It suggests that trade network heterogeneity facilitates technological advancement, enhancing a nation's ability to advance technologically. With control variables added, the heterogeneity of trade networks in column 2 still passes the significance test at the 1% level. The empirical evidence's regression coefficient is 1.182, demonstrating that the adequate size positively contributes to technological advancement. Of these, the degree of openness, the rate of urbanization, and the number of patents passed the significance test at the 1% level; the degree of R&D passed the test at the 10% level; however, the degree of foreign investment, the industrial structure, and the level of economic development failed the test.

Robustness check

This study tests the baseline hypothesis by substituting the main explanatory factors to assess the strength of the empirical evidence. Specifically, it substitutes eigenvector centrality for the centrality index, meaning that a node's importance increases with its connections to other critical nodes. The clustering coefficient is used to measure connectivity and responds to the proximity of network connectivity. Additionally, the trade network's connectivity can be measured using this clustering coefficient. The limiting system quantifies heterogeneity; the more open the trade network a node covers, the lower the limiting system index in the trade network. The empirical test revealed the following results. The centrality passed the significance test at the 10% level. The regression coefficient is positive, indicating that the more critical the node's neighbouring nodes are, the more it can promote the technological progress of the altered nodes. It implies that countries serving as 'intermediary' or 'bridge' within trade networks promote their home country's technological progress. The degree of connectedness also passes the significance test at the 10% level, and the regression coefficient is 0.0292 ($p < 0.05$). It suggests that the more connected nations are, the more technological spillover effects occurs, leading to greater technological development in neighbouring nations. Heterogeneity passes the significance test at the 10% level, meaning that the more centralized nations find it is easier to support one another, which in turn fosters technological development within developing nations. Table 10 illustrates that the significance level of each core explanatory variable matches the regression results of the baseline hypothesis, and the signs of the regression coefficients matches that of the regression model. Consequently, the baseline hypothesis of this article is robust.

Endogeneity test

To address potential endogeneity issues – specifically, the impact of trade network characteristics among BRI countries on technological progress, as well as the possibility that a nation's technological progress may, in turn, affect its trade network

Table 10. Empirical results of robustness tests for replacing core explanatory variables.

variables	1 Total factor productivity	2 Total factor productivity	3 Total factor productivity
centrality	0.0248* (1.730)		
connectivity		0.0292* (1.762)	
heterogeneity			0.311* (1.877)
control variable	YES	YES	YES
country fixed effects	YES	YES	YES
time fixed effects	YES	YES	YES
Constant	1.020*** (28.61)	1.018*** (28.26)	1.008*** (26.86)
R-squared	0.309	0.309	0.310

characteristics – this paper introduces lagged one-period values of three indicators (centrality, connectivity, and heterogeneity) as instrumental variables. Additionally, it employs a benchmark fixed-effects model for endogeneity testing. The results of these tests are presented in Table 11.

As shown in Table 11, the lagged one-period value of centrality is significant at the 1% level, the lagged one-period value of connectivity is significant at the 10% level, and the lagged one-period value of heterogeneity is significant at the 5% level. Furthermore, the regression coefficients for all three indicators are significantly positive, indicating that stronger centrality contributes to greater enhancement of technological progress, connectivity positively influences technological advancement, and a higher concentration of dispersion among countries is beneficial for advancing technological progress across nations. Therefore, the regression results incorporating instrumental variables are consistent with the original regression model, suggesting that the benchmark empirical results are free from endogeneity. This further validates the hypothesis that a country's trade network characteristics can significantly and positively promote improvements in its technological progress.

Heterogeneity analysis

Different countries or regions have varying levels of economic development and other aspects of the differences; therefore, this paper will divide countries along the 'Belt and Road' route into upper-middle-income countries and low-income countries, and separately test the effects of centrality, connectedness, and heterogeneity on technological progress for these two income categories of countries. Table 12 presents the findings. The fixed-effects model's findings for low- and upper-middle-income nations in Table 12. According to this centrality feature, both upper-middle-income countries and low-income countries passed the significance test at the 1% level. The regression coefficients for these countries are 1.005 and 0.709, respectively, and the regression coefficient of upper-middle-income countries is larger than that of low-income countries. It could be because upper-middle-income countries have

Table 11. Empirical test results of lagged one-period core explanatory variables.

Variable	1 Total Factor Productivity	2 Total Factor Productivity	3 Total Factor Productivity
Lagged one-period centrality	0.833*** (3.682)		
Lagged one-period connectivity		0.336* (1.712)	
Lagged one-period heterogeneity			2.231** (2.363)
Control variables	YES	YES	YES
Country fixed effects	YES	YES	YES
Time fixed effects	YES	YES	YES
Constant	1.060*** (17.74)	1.083*** (18.10)	1.071*** (17.80)
R-squared	0.284	0.273	0.276

Table 12. Regression results of trade network characteristics on technological progress in countries with different income levels.

	Upper middle-income countries			Low-income countries		
variables	(1) Total factor productivity	(2) Total factor productivity	(3) Total factor productivity	(4) Total factor productivity	(5) Total factor productivity	(6) Total factor productivity
centrality	1.005***			0.709***		
	(7.363)			(4.459)		
connectivity		0.345***			0.371***	
		(3.596)			(3.804)	
heterogeneity			2.502***			2.379***
			(5.022)			(4.968)
control variable	YES	YES	YES	YES	YES	YES
country fixed effects	YES	YES	YES	YES	YES	YES
time fixed effects	YES	YES	YES	YES	YES	YES
Constant	1.045***	1.027***	1.031***	1.011***	1.004***	1.010***
	(100.7)	(86.35)	(93.78)	(78.77)	(75.12)	(79.09)

more economic development than low-income countries and have a greater impact on their immediate neighbours. Also, they have a superior starting point for their technological development, flawless infrastructure that makes it easier for the nation to overcome technical obstacles, and reorganized labour and soft power reserves. In addition, upper-middle-income nations are more numerous and dispersed geographically than low-income nations, allowing their supply chain to span the whole Belt and Road region and fostering more favourable conditions for reciprocal investments.

Regarding this connectivity characteristic, both upper- and lower-middle-income nations pass the significance test at the 1% level, and their regression coefficients are 0.345 and 0.371, respectively. It suggests that the concentration of trade in both high- and low-middle-income countries contributes to the level of technological progress in their home country. Along the trade network system, it is more advantageous to absorb the current level of technology and knowledge of other nations when trade linkages are closer. Additionally, the more room for advancement, the more it may contribute to the technological advancement of the home country. Regarding the heterogeneity characteristics, both upper-middle-income and low-income countries passed the significance test at the 1% level. The regression coefficients are 2.502 and 2.379, respectively, suggesting that upper-middle-income countries have a higher technological benchmark than low-income countries and have contributed more significantly to technological advancement.

Tests of the mechanism of trade liberalization

The term 'trade liberalization' refers to the trade between two or more nations or regions by removing tariffs and non-tariff trade barriers, allowing domestically produced goods to access global markets and benefit more. Consequently, this article chooses trade freedom as the regulating variable and builds the regulating model based on the two-way fixed effect model, which si structured as follows:

$$\mathrm{TFP_{it}} = \beta + \beta_1 \mathrm{net_{it}} + \beta_2 \mathrm{net_{it}} * \mathrm{tradefreedom_{it}} + \beta \mathrm{X_{it}} + \delta_\mathrm{i} + \mu_\mathrm{t} + \varepsilon_\mathrm{it} \tag{5}$$

The letters i and t represent the country and time, respectively. The explanatory variable is technological development, as measured by total factor productivity, denoted by $\mathrm{TFP_{it}}$. The primary explanatory variable consists of trade network properties, including centrality, connectivity, and heterogeneity, denoted by $\mathrm{net_{it}}$. Trade freedom is the moderating variable, represented by the symbol $\mathrm{tradefreedom_{it}}$, while $\mathrm{X_{it}}$ stands for the control variable. The individual and temporal fixed effects are denoted by δ_i and μ_t, respectively, while the random perturbation term is denoted by ε_it. The coefficients of each are β_0、β_1、β_2、 and β_3

Table 13 presents the empirical test results examining the impact of trade liberalization on this article's baseline hypothesis. The first, third, and fifth columns dispaly the empirical results for centrality, connectedness, and heterogeneity, respectively, consistent with the baseline hypothesis. In contrast, the second, fourth, and sixth columns present the results including the

Table 13. Results of empirical tests of the impact of trade liberalization on the baseline hypothesis.

Variables	1 Total factor productivity	2 Total factor productivity	3 Total factor productivity	4 Total factor productivity	5 Total factor productivity	6 Total factor productivity
centrality	0.295**					
	(2.149)					
centrality* tradefeedom		0.0123***				
		(8.586)				
connectivity			0.367**			
			(2.245)			
connectivity* tradefeedom				0.0269***		
				(6.979)		
heterogeneity					1.317*	
					(1.826)	
heterogeneity* tradefeedom						0.0192***
						(8.031)
control variable	YES	YES	YES	YES	YES	YES
country fixed effects	YES	YES	YES	YES	YES	YES
time fixed effects	YES	YES	YES	YES	YES	YES
Constant	1.055***	1.035***	1.055***	1.006***	1.055***	1.059***
	(23.39)	(111.9)	(23.49)	(124.6)	(23.20)	(132.7)
R-squared	0.337	0.361	0.337	0.367	0.336	0.358

interaction term of trade freedom. The interaction term for centrality and freedom of trade is significant in column 2 ($p < 0.01$). In the fourth column, the interaction term of connectedness and freedom of trade is significant ($p < 0.05$). Similarly, in the sixth column, the interaction term of heterogeneity and freedom of trade is significant ($p < 0.05$). In terms of centrality, connectedness, and heterogeneity, adding trade freedom increases the significance of the empirical results, even though the coefficients may be lower. The impact of these factors on technological advancement is considerably amplified. A country's level of trade and global influence is positively correlated with trade freedom. Lower trade costs and increased trade volume between nations facilitate more sophisticated technology spillovers, which raises a nation's or region's level of technological advancement and enhances its position in the global value chain. Trade liberalization lowers entry barriers and cost of a nation's trade, strengthening the nodes' core position within the network. This expansion increases market size and trade demand for network among these nodes, thereby increasing the trade network's influence on technological advancement. In conclusion, trade liberalization positively influences the technical advancement of the BRI countries' trade network.

VI. Conclusions and implications

This article utilizes Gravity database from the CEPII database to conduct social network analysis, establishing the trade networks of 64 countries along the BRI between 2003 and 2019. The purpose is to examine these trade networks and the relative positions of each country within them, as well as to investigate how trade network characteristics have empirically affected technological progress. The key findings of the study are as follows:

First, the density of the trade network is trending upward, indicating a strengthening structure with China emerging as a key player. The trade network among countries involved in the BRI has grown increasingly strong over time, with trade ties continually strengthening. In the context of the BRI, China and the countries along the routes need to maintain close trade relations and expand their trade cooperation. Second, technological advancement is significantly facilitated by centrality, connection, and heterogeneity. Third, different countries have varying levels of economic development, which significantly impact their technological progress differently. Finally, by analysing the significant effects of trade liberalization on technological advancement through the trade networks of countries along the BRI the findings indicate that the higher a country or region's trade level, the greater its global influence and the higher its degree of trade freedom. Additionally, trade freedom positively affects the enhancement of technological capabilities within the trade networks of countries along the 'Belt and Road'.

The findings provide valuable guidance for nations in developing international trade policies. Governments should continue adapting trade networks and enhance key nodes in the network to foster stronger economic relationships among the BRI nations. It includes expanding trade cooperation through policies such as establishing free trade union with partner countries. From a connectivity perspective, policy makers should eliminate barriers within the BRI countries' trade network and improve inter-country connection. Regarding heterogeneity, it is critical for developing countries to diversify trade partners and reduce trade risks. Policymakers should also implement trade liberalization policies, supporting negotiations for free trade agreement, expanding trade and investment freedom, and fostering closer integration of the regional economies and trade. Furthermore, developed countries should promote digitalization and enhance high-skilled training to attract quality foreign investment. It would foster trade liberalization and support the proposals of M. Y. Zhang and Wang (2023) to establish a digital service trade platform using digital technology. Concurrently, developing nations need to refine their value chains and encourage export diversification to support the growth of trade liberalization. Finally, it is crucial for government to work on achieving trade balance. States should coordinate to maximize the benefits for the BRI countries, establish dialogue mechanisms for equitable and mutually beneficial outcomes, and strengthen infrastructural ties to boost the trade network's development. Additionally, nations should coordinate their trade links, reduce trade gaps, build trade routes, and enhance infrastructure links to encourage the expansion of the trade network while better supporting each nation's technological advancement, as proposed by Lin et al. (2024).

This paper uses social network analysis to quantify the characteristics of national trade networks. The processing methods employed are relatively simplified, and future work would benefit from a more comprehensive evaluation of these methods. Additionally, this study uses total factor productivity as the indicator for measuring technological progress, while the capital input factor is assessed through the capital stock data from the Penn World Table, published by the University of Pennsylvania. However, due to delays in data release, this data is only current up to 2019. As the Penn World Table continues to be updated in the future, research on technological progress in countries along the BRI can be further enhanced.

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