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Review of the input-output network and its application in energy and mineral industries

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Nowadays, it has become a widespread consensus to deal with global warming through carbon emission reduction among mainstream scientists in the world. As the main battlefield and main force to achieve carbon peak and carbon neutrality, the energy and mineral industries play a crucial role. At the same time, as the basic industries provide energy and raw materials, the energy and mineral industries and other industries form a complex and integrated economic system with each other through input-output correlation. It can provide scientific reference for policymakers and market investors to quantitatively reveal the overall structure of the industry and deeply analyze the role and position of energy and mineral industries in it. Combining the input-output analysis with the complex network theory, the input-output network is a set of theoretical methods with strong theory and application to describe the industrial association structure both between economies and within them, and a powerful tool for studying linked character between energy and mineral industries and related industries, carbon emission, environmental protection and so on from the perspective of physical economics. Based on document analysis, this paper introduces the concept and theoretical basis of the input-output network and energy and mineral industries, and then systematically expounds the research status of the input-output network from several dimensions such as data source, research object, and research question. Finally, the paper summarizes research methods, research objects, and application scope of the input-output network, points out the weak links, and prospects some future development directions in energy and mineral industries.

KEYWORDS

input-output network, carbon neutrality, object, question, prospect

1 Introduction

The industry is the result of the social division and the continuous development of productivity, which comes into being and develops with the emergence and development of the social division. The industrial association is one of the basic relationships in economic activities, specifically referring to the extensive, complex and close economic and technological links among various industries (Suga, 2001). Energy and mineral industries provide energy and raw materials for various economic sectors and the national defense industry, playing an important supporting role in the development of many industries such as manufacturing, construction, and chemical industry. At the same time, energy and mineral industries also need to consume a large amount of energy and mineral resources from upstream industries, which has a huge impact on energy consumption, carbon emissions, and the environment. The evidences above indicate that energy and mineral industries have high degree of industrial mutual relation. Especially under the background that it has been widely agreed by all countries in the world to cope with global warming through carbon reduction, there is important theoretical and practical significance to study scientifically the correlation between industries and reveal the role and status of energy and mineral resources.

The input-output model is mainly used to track the direct and indirect supply-demand relationship between various industrial sectors in the economic system, which has a powerful function in the calibration of the economic structure characteristics at the industrial level and the interaction with energy, mineral resources, emissions and other environmental factors (Lenzen et al., 2012; Jetashree et al., 2021; Tian et al., 2022). The concept of complex system and complex network can be traced back to the 1990s (Fan et al., 2014; Interdonato et al., 2020). Later, the complex network theory is widely applied to the field of industrial economics and resource and environmental management by the input-output network.

As a technology combining input-output analysis and complex network theory, the input-output network model is dedicated to studying the specific relationship structure (McNerney, 2009; He et al., 2017; Mundt, 2021), key industries, and industrial clusters among industries (Theodore, 2017; Piccardi et al., 2018; Giammetti et al., 2020), which plays a unique role in discussing the role of energy and mineral industries in the industrial pattern, predicting industrial development and simulating policy effects.

However, the research about the input-output network and its application in energy and mineral industries is still in its infancy. Many scholars discuss industrial association based on the idea of the complex network. Terminologies such as input-output network, industrial complex network, and industrial connection network are scattered in current literature. But there is no clear definition of its connotation, application range, and research paradigm for the input-output network. Therefore, this paper intends to review of the input-output network, and its application in energy and mineral industries, summarize research progress, and finally prospect its future development direction on this basis based on a systematic analysis of existing literature.

2 The concept connotation of input-output network and energy and mineral industries

2.1 Input-output network

The idea of industrial association can be traced back to the Economic Table, which is used to study the trade relations between industries by the founder of the French classical political economy Quesnay (1785). In 1936, Leontief established the input-output model to quantitatively describe the relationship among all industries in America, which thus became the basic method to measure industrial relation (Leontief, 1936). In 1958, Hirschman put forward the concepts of forward relation and backward relation, and applied industrial relation to the study of regional economic strategy for the first time (Hirschman, 1958), which evolved into the Hirschman Benchmark studying key industries and economic development strategy.

Traditional tools based on IO models play an important part in exploring economic structures, such as structural path analysis (SPA) and linkage analysis. SPA is about estimating the contributions of separate paths to particular sectors (Defourny and Thorbecke, 1984; Li et al., 2020; Liu et al., 2022). Linkage analysis goes one step further by studying the effect of the upstream and downstream on the entire economy (Lenzen and Murray, 2010). However, when employing these tools, few treat an economy as a complete, particular system in the IO literature (Xu and Liang, 2019).

Complex network theory developed from graph theory and network theory, which can be traced back to the Konigsberg Bridge Problem proposed by the Swiss mathematician Euler (1735) in the 18th century. Relevant concepts such as complex system and complex network appeared formally in the 1990s. These complex systems such as power network, transportation network, and so on in real life, can be modeled as complex networks. Similar to above networks, the input-output network is also the complex network, in which nodes represent industries or sectors and links represent physical production flows, money flows, or some unique relation between industries or sectors. The input-output network is not only a form of data representation, but also a means of scientific research.

The idea of using network theory to study economic structure is put forward earlier by Slater et al. (1978), who used the maximum flow minimum cut algorithm to identify production and consumption communities in the American input-output table of the year 1967. Based on the network of relatedness between products, or “product space”, Hidalgo et al. (2007) studied how the structure of the product space affects a

TABLE 1 Energy and mineral industries in the main input-output data in the world.

Database	National bureau of statistics of China	WIOD	EORA26	OECD	FIGARO
Energy and mineral industries	Mining and washing of coal	Mining and quarrying	Mining and Quarrying	Mining and quarrying, energy producing products	Mining and quarrying
	Extraction of petroleum and natural gas				
	Mining and processing of metal ores			Mining and quarrying, non-energy producing products	
	Mining and processing of nonmetal and other ores			Mining support service activities	
	Processing of petroleum, coking, processing of nuclear fuel	Manufacture of coke and refined petroleum products	Petroleum, Chemical and Non-Metallic Mineral Products	Coke and refined petroleum products	Manufacture of coke and refined petroleum products
	Manuf. Of non-metallic mineral products	Manufacture of other non-metallic mineral products		Other non-metallic mineral products	Manufacture of other non-metallic mineral products
	Manufacture of metal products	Manufacture of fabricated metal products, except machinery and equipment	Metal Products	Fabricated metal products	Manufacture of fabricated metal products, except machinery and equipment
	Basic metals	Manufacture of basic metals		Basic metals	Manufacture of basic metals

country's pattern of specialization. The term "input-output network" first appeared in the report of McNerney (2009) on the economic structure of major countries in the world. Since then, terms such as industrial complex network, input-output network and industrial associated network have appeared in domestic and foreign literature, whose essence is to discuss the problem of industrial association from the perspective of the complex network (Blochl et al., 2011; Rodrigues et al., 2016; Sun et al., 2018; Yang et al., 2021).

2.2 The concept and connotation of energy and mineral industries

Energy and mineral industries refer to the related industrial sectors in which people treat nature as the object of labor to obtain natural resources, such as the coal industry, the oil industry, and the salt industry through mining and logging and other means. In this paper, energy and mineral industries can be defined in a narrow sense and a broad sense, respectively. In a narrow sense, energy and mineral industries refer to the mining, smelting, and products related to energy and mineral resources in the input-output table, which has the same basic meaning as the energy and mineral industries mentioned above, which can be thought of as its quantitative expression (Table 1). In a broad sense, it is no longer confined to the inherent classification of the input-output table, and can be the whole industrial chain covering the production, supply, storage, sales and trade of energy and mineral resources between different regions.

There list energy and mineral industries in the main input-output databases of the world in Table 1, which can be seen that it basically covers all the main industries in the upstream, midstream and downstream of the production-trade-consumption of energy and mineral resources.

As for Mining and Quarrying, different from WIOD, EORA26 and FIAGRO, it is subdivided into Mining and washing of coal, Extraction of petroleum and natural gas, Mining and processing of metal ores, Mining and processing of nonmetal and other ores in the database from the National Bureau of Statistics of China, and Mining and quarrying, energy producing products, Mining and quarrying, non-energy producing products and Mining support service activities for OECD. As to Smelting and processing, Manufacture of basic metals appears in all the databases except EORA 26. As to Products, it is subdivided into Fabricated metal products and Petroleum, Chemical and Non-Metallic Mineral Products in all databases.

3 Data sources of the input-output network

The main source of data for the input-output network is the input-output table. The input-output table, also known as the department balance sheet, is a balance sheet that reflects the relationship between industries and the balanced proportion in a certain period. As shown in Table 2, Quadrant I reflects the economic and technological linkage between industries, which is the basic part of the table and the main part of input-output

TABLE 2 The basic pattern of the input-output table.

act	Intermediate demand	Final demand	Output
Intermediate input	I (X_{ij})	II(Y_i)	X_i
Primary input	III(N_j)		
Input	X_j		

TABLE 3 The five typical multi-regional input-output tables in the world.

Name	Compilation institution	Number of countries	Number of industries	Time sequence	Latest version
WIOD	European Union	43 (28 + 15)+RoW	56	2000–2014	2016
EXIOBASE	European Union	44 (28 + 16)+5RoW	163	1995–2011_2022	V3.8.1
EORA	Australia	189 + RoW	26–429	1990–2015	Full Eora
		189 + RoW	26	1990–2015	Eora26
OECD	OECD	66 (38 + 28)+RoW	45	1995–2018	2021
FIGARO	European Union	29 (27 + 2)+RoW	64	2010–2019	2018

network construction. Quadrant II reflects the final use of products in each industry; Quadrant III reflects the primary distribution of national income; Quadrant IV reflects the redistribution of national income, which may sometimes be omitted because the redistribution process it illustrates is incomplete.

From a regional perspective, it can be divided into global, national and regional levels for the input-output table. Input-output analysis, originally derived from the national input-output table, is a quantitative description of the economic structure of a single country. The expansion and extension of the national input-output table to other national economies is the global input-output table, while the detailed deepening of the national input-output table to regional economies is the regional input-output table, which can refer to single or multiple domestic regional economies or national economies. National input-output tables are generally compiled by national statistical offices, for example, China's National Bureau of Statistics[1] and Bureau of Economic Analysis, and the United States Department of Commerce[2] may regularly release national input-output data. Input-output tables of a single region are generally compiled and published by provincial and municipal statistical departments.

Compared with the input-output tables of a single economy, the joint input-output tables of multiple economies are particularly complex due to the addition of regional dimensions. Most of them are compiled and published by third parties based on official data of each country/region and international/inter-regional trade data (Lenzen et al., 2012; Stadler et al., 2018; Zheng et al., 2020). As an extension of interregional input-output analysis in the international field, the international input-output analysis began in the 1960s. Japan's Institute for Development Economics (IDE) first tried to compile input-output tables for six international regions, including North America, Europe, Oceania, Latin America, Asia and Japan. At present, there are five most typical international input-output databases, namely WIOD[3], EXIO[4], EORA[5], OECD[6] and FIGARO[7] (Table 3).

As mentioned above, Quadrant I of the input-output table is the core part of the table, also known as the intermediate matrix, where the detailed breakdown of production (consumption) sectors is listed. The industry sector or product classification standards of the intermediate matrix are mainly taken from the fourth edition of the International Standard Industry Classification of All Economic Activities (ISIC) or its derivatives. The ISIC is an international benchmark classification of productive economic activities whose main purpose is to provide a set of activity categories that can be used to compile statistics on such activities. Since the first edition of ISIC is adopted in 1948, most countries in the world have

1 https://data.stats.gov.cn/easyquery.htm?cn=C01
2 https://www.bea.gov/industry/input-output-accounts-data
3 https://www.rug.nl/ggdc/valuechain/wiod/
4 https://www.exiobase.eu/
5 https://www.worldmrio.com/
6 https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm
7 https://ec.europa.eu/eurostat/web/experimental-statistics/figaro

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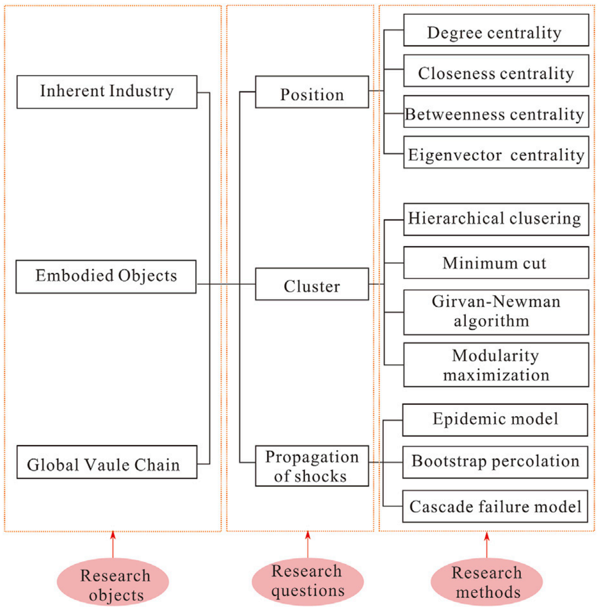

FIGURE 1
Research objects, questions and methods of the input-output network.

adopted The ISIC or formulated their own national classifications based on the ISIC.

It is worth mentioning that major databases also publish satellite accounts of input-output data, covering socio-economic and environmental accounting data. Socioeconomic accounts generally include data on employment, capital stock, total output and addedvalue in relevant industries in each country. The environmental account provides data on industrial energy consumption, land use, material consumption, carbon emissions, and atmospheric emissions. Satellite accounts provide researchers with a unique tool to analyze the socio-economic situation and the environmental impact of economic activities from an industrial perspective.

4 Research status analysis

4.1 Research objects

Through the screening and comprehensive analysis of relevant literature, it is found that the relevant research objects of the input-output network at home and abroad are mainly divided into three categories, namely the inherent industries in the input-output table, embodied objects, and global value chain (Figure 1). Note that the application of input-output network in the field of energy and minerals mainly focuses on the analysis of embodied objects, which will be discussed in Section 4.3.

4.1.1 Inherent industries in the input-output table

The inherent industry sectors in the input-output table are the initial research objects of the input-output network. Researchers use input-output data to construct a complex network with the industry as the point and the input-output relationship as the edge, and analyze the network topology and even the temporal evolution characteristics based on concepts such as degree distribution, weight distribution, and network path length. James et al. (2013) discussed the characteristics of industrial association of 45 economies by the OECD database, and found that edge weight of input-output network follows typical Weibull distribution, and industry size follows exponential distribution. Liang et al. (2016) expanded the index analysis range of point degree and edge weight in the input-output network (total output, final demand and added value, etc.), and further tested the influence of different input-output data selection on the scale characteristics of the input-output network.

At the same time, many scholars directly use the input-output network model to identify key industries and industrial communities, and discuss the transmission mechanism of risk shock among industries. Bochl et al. (2011) selected and compared the key industries of each country in the OCED database by random walk centrality and counting betweenness. Cerina et al. (2015) identified industrial communities worldwide by the WIOD database, and found that the division of communities was still based on countries or geography as the main dividing factor. There were two large groups in the world production system, the European group and the North American group, with Germany as the core (countries in the Far East were temporarily absent). Wang et al. (2021) constructed multiple input-output networks from 2007 to 2012 for the selection of key industries and associations by China's multi-regional input-output table, and found that the provinces covered by industrial associations were less and less, while the key industries were mostly distributed in Guangdong Province, Jiangsu Province and many other coastal provinces in Southeast China.

4.1.2 Global value chain

Global value chain is one of the recent research hotspots in the field of the input-output network. In recent years, the progress of science and technology and the reduction of trade barriers have promoted the formation of the global value chain (Gereffi et al., 2005; Grossman and Rossi-Hansberg, 2008). Nowadays, the global value chain has covered most economies in the world and become a link connecting the economies of all countries in the world. Its development has brought unprecedented development opportunities and challenges to all participants in the global value chain.

At present, the research of global value chain mainly focuses on two aspects: value chain accounting and the impact of global value chain on industrial economy. The input-output model can clearly reflect the relationship between production and consumption of products in various countries or regions and among various departments by the checkerboard pattern, and is currently the mainstream tool for tracking product flow and global value chain (Piccardi et al., 2018). Los et al. (2015) constructed an input-output model based on the global multi-regional input-output table from 1995 to 2011, and found that the value chain was increasingly internationalized except for the temporary pause caused by the 2008 financial crisis. Johnson and Noguera (2012) provided a method using input–output and trade data to compute bilateral trade in value added, and verified there are significant differences between value added and gross trade flows. Antras et al. (2012) put forward an indicator to measure the industry "upstreamness" (or. average distance from final use), which is an industry-level measure of relative production-line position. Xing et al. (2021) built a global industrial value chain network model by the international input-output data, and analyzed the correlation, hierarchy, and robustness of economic development indicators and system structure measurement indicators of countries or regions from the perspective of physics and economics. The functions and positions of economies in global value chain were discussed from national, inter-national and international levels.

The development and spatial-temporal evolution of global value chain directly promote the continuous growth of industrial transfer, thereby affecting industry upgrading. Tian et al. (2019) proposed a different approach including eight indicators in factor analysis to examine the multidimensionality of industrial upgrading. A group of scholars believe that the global value chain specialization could reduce production costs, improves productivity, and then promoted industrial upgrading (Bhagwati et al., 2004; Baldwin and Robert-Nicoud, 2014; McWilliam et al., 2020).

4.2 Research questions and methods

The research about the input-output network focuses on the identification of industrial position, the selection of industrial clusters, and the propagation mechanism of shocks in the network (Figure 1). The input-output network mainly conducts correlation and hierarchical analysis of economic development indicators and system structure measurement indicators from the perspective of econophysics. Its ideological core is the complex network theory, so its main research issues are similar to those of mainstream complex networks.

4.2.1 The position of industry

The identification of industrial position is one of the most primitive and nuclear research problems in the input-output network. The input-output network is a typical heterogeneous network with scale-free characteristics. Different nodes and links play different roles in network propagation, and key nodes have more influence on network structure and information transmission than other nodes (Zhou et al., 2019; Jiang and Wang, 2020).

Intuitively, the closer you are to the center of the network, the more important the node is, which is called node centrality. The main indexes to measure node centrality in the network include degree centrality (Sigler et al., 2021; Li et al., 2022), closeness centrality (Dekker, 2005), betweenness centrality (Stolz and Schlereth, 2021), and eigenvector centrality (Figure 1).

4.2.2 The cluster of industry

The cluster of industry is another major hotspot in the field of input-output networks coupled with the identification of industrial position. Nodes in the complex network tend to form clusters and exhibit cluster characteristics. The existence of cluster structure also reflects the heterogeneity of the complex network. It is generally believed that the connections between nodes within a cluster are relatively dense, while the connections between nodes in different clusters are relatively sparse (Leicht and Newman, 2008; Chen et al., 2009; Li et al., 2013). At present, there are four kinds of mainstream algorithms, i.e. Hierarchical clustering (Defays, 1977), Minimum cut (Newman, 2004), Girvan-Newman algorithm (Girvan and Newman, 2002), and Modularity maximization (Newman, 2004) for cluster selection.

In recent years, scholars often start with the structural attributes of input-output networks, study industrial position and industrial clusters simultaneously, and explore the correlation between industries (Theodore, 2017; Wang et al., 2021). In terms of time and space, with the enrichment of input-output data and the improvement of input-output data in multiple regions, relevant research has also developed from the original single-year and single-region research to multi-year and multi-region research (Cerina et al., 2015; Piccardi et al., 2018; Xu and Liang, 2019).

4.2.3 Propagation of industry

Propagation of industry belongs to the category of complex network dynamics and is an extension of network topology. Since being introduced into the input-output network, it has attracted great attention immediately. With the rapid development of economic globalization and network information technology, the dependence and restriction relationship between industries continuously strengthen, and the world's economies form an inseparable network relying on their respective crisscrossed industries. The disturbance of economic shock to industrial sectors will produce a butterfly effect, which will have a profound impact on the global economic system. Therefore, research on the propagation path and dynamic mechanism of shocks in the input-output network is the basis for effective risk control, and the establishment of an appropriate transmission model can accurately predict economic development and simulate policy effects. At present, network dynamic models are effective in simulating the chain reaction of potential supply risks, such as the epidemic model, bootstrap percolation, and cascade failure model (Figure 1).

The research on the impact of shocks on the economic system is mainly qualitative in the early stage, and the research questions mainly focus on whether micro-impact from specific industrial sectors can lead to significant total fluctuation in the economic system. Initially, the conventional wisdom in macroeconomics was that when aggregate output was concentrated around its mean, particular shocks would dissipate quickly and have a significant effect on the economic system. With the introduction of the input-output model, especially the complex network theory, the majority of scholars have demonstrated that the micro impact will have a significant impact on the entire economic system by building models between the structure of various industrial networks and aggregate fluctuation (Carvalho, 2009; Acemoglu et al., 2012; Harvey and O'Neale, 2020).

With the development of complex network theory, it is possible to explore the relationship between micro shock and aggregate fluctuation in a semi-quantitative or even quantitative way. The construction of the complex network model and the setting of network indicators can quantify the contribution of shocks to the total output volatility of specific industries (Ando, 2014) and measure the propagation of shocks (Li et al., 2014; Grazzini and Spelta, 2015), and the process of long-term and short-term diffusion effects of industrial sectors (Xing et al., 2016). Later, based on previous qualitative and quantitative studies, scholars begin to explore the influencing factors of the transmission range of micro shocks (Contreras and Fagiolo, 2014), and the reasons for the changes in the vulnerability of the economic system to microshocks (Distefano et al., 2018). Further, the macroeconomic impact of microeconomic shocks is decomposed into pure technological effect and allocative efficiency effect (Baqaee and Farhi, 2020).

4.3 Application of input-output network in energy and mineral resources

In recent years, with the occurrence of the global issues such as ecological imbalance, environmental pollution, and resource shortage, the research objects of the input-output network gradually expand from the inherent industries to resources and environment, namely embodied objects.

4.3.1 Embodied objects

Embodied objects in this paper specifically contain embodied energy, embodied minerals, embodied emissions and embodied water, etc. (Table 4), corresponding to the satellite account in the input-output table mentioned in Section 3. Embodied analysis, derived from the embodied energy first proposed at the 1974 Meeting of the International Federation of Advanced Research Institutions (IFIAS) Energy Analysis Working Group, refers to the total amount of direct and indirect resource consumption or pollution emissions and labor occupation in the production of goods or services (IFIAS, 1974; Brown and Herendeen, 1996). The accounting of embodied objects, which covers all historical information of products or services from producer to consumer, can provide a more systematic perspective for the economic accounting of various industrial sectors (Baral and Bakshi, 2010; Duarte et al., 2018).

4.3.2 Data

The extended input-output model is the mainstream method of embodied accounting from a macro point of view. The extended input-output table is the basis of embodied analysis based on the complex network. In the development of the extended input-output table, environmental factors can be directly included in the input-output table as a separate production industry (Leontief, 1970). More often, the associated effects of various production activities in the input-output table can be calculated by building the extended input-output table with the associated coefficients (such as CO_2 emission intensity, resource consumption intensity, etc.). Relevant studies are summarized in Table 4. Currently, satellite accounts of the major input-output databases now contain a growing variety of objects. For example, EXIOBASE alone contains five types of carbon emissions, 2 types of hidden water, and 4 types of substance use lists. Moreover, they are all multi-region input-output models.

4.3.3 Methods

The emission/consumption intensity of embodied objects is shown as Eq. 1

$$q = h(\hat{x})^{-1}(I - A)^{-1} \tag{1}$$

Where, the column vector x refers to the total output of each sector. The row vector h refers to the satellite account row vector of total emission/consumption of each sector. The hat () refers to diagonalizing the vector. $(I - A)^{-1}$ refers to the Leontief inverse, it means the sector output driven by a unit of terminal consumption.

The flow of embodied objects between industrial sectors is expressed in Eq. 2

$$E_{ij} = q_i{}^{*}x_{ij} \tag{2}$$

Where, q_i refers to the emission/consumption intensity of embodied objects in the sector i. x_{ij} refers to the input from sector i to sector j.

A complex network consists of nodes and edges that link the nodes, as in Eq. 3

$$G = (N, E) \tag{3}$$

Where, G represents a complex network. N denotes the set of nodes in the network. E represents the set of edges in the network. An

TABLE 4 Summaries of related research on the.

Research perspectives	Research objects	References
Climatic environment	Carbon emission	Wiebe et al., 2012; Chen and Chen, 2013; Jiang et al., 2019a; Jiang et al., 2019b; Lv et al., 2019; Ma et al., 2019
	PM 2.5	Wang et al., 2017b; Gao et al., 2020; Yang et al., 2018
Natural resources	Energy	Chen et al., 2018; Chen and Chen, 2013; Xia et al., 2016
	Minerals	Jiang et al., 2018; Liang et al., 2020; Wang et al., 2017a; Wang et al., 2019; Zhang et al., 2022
	Water	Chen et al., 2012; Distefano et al., 2018; Yang et al., 2021
Social economy	Global value chain	Piccardi et al., 2018; Xing et al., 2021

element E_{ij} of matrix E indicates the direct and indirect input from sector i to sector j required to produce unitary output of sector j.

4.3.4 Hotspots

Carbon emission is one of the most important hotspots in the field of embodied analysis. The greenhouse effect caused by carbon emission is a global environmental problem that hinders the sustainable development of the human economy and society. The transfer of carbon emissions in quantified trade has become a topic of widespread concern in academia and the public. The environmental extended input-output method can be used to quantitatively divide the actual place where carbon emission is generated and the final consumption place that drives carbon emission (Wiebe et al., 2012). Scholars combine the complex network theory with the input-output analysis to build a hybrid network model of interregional carbon flow. Based on quantifying direct and embodied carbon emission, the main processes and key industries of trans-regional carbon transfer can be determined (Chen, 2016; Lv et al., 2019). Identify the role of countries in the process of carbon transfer (Jiang et al., 2019b), and then discuss its driving factors (Jiang et al., 2019a). If multiple years of data are available, multiple embodied carbon emission networks can be constructed to explore their temporal structure characteristics and key industries (Ma et al., 2019).

At the same time, based on the extended input-output table, a large number of scholars also use the input-output method and the complex network theory to target $PM_{2.5}$ (Wang et al., 2017b; Yang et al., 2018; Gao et al., 2020), energy (Chen and Chen, 2013; Xia et al., 2016; Chen et al., 2018), minerals (Wang et al., 2017a; Jiang et al., 2018; Wang et al., 2019; Liang et al., 2020; Zhang et al., 2022), water (Chen et al., 2012; Distefano et al., 2018; Yang et al., 2021), and so on (Table 4). Research orientations mainly focus on the discussion of network structure and the identification of key industries and industrial communities as well as the driving mechanism.

5 Summary and prospect

This paper draws the following conclusions by clarifying the existing literature:

(1) In terms of application scope, previous scholars first directly used the single-regional input-output (SRIO) model for research work, such as the national input-output table and provincial input-output table. Later, the multi-regional input-output (MRIO) model came into being and was more widely used in the study of cross-border trade and related issues. However, all countries in the world have different degrees of spatial differences. Such differences not only come from differences in natural endowments and geographical conditions of different regions within a country, but also differences in development level and industrial structure. The existing multi-regional input-output tables are mostly input-output databases between countries, which are weak in decomposition and extension at the provincial level. As a result, it is easy to ignore the heterogeneity of provinces in the target country in terms of economic endowment, geographical location, development stage, and industrial structure. Therefore, the decomposition and extension of the existing multi-regional input-output table to the sub-regional level are one of the preconditions to expanding the input-output network research work in the future.

(2) In terms of research objects, previous studies may be implemented to explore network attributes and industry associations from the perspectives of the whole industry pattern, or just a single industry in the input-output table, such as manufacturing, finance, construction, or embodied objects (embodied energy, embodied mineral, embedded emissions). But overall, research objects of the input-output network are still relatively limited, such as the implications of GVC for energy and materials sectors, footprint family. Therefore, there is a lot of space to explore both the inherent industries in the input-output table and the objects in the extended input-output table.

(3) In terms of research methods, the input-output network initially focuses on the mining of key industries and industrial communities in economic networks, and then use the information transmission

model in the complex network to discuss the transmission process and dynamic mechanism of shocks. However, complex network theory is something broad and profound, and a large number of related models and analytical techniques (such as degree rank, path search, robustness, machine learning, transmission dynamics, etc.) are not fully applied to the study of the social and economic system. Meanwhile, to mine the economic implications of such dense weighted and directed networks, many algorithms also need to be improved combined with the practical significance to the research of the social economic system thought and method.

(4) In terms of energy and mineral industries, the current research mainly focuses on energy and a few mineral resources such as rare earth, etc. For critical energy minerals and bulk minerals such as iron, copper, and aluminum, the research efforts are relatively weak either because of the difficulty of obtaining data or the lack of attention. In addition, research on the role and status of the inherent energy and mineral industries in the input-output table, such as mining, smelting, and products industry, as well as the temporal evolution characteristics of the regional and even global industrial pattern, also needs to attract people's attention.

Since the emergence of the input-output network, research methods, research objects, and application scope have been greatly expanded, but it is still in the initial stage on the whole. The future research on the input-output network may have more research objects, more diverse research methods, and more applications.

Author contributions

LW and LJ contributed to the conception and design of the study. HM provided the method and LW completed the first draft of the manuscript. LJ and WB contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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