Economic Research-Ekonomska Istraživanja

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rero20

Structural defects of industrial system and impacts on CEC's technology diffusion: an approach of multi-regional industrial technology flow tree

Chong Yin, Yue Liu & YingXin Cui

To cite this article: Chong Yin, Yue Liu & YingXin Cui (2023) Structural defects of industrial system and impacts on CEC's technology diffusion: an approach of multi-regional industrial technology flow tree, Economic Research-Ekonomska Istraživanja, 36:3, 2204902, DOI: 10.1080/1331677X.2023.2204902

To link to this article: https://doi.org/10.1080/1331677X.2023.2204902

Published online: 25 May 2023.

ECONOMIC RESEARCH-EKONOMSKA ISTRAŽIVANJA
2023, VOL. 36, NO. 3, 2204902
https://doi.org/10.1080/1331677X.2023.2204902

Routledge
Taylor & Francis Group

OPEN ACCESS Check for updates

Structural defects of industrial system and impacts on CEC's technology diffusion: an approach of multi-regional industrial technology flow tree

Chong Yin, Yue Liu and YingXin Cui

Institute of Science and Technology for Development of Shandong, Qilu University of Technology (Shandong Academy of Sciences), Jinan, China

ABSTRACT

The Capital Economic Circle (CEC) is one economic growth pole and occupies important position in China. However, imbalance of allocation of technological resources leads to heterogeneous industrial productivity and economic development in the CEC. To analyze and solve this problem, we combined input-output and network methods to explore structural defects of technology diffusion system of CEC and effective measures to promote industrial technology synergy and integrated development. Firstly, the principles of Multi-Regional Industrial Technology Flow Tree (MR-ITFT) modelling and methods were proposed. Secondly, the structural indexes and the effect indicators including technology spillover and absorption intensity, and spillover and absorption multiplier were designed based on MR-ITFT, which were applied to identify structural defects of industrial system and its effects on technology diffusion. The empirical research shows that heterization and polarization, imbalance of supply and demand, non-integrated vertical function, and centralization and convergence in industrial technology system are structural factors that interferes the circulation of technology flow, and further was reflected in the reduced, inverse and unstable structural effects. Contradiction between low return and high demand of technology investment results in an unsustainable circulation system of CEC. Construction of industrial technology system with high integration and cooperation was suggested.

ARTICLE HISTORY
Received 11 October 2022
Accepted 15 April 2023

KEYWORDS
Multi-regional industrial technology flow tree (MR-ITFT); Capital Economic Circle (CEC); technology diffusion

JEL CODES
O1; O3; C6

1. Introduction

At present, the problem of China's economic gap between the east and the west has turned into the widening gap between the north and the south. Beijing is at the center of the northern China, and has huge comprehensive advantages in geographic location, political and economic status, and innovation power. In China's economic

CONTACT Chong Yin yc81@qlu.edu.cn

development plan, Beijing, Tianjin and Hebei are classified as Capital Economic Circle (CEC). The GDP and population of the CEC account for about 8.62% and 8.08% of the total in the country respectively in 2019. As one of China's economic growth poles, the CEC is responsible for driving the overall development and revitalization of the northern China and providing strong support to restructuring economic structure, strongly interacting with the rapidly growing Central Plain urban agglomeration and Shandong peninsula urban agglomeration.

The CEC focuses on transferring the industries with high-resource and high-pollution consumption in Beijing and Tianjin to Hebei, developing the new emerging industries and improving the traditional industries, to realize the complementary advantages of the three regions, build an integrated industrial system and achieve sustainable and synergistic economic development. However, the per capita GDP of Beijing, is 1.82 and 3.55 times that of Tianjin and Hebei respectively in 2019. Obviously, there is a huge gap of economic productivity among the regions. Technological innovation is crucial in any economic development process (Schumpeter, 1934) and R&D investment is generally related to industrial technological progress. The internal industrial R&D investment in Beijing was nearly 22 times that of Hebei, and the per capita investment was more than three times that of Hebei. It can be seen that the highly heterogeneous industrial productivity and economic efficiency can be attributed to imbalance of talents and technological resources in some degree. On the other hand, technology diffusion is an important way to promote technological progress and efficiently reallocate innovation resources, and prominent factor for improvement of industrial production efficiency (Scherer, 1982). However, the process of the high-quality technological resources effectively diffused and shared in the full scope industrial system of the CEC is highly inhibited, and the balanced and efficient allocation of technology resources can't be implemented. There are large differences in innovation efficiency, development potential and industrial structure in the CEC and the problem of the one-way flow of innovation factors is still prominent (Bo & Chen, 2015). Therefore, it is necessary to identify the defects of the system of industrial technology diffusion and find reasonable way to improve the system to effectively relocate technological resource.

Technology resources enter the industrial market exchange system as the initial input, and the structure of industrial system is key in influencing technology diffusion. However, the existing literatures have little discussion on this. Industrial linkage is described by the input-output relationship, and when integrated the R&D investment, technology diffusion can be analyzed on the input-output (I-O) method (Dietzenbacher & Los, 2002). R&D expenditures and I-O table are combined to measure inter-sectoral product-embedded R&D flows to identify the main technology-providing and technology-using industries in the process of technology diffusion. However, information obtained through I-O model is too scattered, and is difficult to fully reflect structural features of industrial system (Norbu et al., 2021). On the other hand, technology diffusion interacts with inter-industry network structure (Semitiel-Garcia & Noguera-Mendez, 2012), can reallocate production factors, and thus promote optimization of industrial network structure. In regard to the weaknesses of I-O analysis in processing structural information, the industrial technology diffusion network was introduced, taking industrial sectors as nodes and economic relationships among industrial sectors as edges. Technological inputs in multiple sectors can be used in production of a specific commodity embodying technology flow, and conversely, the commodity can also be used in the production process of multiple sectors, forming a complex interconnected industrial network system (Tang et al., 2019). Structural adjustment of the network can improve efficiency of technology diffusion (Cai et al., 2022; Zuo et al., 2022) and industrial network method is appropriate on analyzing structure of technology diffusion system.

To improve structure of industrial technology diffusion system in the CEC, this paper combines I-O method and network model to explore the structural defects of interregional and inter-industry technology diffusion system of the CEC and improvement measures. Firstly, we measured inter-regional industrial relationship based on I-O tables and the MR-ITFT was modeled to describe the foundational skeleton of industrial technology diffusion system. Secondly, we designed the structural indexes including root, center of gravity, diameter, trunk and hierarchy on the MR-ITFT to find structural factors that affect industrial technology diffusion in the CEC. Further, we applied the indicators including the industrial technology spillover and absorption intensities and multipliers to reveal the comprehensive effects of structural factors, which reflect the imbalance of technology flow in the CEC. Finally, suggestions on improving the system were given. This research proposed the modeling of MR-ITFT and contributes to improving the structural analysis method of industrial technology diffusion, and investigating its application in analyzing and solving the problem of imbalance and inefficient allocation of industrial technology resources in the CEC.

2. Literature review

2.1. Researches on technology synergy and diffusion of CEC

The space-time evolution characteristics and mechanism of technology synergy in urban agglomeration and metropolitan areas has attracted a lot of attention (Jiang et al., 2021; Sefer & Ercan, 2011; Zhong et al., 2023) and efficient technology synergy can significantly improve quality of regional development (Timothy et al., 2002; Zhao & Zhu, 2021). The industrial technology synergy is regarded as a gradient and differential industrial technology transfer or diffusion. Many dilemmas of industrial synergy and technology diffusion in the CEC have been discussed. Especially due to continuous siphonage of advantageous technology elements, industries in the CEC show hierarchical differences and the industrial development of the CEC has been very uneven (Wei & Miao, 2017). As a result of the hierarchical difference, Hebei is excluded from integration of emerging industries in the CEC, and Tianjin is also inhibited in updating industrial structure. Based on the spatial lag model including foreign trade, policy, human investment, environment and technological progress, Xie and other scholars further explored the main factors affecting the effect of technology synergy (Xie & Hu, 2021). It can be seen that reasonable collaboration and allocation mechanism of technology resources has not been yet established in the CEC, and there is a phenomenon of ‘technology islands’. Industrial, innovation, service and capital chains can't be effectively integrated and motivation of government is insufficient (Sha, 2015), and the long-term split interest pattern among local governments in the CEC has caused lack of effective commitment to cooperation in reality (Yin & Wang, 2016). Specifically, technology resources are input into the industries and then organized through inter-industrial market transactions and the relationships among industries and so industrial structure is critical to understand the transfer and distribution of technology resource. However, from the perspective of qualitative analysis, the relevant literatures only focused on impact of single factors on technology synergy or diffusion, and haven't involved analysis of heterogeneity of the overall multi-regional industrial structure and adaptability of the multi-industrial technology system. Thus, the global, systematic, multi-regional and inter-industrial structure that can be related to the imbalance of technology resources can't be clearly described and identified, and it is difficult to find reasonable and effective implementations for the problem.

2.2. Researches on industrial technology diffusion

Technology diffusion refers to the continued diffusion of the technology through the market or non-market channels after it has been utilized for the first time (Rogers et al., 2008). In regional industrial clusters, technology flows among industrial chains through the process of technology diffusion, leads to an increase in the technological capability of the industries within the chain, as well as the firms included in the industries. Therefore, technology diffusion of a region is one of the most fundamental relationships and activities, and is usually defined as the knowledge transfer and interaction among sectors or innovators by movement of products, capital, human or other knowledge carriers (Rogers & Valente, 1991), who actively or passively learn from each other and innovate themselves through product trade or technology investment. During the process, technology spillover occurs to affect other related industries (Jaffe, 1998). In this sense, the study of technology diffusion based on industrial chains (or network) is particularly important, which can help us to study the vertical integration of industries and the diffusion processes of innovation (Debresson & Andersen, 1996). The vertical technology diffusion happens between upstream and downstream industries and the horizontal technology diffusion happens among industries with certain technological commonalities due to the similar input or output structures (Yin, 2017).

There are generally two methods of analyzing technology diffusion among industries: I-O models and industrial networks. The I-O approach was developed by combining input-output tables of intermediate goods with a conformable matrix of sectoral innovative effect (R&D), thus obtaining a particular input-output matrix of technology flow (Leoncini & Montresor, 2000). Technology spillover obtained by one sector is the weighted sum of R&D inputs of other sectors, which is called 'indirect R&D' (Pan et al., 2011). Taking into account both supply and demand factors, describing the diffusion process of technological R&D embodied in products with data of R&D and input-output transactions matrixes, and measuring the technological R&D flow across sectors and countries, I-O models can model a technology system on basis of technology flow contained in the intermediate products and capital products (Hauknes & Knell, 2009). However, I-O method is insufficient in analyzing multi-dimensional structure of complex technology systems. Besides, difficulty of compiling interregional input-output tables limits application of this method in the multi-regions. Based on I-O model, scholars further constructed regional technology spillover, transfer and diffusion networks for identifying the structural characteristics (Dimitrios et al., 2022; García-Muñiz & Vicente, 2014; Jiao et al., 2018; Kim et al., 2016). The technology flow matrix is transformed into a 0-1 matrix, which is the adjacency matrix of industrial technology diffusion network (Essletzbichler, 2015), where sectors are treated as nodes, while their product-embedded R&D flow as edges and direction of an edge indicates spillover and absorbed technology flow among industries. On the network, such indicators of inter-sectoral technology diffusion as density, the shortest distance, network size, and strong or weak ties (Magalhães & Afonso, 2017) could be used to analyze structure characteristics of the technology system (Chang & Shih, 2005; Jiao et al., 2017, 2018). Industry Technology Flow Network (ITFN) is defined as random, dynamic and complex network and could be constructed on the graph theory and network method (Yin, 2017). ITFN is a dynamic stochastic network describing relationships and structure of industry technology flow. The core-periphery of the ITFN reflects difference of sector aggregation, and the structural hole reflects role and influence of industrial sectors (Chang & Shih, 2005; García-Muñiz et al., 2010; Semitiel-Garcia & Noguera-Mendez, 2012). But few models are suitable to describe the foundational structure of technology diffusion system in multi-regions, and the structural indicators are also relatively single and cannot identify the multi-dimensional effects. Tree is an important model in graph theory. Based on the tree model, foundational structure of the system could be explored (Aroche, 2006; Hu et al., 2017), and key sectors can be identified, but it hasn't been applied in analysis of technology system, especially interregional technology system.

3. Methods and models

The research framework is shown in Figure 1. The research process is composed of three levels. The first includes measurement on relationships and structural modeling, which is the foundation for the other levels. Mining of patterns and evaluation on effects are on the second level and is critical in identifying the defects of industrial system and impacts on CEC's technology diffusion. Suggestions are to provide solutions for the problem of structural defects leading to imbalance of technology resources allocation. Detailed models and methods are analyzed in 3.1 to 3.4.

3.1. Measurement of interregional industrial technological relationship

Input coefficient in I-O table can systematically reflect the economic and technological relationships among industries in production process. Multi-regional industrial technological relationship is measured by integrating input coefficient, market competitiveness and policy intensity (Yin et al., 2021). Define that there are m regions,

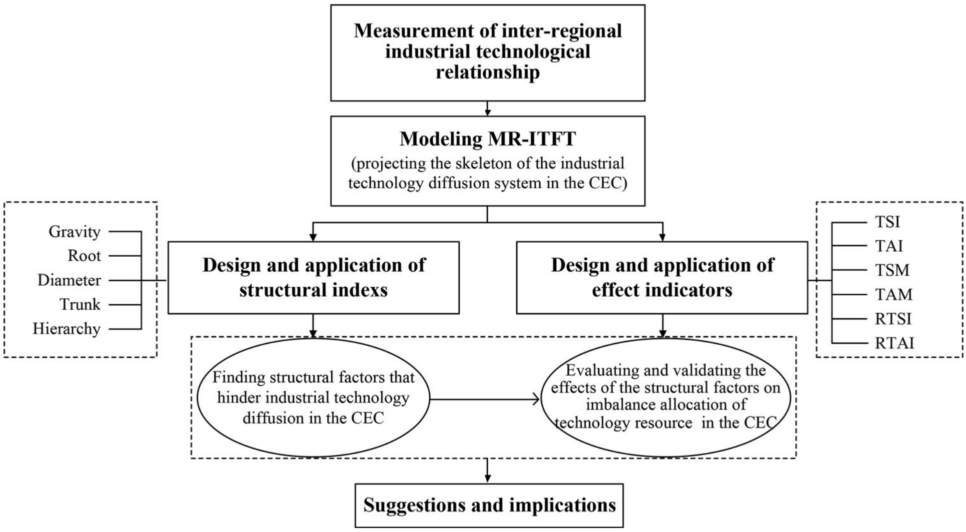


Figure 1. Research framework.
Source: the authors.

and each region has n industrial sectors. For industry i in region r and industry j in region s, the measurement is

$$RS(ri,sj) = \left[simO(ri,sj)\cdot simI(ri,sj)\cdot \frac{1}{||M_r - M_s||+1}\cdot \frac{1}{||P_r - P_s||+1}\right] \cdot \big(wR(ri,sj)\cdot A(ri,rj) + wS(ri,sj)\cdot A(si,sj)\big)$$

$$\mathrm{simO}(ri,sj) = \begin{cases} \dfrac{OR_i \cdot OS_i}{||OR_i||||OS_i||}, if||OR_i||||OS_i|| \neq 0 \\ 0, otherwise \end{cases}$$

$$\mathrm{sim}I(ri,sj) = \begin{cases} \dfrac{IR_i \cdot IS_i}{||IR_i||||IS_i||}, if||IR_i||||IS_i|| \neq 0 \\ 0, otherwise \end{cases}$$

$$WR(ri,sj) = \frac{P_r}{P_s}\frac{M_r}{M_s}\frac{OR_i}{OR_i + OS_i}$$

$$WS(ri,sj) = \frac{P_s}{P_r}\frac{M_s}{M_r}\frac{IS_j}{IR_j + IS_j}$$

$$wS(ri,sj) = \frac{WR(ri,sj)}{WR(ri,sj) + WS(ri,sj)}$$

$$wR(ri,sj) = \frac{WS(ri,sj)}{WR(ri,sj) + WS(ri,sj)} \quad (1)$$

Table 1. Interregional industrial technological relationship matrix ($mn \times mn$).

		region 1			… …	region m		
		sector 1	… …	sector n	… …	sector 1	… …	sector n
region 1	sector 1							
	… …							
	sector n							
… …	… …							
region m	sector 1							
	… …							
	sector n							

Source: the authors.

where OR_i is i's intermediate output vector, IS_j is j's intermediate input vector, P represents policy intensity, M represents the marketability index, and A is the input coefficient matrix of region r and s. RS is a matrix with mn columns and mn rows, as shown in Table 1. $RS(ri, rj)$ is the y-th row and z-th column element of the matrix, where $y = [(r\text{-}1) \times \text{n} + i]$ and $z = [(s\text{-}1) \times \text{n} + j]$.

3.2. Modeling MR-ITFT

Industrial tree can be obtained as the smallest structure that connects industries with the minimum number of relations (Aroche-Reyes, 2003), which is advantageous in studying foundational structure of technology diffusion system. Multi-regional industrial technology flow tree (MR-ITFT) is one kind of industrial technology flow network with maximum edge weights and non-cycles. The MR-ITFT is denoted as $\{V_T, E_T, W(V_T), W(E_T)\}$, where V_T is set of all the industrial nodes, E_T is set of edges among nodes, $W(E_T)$ is the edge weight, measured by the matrix MT and $W(V_T)$ is the node weight, measured by the R&D investment of industries. Technology spillover and absorption reflect the technology diffusion activities of sectors (Dietzenbacher & Los, 2002) and the total technology flow matrix, including absorption flow matrix T_f and spillover matrix T_b is

$$T = (\widehat{rd})(\hat{x})^{-1}(I - MT)^{-1} + (I - MT)^{-1}(\widehat{rd})(\hat{x})^{-1} = T_f + T_b \qquad (2)$$

According to Kruskal's algorithm, method for modeling the MR-ITFT is as follows (Cherif & Madkour, 2023; Wu et al., 2021): a) Set an empty set F and put all the node $v_i \in V_T$ into F; b) Select the edge with the maximum weight in $RS(i,j)$, if the node to which the edge is attached does not form a cycle, then put it into F, and set $MT(i,j) = RS(i,j)$. Otherwise, this edge is discarded and the next edge with the maximum weight is tested one by one until an edge is suitable; c) Repeat Step b) until all the nodes are on the same connected component.

3.3. Structure index of MR-ITFT

According to the existing achievements and graph theory, the structural characteristics of trees can be described in terms of nodes, paths and hierarchy, and the following five indexes are reasonably selected.

1. *Root and center of gravity*. The root is the node with the largest R&D investment in the MR-ITFT and taken as the industry with the greatest demanding of technology flow. The center of gravity is a node in the MR-ITFT whose largest subtree is the smallest. The center of gravity is taken as a node with the power over the global technology diffusion relationships. The process to find the center of gravity is as follows: a) Start from any node r and perform Depth First Search (DFS) on the subtree of this node, and take the weight of its largest subtree as max_part(r); b) Repeat a) for all the nodes; c) Find the minimum value of max_part and the smallest subtree and the root of this subtree is the center of gravity (Guha Neogi & Goswami, 2021).
2. *Diameter and trunk*. The diameter is the path with the maximum distance of the shortest weighted distance between any two nodes (López & Pérez-Rosés, 2015) in the MR-ITFT. The diameter means the longest industrial technology chain. The method for diameter of MR-ITFT is as follows: a) Start from any node $u \in V_T$, and do DFS to find the farthest node v of u; b) Do DFS on v to find the farthest node w. The length of the path from v to w is the diameter of the MR-ITFT. The trunk is the path between any two nodes in the MR-ITFT with the largest weight, that is, the sequence of edges with the strongest technology flow. The trunk is the industry cluster that can obtain the most efficient transmission and utilization of technology flow (Wu et al., 2021).
3. *Hierarchy*. Hierarchy is the clustering nodes based on the heterogeneity of status, role and function in transmission of technology flow. In hierarchy, the first-level nodes are those with no inflow and the source of technology flow. The middle-level nodes have both inflow and outflow. The last-level nodes are the sink of technology flow with no technology outflow. A hub in hierarchy is a node that connects more than five lower-level nodes and has the function of technology flow reassignment, related to the efficiency of allocation of technology resource.

3.4. Indicators of technology diffusion effect

The total forward and backward linkage was suggested as a reasonable measure of diffusion effect (Beyers, 1976). The indicators, including technology spillover intensity (TSI) reflecting forward technology spillover and technology absorption intensity (TAI) reflecting backward technology absorption on the MR-ITFT can be applied. The industrial technology diffusion intensity including TSI and TAI describes the level that an industry interacting with other industries in process of technology diffusion, benefits from other industries' R&D activities, or its own innovation activities benefit other industries (Pan, 2015).

a. TSI describing the level of influence of specific industries in the process of technology spillover is

$$TSI_i = \sum_{j=1}^{mn} T_{i,j} / \sum \sum T \tag{3}$$

b. TAI describing the level of influence of specific industries in the process of technology absorption is

$$TAI_j = \sum_{i=1}^{mn} T_{i,j} / \sum \sum T \tag{4}$$

The technology flow is fed back repeatedly through the diffusion channel, constantly amplified and accumulated including the output multiplier and input multiplier (Oosterhaven & Dirk, 2002) describe the amplification effect of technology investment on the key industries achieved by the forward and backward interaction of the sustainable technological flows in the process of technology diffusion (Huang & Zhang, 2020). The technology spillover multiplier (TSM) and technology absorption multiplier (TAM) can be applied in the MR-ITFT.

c. TSM describing the amplification effect of the technology diffusion of a specific industry is

$$TSM_i = x_i \sum_{j=1}^{mn} T_{i,j} / R\&D_i \tag{5}$$

d. TAM describing the amplification effect of technology flow absorbed by a specific industry is

$$TAM_j = x_j \sum_{i=1}^{mn} T_{i,j} / R\&D_j \tag{6}$$

Multi-regional technology diffusion intensity can describe impacts of industrial technology innovation activities of one region on other regions in the process of technology diffusion (Ye & Jiang, 2020). The interregional technology spillover intensity (RTSI) and interregional technology absorption intensity (RTAI) can be applied in the MR-ITFT.

e. RTSI is the sum of technology flows from region r to region s, as shown in Equation (7). The higher the indicator is, the greater the spillover effect of technological diffusion is

$$RTSI_{r,s} = \sum_{i=(r-1)n+1}^{rn} \sum_{j=(s-1)n+1}^{sn} T_{i,j} \tag{7}$$

f. RTAI is the sum of the feedback technology flows received by region s from region r, as shown in Equation (8). The higher the indicator is, the greater the absorption effect of diffusion is

$$RTAI_{s,r} = \sum_{i=(s-1)n+1}^{sn} \sum_{j=(r-1)n+1}^{rn} T_{i,j} \tag{8}$$

where $r, s = 1, 2, , \ldots, m,\ r < s$ and n is the number of industrial sectors in region r or region s.

4. Empirical results and discussion

4.1. Data collection and processing

The I-O tables of the three regions in the CEC for 2012 and 2017 were applied. The period from 2012 to 2017 before COVID-19 is just in the economic fluctuation cycle of China and is of great value in structural analysis, and the input-output data can just reflect the typical changes in this period. To cope with the dilemma of economic growth after the financial crisis in 2008, from 2012 to 2017, China intensively issued many very important policies, such as 'innovation-driven development strategy' in 2012, 'mass entrepreneurship and innovation' in 2015, 'supply-side structural reform' in 2016, 'rural revitalization strategy' in 2017, which had deeply changed the economic and industrial structure, the level of investment and consumption, and supply-demand relationships, which promoted technological progress. The changes are necessary implied in the I-O tables, and the iteration of technical coefficient matrix can indicate the changes of economic and industrial structure from 2012 to 2017 and the impact of environment of system. Besides, referred to related literatures (Leoncini & Montresor, 2000; Pan et al., 2022), the investment of R&D on industry sectors was integrated with the input-output model, which fully absorbed the impact of technical fluctuations from 2012 to 2017, so that the data can better reflect the dynamic relationship of this period, and the structural factors can be more fully displayed.

The data sets of R&D expenditure, fiscal expenditure, and GDP come from the China Statistical Yearbook. The competition of the regions in 2012 and 2017 is measured by the marketization index (Wang et al., 2019). 42 sectors were merged into 25 sectors, as shown in Appendix, with a total of 75 sector nodes. Industry nodes in Beijing, Tianjin and Hebei are marked as numbers 1 ∼ 25, 26 ∼ 50, 51 ∼ 75 respectively. The data is stored in Excel software, programming is performed by MATLAB, NETDRAW of UCINET is used to draw the network and the indexes and indicators were computed by C++ and MATLAB.

4.2. Analysis of structural indexes of MR-ITFT in CEC

The MR-ITFT was identified as Figure 2. Nodes in Beijing, Tianjin, and Hebei are marked with red, yellow, and blue colors respectively. MR-ITFT-2012 contains a total of 74 interconnected industry nodes. The industry 55 in Hebei is an isolated island. Industry 38 and industry 52 are the tree nodes that form the largest number of branch nodes and leaf nodes (generates 24 branch and 13 leaf nodes, respectively). In contrast, MR-ITFT-2017 contains a total of 75 interconnected industry nodes and there is no more isolated industry island. All the industries are on the foundational technology chains. From 2012 to 2017, the structural evolution of industrial technology system was obvious, but there were prominent structural defects in industrial technology system of the CEC.

a. The regional subsystems of industrial technology system appeared polarized and heterogeneous, but the subsystems hadn't reached a better equilibrium state. In 2012, there were more nodes with degrees above 2 in Beijing and Tianjin than in

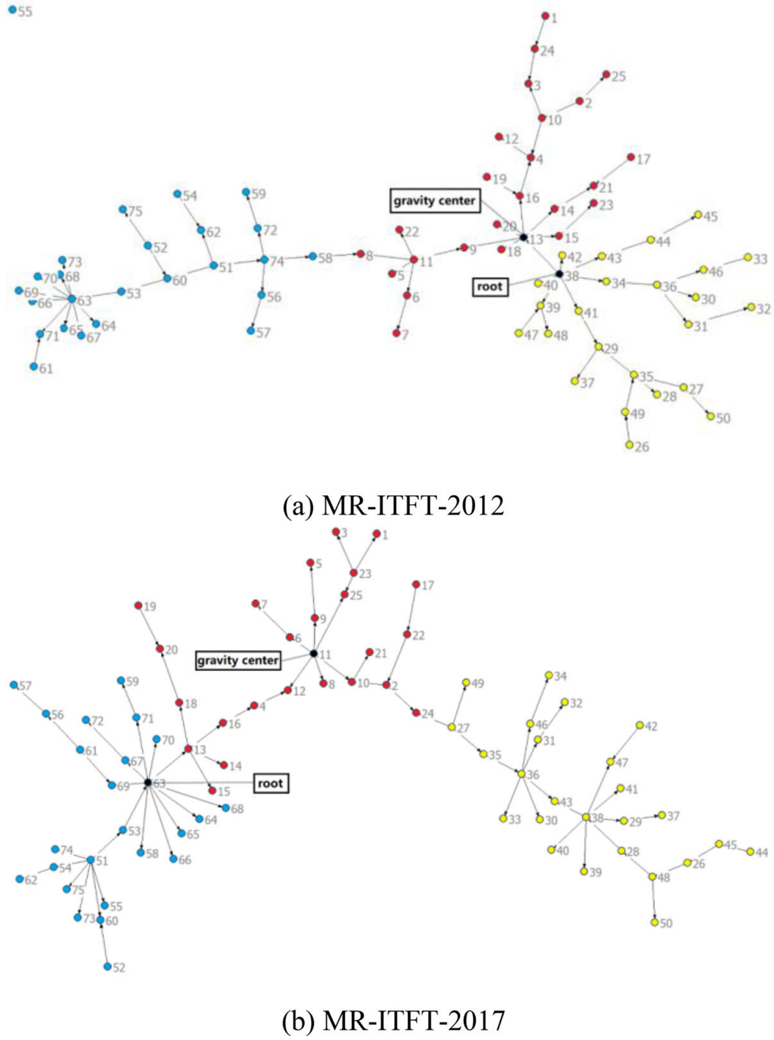


Figure 2. MR-ITFT of the CEC.
Source: the authors.

Hebei. Beijing and Tianjin were characterized by hierarchical connection, with many branch nodes distributed at multiple levels and orderly connected among levels. However, Hebei was divided into two parts with node 53 as the boundary. One part was an industrial cluster around node 63 on the left side of the tree, and the other on the right side approximated a straight line with sequential connection of industrial sectors. The technology flow was either constrained in local scope or difficult to penetrate through multi-level industries in the path. Besides, there was even isolated industry 55, known as 'technology island' (Xie & Hu, 2021). In 2017, structure of industrial technology system in Hebei turned to another extreme, forming a dual centralized substructure with node 51 and 63, where the technology flow of peripheral nodes was restricted around the central node and the reorganization and interaction of technology flow was inhibited as a result of insufficiency branches.

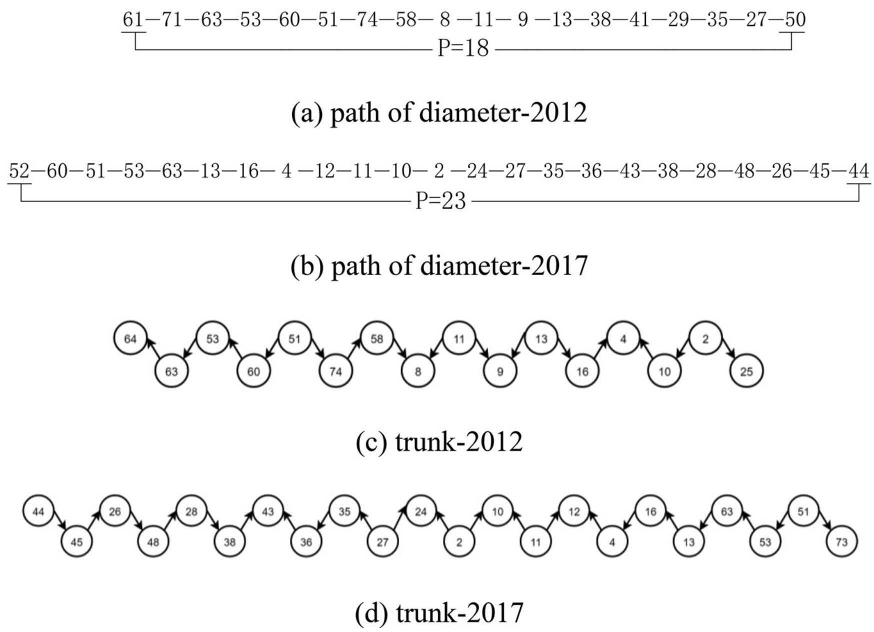
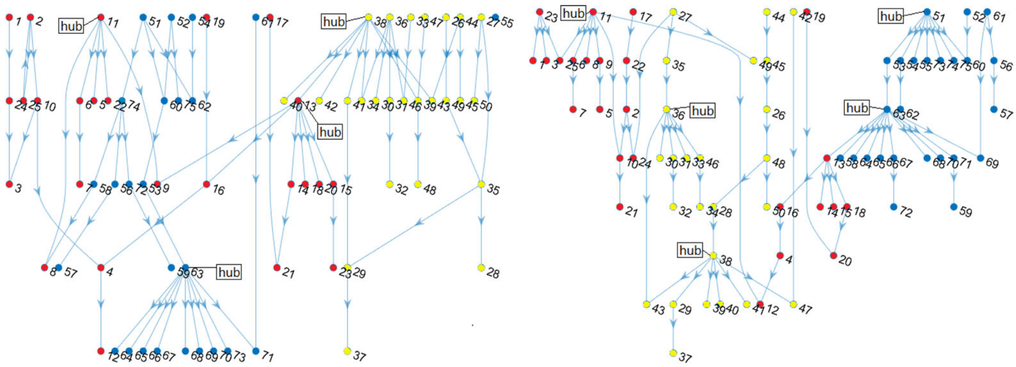


Figure 3. trunk of MR-ITFT in Capital Economic Circle.
Source: the authors.

b. The supply and demand structure of technology flow was not coordinated. The root was node 38 of Tianjin in 2012 and was node 63 of Hebei in 2017. It means that the technology demands had been transferred from Tianjin to Hebei and Hebei had a strong technological iterative pressure on industries of raw materials and products. Industry 51 was the node that forms the largest number of branch nodes and leaf nodes (generates 28 branch and leaf nodes). It is seemed that technology flow was stored and operated, and the core functional system was constructed all around the sectors of coal and steel in Hebei. On the other hand, the center of gravity was industry 13 of Beijing in 2012 and that was industry 11 of Beijing in 2017. The most innovative and dynamic industry in the CEC had changed from the metal processing industry to the chemical industry which was the key source of high-quality technology flow. But the technological distance between this sector and that in Tianjin and Hebei was 11 steps, passing through the industry cluster or technological black hole centered on the root in Hebei, which can intensify the imbalance of supply and demand of technology flow. The building of multi-dimensional and coordinated technology system is urgent, and inter-regional and multi-agent platforms for industrial common technology should be programmed.

c. The vertical technology diffusion system had not been integrated. As shown in Figure 3, it is the same on diameter and trunk that numbers of nodes of the paths in 2017 were more than that in 2012 and industries in different regions were separated from each other. The extension of the industrial technology chain reflects the substitute of industrial horizontal diffusion relationship for vertical relationships, but the integrated vertical technology diffusion system had not been established across the overall technology system of the CEC. The number of



(a)2012 (b)2017

Figure 4. Hierarchy of nodes in the CEC.
Source: the authors.

nodes in Hebei had been greatly reduced, with some manufacturing sectors eliminated from the main path, such as node 71, 74, etc. Obviously, Hebei was excluded from integration with emerging industries, which is in line with the views of Wei and Miao (2017). We think that the industrial production transfer among the regions mainly driven by the industrial policy was separated from intensive technical support. Further, we can see that there were considerable differences in the distribution of nodes and edges between the trunk and the diameter in 2017, and the longest path and the strongest path were inconsistent, which means that the channel of vertical technology diffusion along the main path had not been opened, and the technology flow cannot effectively reach the peripheral industries of the industrial system of the CEC. Digital strategy needs to be joined in industrial policies, and intelligent production technologies and models should be used to promote multi-regional vertical integration of industries that can respond quickly to technological needs spatially dispersed.

d. The trend of centralization and convergence of technology relationships was enhanced. As shown in Figure 4, MR-ITFT in 2017 had more layers but less number of nodes in the first layer, indicating that although the industrial technology flow chain was highly extended, the original technological flow was more centralized in the resource-consuming industries which had a dominated role in the upstream technology chain. The hubs in 2012 were industry 11, 13, 38, 63(Smelting and Pressing of Metals industry) and industry 36 and industry 51 were included into the hubs in 2017. The hub nodes in 2017 were more evenly distributed among the regions which may be advantageous to the integration of technology chains. However, the increase in the degrees of hubs represented a centralization of technology flow and can reduce the complexity and randomness of technology overflow and inflow, which can explain the ‘siphonage’ proposed in the literatures. Especially for Hebei, the status of its two hubs of energy and metal industry had jumped from layer 4 to layer 1, which can further result in shielding technology flow towards downstream industries. Structurally, the industry segmentation of hub nodes, producing industries such as new energy and

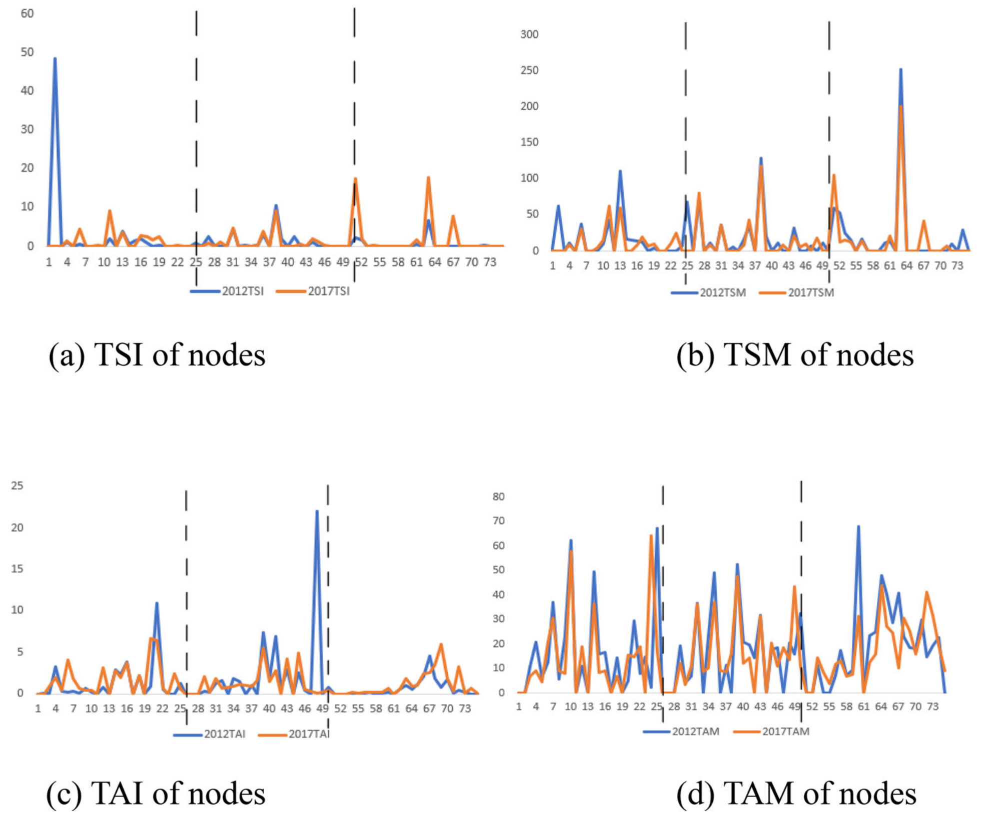
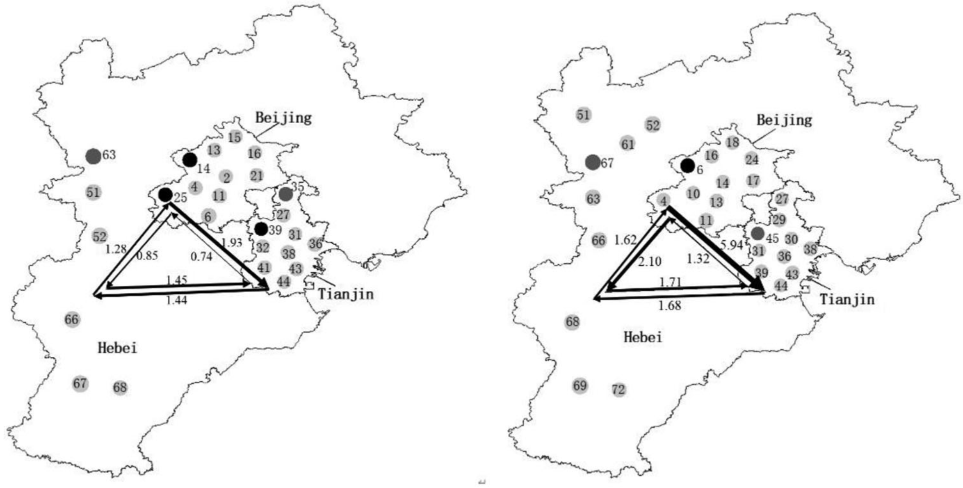


Figure 5. Industrial technology diffusion effect.
Source: the authors.

new materials, can promote the diversified flow of technology and activate technological innovation synergy of upstream and downstream industries.

4.3. Analysis of industrial technology diffusion effect

The spectrums of diffusion indicators are shown in Figure 5. The impact of the structural defects in the technology diffusion system can be summarized as follows. (a) The overall positive effect of the technological flow of the industrial system was inhibited, and the technological progress was differential. From the industrial technology spillover spectrum, there were fragmented and discrete segments in all the three regions. The curves of industrial technology flow intensity and amplification effect had obvious discontinuity, especially among the mining, primary processing, deep processing, equipment manufacturing and energy industries. From 2012 to 2017, the technology outflow showed a sharp fluctuation trend, and in some large segments, such as the entire section 20 ~ 26, 53 ~ 59, 68 ~ 75 the indicators were close to zero. These segments were mainly concentrated in technology-intensive industries. (b) The reverse movement effect of technology flow hinders the upgrading of traditional industries and the competitiveness of high-tech industries. From the technology spillover spectrum, industries with high overflow intensity or high overflow multiplier were mostly concentrated in industries



(a)2012 (b)2017

Figure 6. Correlation coefficient between the regions.
Source: the authors.

such as No.2 and 13. The technology outflows of traditional resource and primary processing industries were more active. It is known that those industries were mainly concentrated in Hebei, and the technology absorption intensity of primary processing industries such as wood and metal raw materials (52 ~ 60) was low. On the contrary, the TAI of high-technology industry in the three regions were very high in the past two periods, especially in Beijing and Tianjin, such as 19 ~ 21 and 43 ~ 46.The strong absorption of low-intensity technology flow in high-tech industries and the strong outflow of traditional industries indicate that the technology flow reversal was more prominent, which not only hinders the upgrading of technical equipment and production processes in traditional industries, but also further increases the cost of investment, production and operation of high-tech industries. (c) The comprehensive effect of industrial technology diffusion was unstable, increasing the cost of innovation resource allocation. Obviously, industry 2 in 2012 had the high TSI and TSM, which then declined sharply in 2017. The TSI of industries 6, 11, 31, 67 showed a rapid jump in 2017 compared with 2012. TSI of industries 27, 41, and TSM of industries 13, 25, 74 were much lower in 2017 than in 2012. These industries belonged to the energy and heavy industries. On the other hand, TAM in 2017 was generally lower than that in 2012. Absorption of technology flow in these industries was nearly saturated. The decline of inflow and the instability of rapid expansion and contraction of outflow were partly caused by the imbalance of technology supply and demand structure.

4.4. Analysis of technology flow among the regions of CEC

The multi-regional technology diffusion intensity was summed and the industrial technology diffusion triangles were established in Figure 6. The identified key industries of technology spillover, transfer and absorption were marked on the map.

The direction and the width of the edge represent the direction and the strength of technology flow respectively. Technology flow in the outer triangle is in the direction from Beijing to Hebei through Tianjin, and that in the inner triangle is on the opposite. The three regions of the CEC had formed the pattern of 'one core and two fulcrums'. Beijing was the core in regional interaction and the supporter of industrial and technological progress in Hebei and Tianjin, but the industrial technology distance between Beijing and Hebei was still large. From 2012 to 2017, the strength of the Beijing-Tianjin edge in the outer triangle increased in some degree, and the width of the Beijing-Hebei edge in the inner triangle increased highly. Beijing was the stable technology source for the other two regions and its technology spillover intensity was greater than its absorption intensity. In 2017, the strength of each edge was greater than in 2012, which shows that the depth of technology cooperation was increasing. It can be seen that Beijing had formed the clear vertical diffusion pattern with the other two regions, and Hebei and Tianjin were in the horizontal relationship of diffusion. However, the three regions had not yet been integrated into a sustainable circulation system of industrial technology flow, industrial technology integration relationships of Beijing with Tianjin and Hebei were unbalanced and Beijing exported more technology flows than it imported. As the cooperation between regions should be mutually beneficial, the unbalance can inhibit the power of Beijing's continuous technology output, and Yin and Wang (2016) also stated that the long-term split interest pattern among regions has caused lack of effective commitment to cooperation. The low return of technology investment in Hebei is also the reason for restraining the re-investment of resources. Instead, Hebei needs more technology resources investment to support upgrading of traditional industries as the metal smelting and metal products, and cultivation of emerging industries with high return as traffic equipment manufacturing. For this dilemma, mutual coordination and integrating of industrial technology chain is necessary.

5. Conclusion and suggestions

Imbalance of the allocation of technological resources leaded to heterogeneous industrial production efficiency in the CEC. To solve this problem, we combined I-O method and network model to explore structural defects of technology diffusion system and the impact of such defects on diffusion effect of the CEC. Firstly, MR-ITFT was modeled on industry complex network to describe the foundational structure of industrial technology diffusion. It can be seen that from 2012 to 2017, the MR-ITFT became more complex and the hierarchy was growing in the CEC. Referring to relevant theories and research literature, structural indexes and effect indicators were designed on the MR-ITFT, which were applied to investigate the defects of the technological diffusion system, and effects of the defects. We found that heterization and polarization of subsystems, imbalance of supply and demand, non-integrated vertical function and trend of centralization and convergence were the structural factors interfering circulation of technology flow and allocation of technical resources, which can be further reflected on the reduced, inverse and unstable comprehensive effects on technology flow, resulting in the heterogeneity of regional industrial productivity.

Contradiction between low return of technology investment and high demand on technology investment among the regions can lead to an unsustainable circulation system of the CEC, so under the current situation of China, construction of industrial technology system with high integration and cooperation is suggested.

Firstly, policymakers should build a multi-dimensional and coordinated technology innovation and diffusion system. Collaboration among businesses, research institutions, and universities should be facilitated and strengthened by the government and society. The government needs to actively promote technology exchange among industries, promote high-quality and high-tech industrial talents, and create an efficient system for flow of human capital. Financial support should be increased for these key industries and special R&D funds are set up, providing enterprises with appropriate financial support and guarantees. Secondly, policymakers should promote the application of digitalization, networking and intelligence technology, and integrate 'traditional manufacturing capabilities' and 'emerging digital technologies' in the CEC. Cultivating intelligent manufacturing and advanced manufacturing cluster and building an autonomous and controllable modern industrial system should be taken as the main direction. Regions of the CEC should focus on strengthening the collaborative innovation ability of intelligent manufacturing technology, improving the application level of intelligent manufacturing and building an ecological service system for intelligent manufacturing. The public service platform for intelligent manufacturing data resources should be launched. Policymakers should also promote the Industrial Internet to help enterprises solve the problem of isolated data during cross-chain connection, interaction, and interoperability, realizing the building of the industrial production and innovation ecosystem of the CEC. Thirdly, policymakers should accelerate technological innovation and integration in the fields of new energy, transportation, and new material, and especially coordinate the development of electric, networked and intelligent automobile industries. Based on complementation of regional advantages, the development and application ecology of in-depth cooperation among market players in the fields should be built. Industrial cooperation should be extended from the production and manufacturing link of complete vehicles, key parts, basic data and software, and vehicle operating systems to the whole chain of technology research and development, marketing, etc. A number of new emerging industrial clusters with international influence and competitiveness, which can promote upstream and downstream collaborative innovation, facilitate the development of large and medium-sized enterprises, and promote the modernization of the industrial chain should be cultivated.

This study has some limitations, highlighting future research opportunities. We should pay attention to the updating method of input-output table to make the data to better describe the current situation. Further, network technology can be applied to study the industrial chain and technology chain in detail and future researches could be focused on the development of circular networks based on multi-regional input-output models, so as to explore the structural optimization of technology flow. In addition, we can explore how econometric, machine learning, and other methods are combined with I-O methods and even industrial networks to better grasp the essence of economic and technological structure.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research is supported by the Planned Fund on Humanities and Social Sciences Research of Ministry of Education (grant no. 22YJA630106), and Shandong Humanities and Social Sciences Project (grant no. 2021-JCGL-06).

Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request. The multi-regional input-output data used in this paper is the open-resource data provided by Carbon Emission Accounts & Datasets for emerging economies at https://www.ceads.net.cn/data/input_output_tables/.

References

Aroche, F. (2006). Trees of the essential economic structures: A qualitative input-output method. *Journal of Regional Science*, *46*(2), 333–353. https://doi.org/10.1111/j.0022-4146.2006.00444.x

Aroche-Reyes, F. (2003). A qualitative input-output method to find basic economic structures. *Papers in Regional Science*, *82*(4), 581–590. https://doi.org/10.1007/s10110-003-0149-z

Beyers, W. B. (1976). Empirical identification of key sectors: Some further evidence. *Environment and Planning A*, *17*, 73–99.

Bo, W. G., & Chen, F. (2015). The coordinated development among Beijing, Tianjin and Hebei: Challenges and predicaments. *Nankai Journal (Philosophy, Literature and Social Science Edition)*, *1*, 110–118.

Cai, L. R., Wu, X. H., & Du, Z. W. (2022). The spatio-temporal pattern of environmentally-friendly agricultural technology diffusion and its influencing factors: From the social network perspective. *Geographical Research*, *41*(01), 63–78.

Chang, P. L., & Shih, H. Y. (2005). Comparing patterns of intersectoral technology diffusion in Taiwan and China: A network analysis. *Technovation*, *25*(2), 155–169. https://doi.org/10.1016/S0166-4972(03)00077-4

Cherif, E. M., & Madkour, J. (2023). Dynamics of the Moroccan industry indices network before and during the Covid-19 pandemic. *International Journal of Banking and Finance*, *18*(1), 31–50. https://doi.org/10.32890/ijbf2023.18.1.2

Debresson, C., & Andersen, E. S. (1996). *Economic interdependence and innovative activity: An input-output analysis*. Edward Elgar.

Dietzenbacher, E., & Los, B. (2002). Externalities of R&D expenditures. *Economic Systems Research*, *14*(4), 407–425. https://doi.org/10.1080/0953531022000024860

Dimitrios, S., Petros, D., & Aggelos, T. (2022). Exploring the structural effects of the ICT sector in the Greek economy: A quantitative approach based on input-output and network analysis. *Telecommunications Policy*, *46*(7), 102332. https://doi.org/10.1016/j.telpol.2022.102332

Essletzbichler, J. (2015). Relatedness, industrial branching and technological cohesion in US metropolitan areas. *Regional Studies*, *49*(5), 752–766. https://doi.org/10.1080/00343404.2013.806793

García-Muñiz, A. S., Raya, A. M., & Carvajal, C. R. (2010). Spanish and European technology diffusion: A structural hole approach in the input–output field. *The Annals of Regional Science*, *44*(1), 147–165. https://doi.org/10.1007/s00168-008-0247-6

García-Muñiz, A. S., & Vicente, M. R. (2014). ICT technologies in Europe: A study of technological diffusion and economic growth under network theory. *Telecommunications Policy*, *38*(4), 360–370. https://doi.org/10.1016/j.telpol.2013.12.003

Guha Neogi, P. P., & Goswami, S. (2021). Force of gravity oriented classification technique in machine learning. In N. Sharma, A. Chakrabarti, V. Balas, & J. Martinovic (Eds.), *Data management, analytics and innovation. Advances in intelligent systems and computing* (Vol. 1174, pp. 299–310). Springer. https://doi.org/10.1007/978-981-15-5616-6_21

Hauknes, J., & Knell, M. (2009). Embodied knowledge and sectoral linkages: An input–output approach to the interaction of high- and low-tech industries. *Research Policy*, *38*(3), 459–469. https://doi.org/10.1016/j.respol.2008.10.012

Hu, F., Zhao, S., Bing, T., & Chang, Y. (2017). Hierarchy in industrial structure: The cases of China and the USA. *Physica A: Statistical Mechanics and Its Applications*, *469*, 871–882. https://doi.org/10.1016/j.physa.2016.11.083

Huang, R. L., & Zhang, X. (2020). A comparative study of industrial multiplier, spillover and feedback effect in the Yangtze River delta region-based on multi-region input-output model. *Financial Economics Xinjiang*, *224*(3), 17–28.

Jaffe, A. B. (1998). The importance of "spillovers" in the policy mission of the advanced technology program. *The Journal of Technology Transfer*, *23*(2), 11–19. https://doi.org/10.1007/BF02509888

Jiang, Y. M., Meng, Q. C., & Li, X. Y. (2021). Performance evaluation of regional technological innovation driving high-quality economic development. *Statistics & Decision*, *37*(16), 76–80.

Jiao, J. L., Jiang, G. L., & Yang, R. R. (2018). Impact of R&D technology spillovers on carbon emissions between China's regions. *Structural Change and Economic Dynamics*, *47*, 35–45. https://doi.org/10.1016/j.strueco.2018.07.002

Jiao, J. L., Yang, Y. F., & Bai, Y. (2017). R&D spillovers of China's industry based on social network. *Forum on Science and Technology in China*, *10*, 55–64.

Kim, D. H., Lee, B. K., & Sohn, S. Y. (2016). Quantifying technology–industry spillover effects based on patent citation network analysis of unmanned aerial vehicle (UAV). *Technological Forecasting and Social Change*, *105*, 140–157. https://doi.org/10.1016/j.techfore.2016.01.025

Leoncini, R., & Montresor, S. (2000). Network analysis of eight technological systems. *International Review of Applied Economics*, *14*(2), 213–234. https://doi.org/10.1080/02692170050024750

López, N., & Pérez-Rosés, H. (2015). Degree/diameter problem for mixed graphs. *Procedia Computer Science*, *74*, 2–9. https://doi.org/10.1016/j.procs.2015.12.066

Magalhães, M., & Afonso, Ó. (2017). A multi-sector growth model with technology diffusion and networks. *Research Policy*, *46*(7), 1340–1359. https://doi.org/10.1016/j.respol.2017.05.004

Norbu, N. P., Tateno, Y., & Bolesta, A. (2021). Structural transformation and production linkages in Asia-Pacific least developed countries: An input-output analysis. *Structural Change and Economic Dynamics*, *59*, 510–524. https://doi.org/10.1016/j.strueco.2021.09.009

Oosterhaven, J., & Dirk, S. (2002). Net multipliers avoid exaggerating impacts: With a Bi-regional illustration for the Dutch transportation sector. *Journal of Regional Science*, *42*(3), 533–543. https://doi.org/10.1111/1467-9787.00270

Pan, W. Q. (2015). Regional economic development in China: An analysis based on spatial spillover effect. *Journal of World Economic*, *38*, 120–142.

Pan, W. Q., Li, Z. N., & Liu, Q. (2011). Inter-industry technology spillover effects in China: Evidence from 35 industry sectors. *Economic Research Journal*, *46*(7), 18–29.

Pan, Y. L., Jiang, Y. L., & Jiang, L. H. (2022). A research on transmission effect of innovative network from perspective of industrial relevance. *Journal of Hangzhou Dianzi University (Social Sciences)*, *18*(3), 8–16.

Rogers, E. M., & Valente, T. W. (1991). *Technology transfer in high-technology industries*. Oxford University Press.

Rogers, E. M., Singhal, A., & Quinlan, M. M. (2008). *An integrated approach to communication theory and research*. Routledge.

Scherer, F. M. (1982). Inter-industry technology flows and productivity growth. *The Review of Economics and Statistics*, *64*(4), 627–634. https://doi.org/10.2307/1923947
Schumpeter, J. A. (1934). *The theory of economic development: An inquiry into profits, capital, credit, interest, and the business cycle*. Transaction Publishers.
Sefer, S., & Ercan, S. (2011). The effects of science-technology-innovation on competitiveness and economic growth. *Procedia - Social and Behavioral Sciences*, *24*, 815–828.
Semitiel-Garcia, M., & Noguera-Mendez, P. (2012). The structure of inter-industry systems and the diffusion of innovations: The case of Spain. *Technological Forecasting and Social Change*, *79*(8), 1548–1567. https://doi.org/10.1016/j.techfore.2012.04.010
Sha, H. (2015). Accelerate the construction of regional collaborative innovation community with the help of the Beijing-Tianjin-Hebei collaborative development strategy. *CPPCC Tianjin Municipal Committee Journal*, *336*(19), 7.
Tang, M., Hong, J., Liu, G., & Shen, G. Q. (2019). Exploring energy flows embodied in China's economy from the regional and sectoral perspectives via combination of multi-regional input–output analysis and a complex network approach. *Energy*, *170*, 1191–1201. https://doi.org/10.1016/j.energy.2018.12.164
Timothy, F. B., Erik, B., & Lorin, M. H. (2002). Information technology workplace organization and the demand for skilled labor: Firm-level evidence. *The Quarterly Journal of Economics*, *117*(1), 339–376.
Wang, X. L., Fan, G., & Hu, L. P. (2019). *China's provincial marketization index report*. Social Sciences Academic Press.
Wei, Y. Q., & Miao, Y. C. (2017). Discussion of Industrial Structure in the Integration of Beijing. *Tianjin and Hebei. Reformation and Strategy*, *33*(10), 150–154.
Wu, J., Liu, H., Ruan, Y., Wang, S., Yuan, J., & Lu, H. (2021). A novel method for network design and optimization of district energy systems: Considering network topology planning and pipe diameter. *Applied Sciences*, *11*(4), 1795. https://doi.org/10.3390/app11041795
Xie, S. S., & Hu, W. (2021). Coupling and coordination of high-quality economic development and technological innovation: Taking the Beijing-Tianjin-Hebei region as an example. *Statistics & Decision*, *37*(14), 93–96.
Ye, Z. Y., & Jiang, Q. W. (2020). Industrial linkage and spatial spillover effects under regional integration of Yangtze River Delta. *Journal of Nanjing University of Finance and Economics*, *4*, 34–44.
Yin, A. N., & Wang, H. S. (2016). Evolution of government cooperation game in industrial gradient transfer of Beijing-Tianjin-Hebei region. *Journal of Technology Economics*, *35*(01), 78–82. +109.
Yin, C. (2017). Modeling industry technology flow network and its structural effects. *Science & Technology Progress and Policy*, *34*(16), 62–70.
Yin, C., Ding, Q. Y., Yang, Z. Y., & Cui, Y. X. (2021). Industrial technology diffusion mechanism and innovation synergy effect of central plains urban agglomeration. *Science and Technology Management Research*, *41*(20), 35–43.
Zhao, X. C., & Zhu, D. P. (2021). Impact of R&D investment on high quality development of Jiangsu economy. *Science and Technology Management Research*, *41*(12), 70–76.
Zhong, X. S., Liu, Y. L., & Chen, W. (2023). *Research on the coupling and coordination degree between scientific-technical innovation and high-quality economic development—An empirical analysis based on panel data from nineteen major urban agglomerations in China*. Resource Development and Market, pp. 1–17.
Zuo, X. M., Gao, R. Y., Chen, Y. L., Huang, H., Chen, A. J., & Jin, W. (2022). *The mechanism of manufacturing cluster network in the Pearl River Delta on technology diffusion*. Guangdong Economy, (06), 20–27.

Appendix. Name and number of industrial sectors.

Number			
Beijing	Tianjin	Hebei	Name of industry
1	26	51	Mining and Washing of Coal
2	27	52	Extraction of Petroleum and Natural Gas
3	28	53	Mining and Processing of Metal Ores
4	29	54	Mining and Processing of Nonmetal Ores and Other Ores
5	30	55	Manufacture of Foods and Tobacco
6	31	56	Manufacture of Textile
7	32	57	Manufacture of Textile Wearing Apparel, Leather, Feather and Related Products
8	33	58	Processing of Timber and Manufacture of Furniture
9	34	59	Manufacture of Paper, Printing and Manufacture of Articles For Culture, Education and Sport Activities
10	35	60	Processing of Petroleum, Coking, Processing of Nuclear Fuel
11	36	61	Manufacture of Raw Chemical Materials and Chemical Products
12	37	62	Manufacture of Non-metallic Mineral Products
13	38	63	Smelting and Pressing of Metals
14	39	64	Manufacture of Metal Products
15	40	65	Manufacture of General Purpose Machinery
16	41	66	Manufacture of Special Purpose Machinery
17	42	67	Manufacture of Transport Equipment
18	43	68	Manufacture of Electrical Machinery and Equipment
19	44	69	Manufacture of Computers, Communication Equipment and Other Electronic Equipment
20	45	70	Manufacture of Measuring Instruments
21	46	71	Manufacture of Other Manufacturing Recycling and Disposal of Waste
22	47	72	Repairing of Metal Products, Machinery and Equipment
23	48	73	Production and Supply of Electric Power and Heat Power
24	49	74	Production and Supply of Gas
25	50	75	Production and Supply of Water

Source: the input-output table.