Presentation for 30th International Input-Output Association Conference

中国科学院大学
University of Chinese Academy of Sciences

30th International Input-Output Association Conference
and
12th Edition of the International School of I-O Analysis
1st - 5th July 2024, Santiago, Chile

Research on the Spillover Effects of Technological Progress from the Perspective of Production and Innovation Networks

Reporter: Li Chuan

Co–authors: Xu Jian; Sun Jialu; Su Qi Jiang Zhijiang

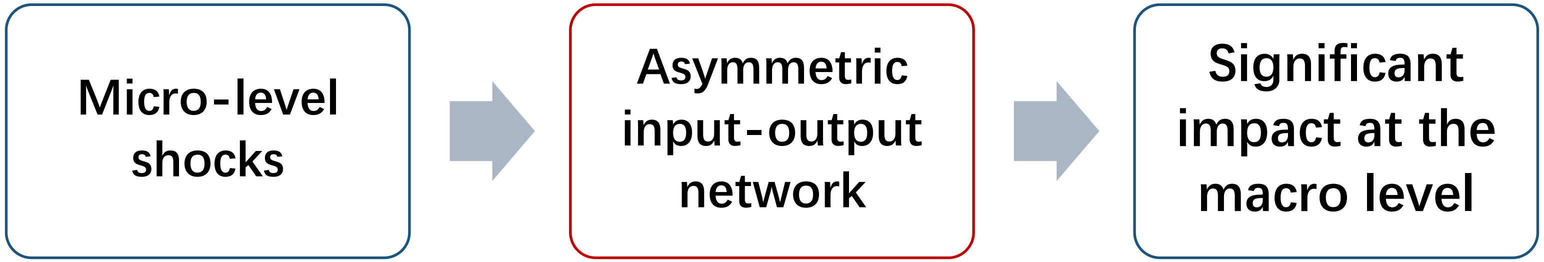
University of Chinese Academy of Sciences

中国科学院大学
University of Chinese Academy of Sciences

Contents

Theoretical Background 1: Production linkages have become an important source of technological spillovers

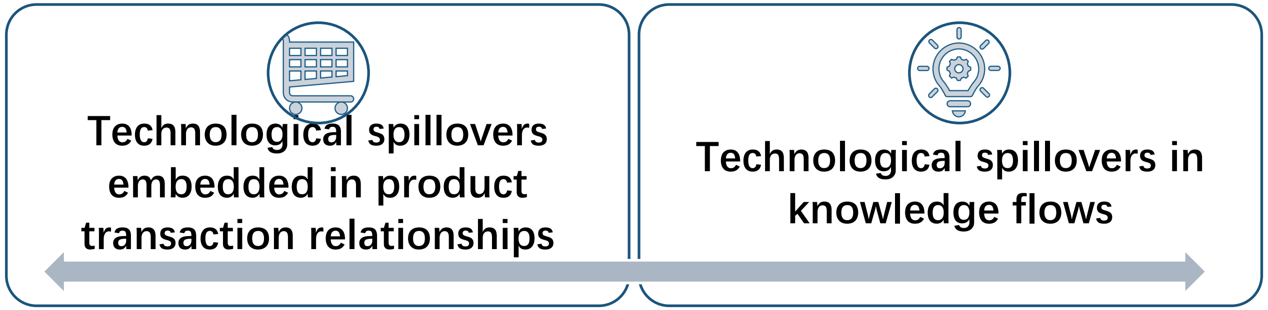
- Traditional neoclassical economic growth theories assume independent technological progress among economic entities and measure total factor productivity based on this assumption.
- The evolution of production networks challenges this assumption of independence, as increasing specialization enhances interconnections among economic entities, making production links an important channel for knowledge spillovers.



- In recent years, a series of studies on production networks have recognized that **the linkage of intermediate inputs is an important mechanism for transmitting productivity shocks and influencing economic growth** (Acemoglu et al., 2016; Liu Weigang, 2022). These studies provide a theoretical foundation for the cyclical spillover of technological progress and attempt to develop corresponding models and accounting methods.

Theoretical Background 2: The Spillover Effects of Knowledge Diffusion Cannot Be Substituted by Product Transactions

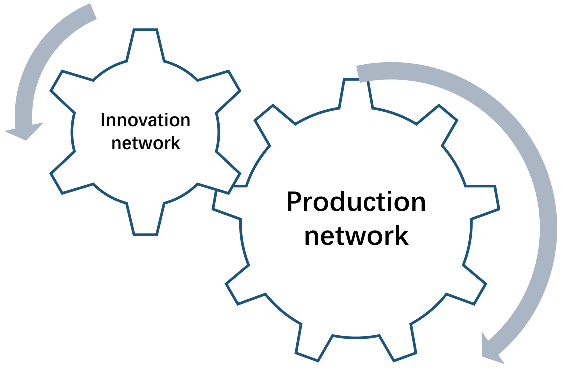
- These studies generally rely on the association of products among industries to analyze the impact of production network structures on innovation diffusion (Chen et al. 2014). The economic logic implied behind them is that upstream and downstream industries can only form supply-side or demand-side technological spillovers through product purchases or sales.



- Although empirically, the technological spillovers brought by this knowledge and information and the technological spillovers embedded in products are indistinguishable because measuring the overall technological level of a particular industry will reflect both (Gonçalves et al. 2016; Semitiel-García et al. 2012). **However, the relationship between technological spillovers in knowledge flows and those in product flows does not always overlap.**

Theoretical Background 2:The Spillover Effects of Knowledge Diffusion Cannot Be Substituted by Product Transactions

- Some literature attempts to fill this gap and believes that industry sectors benefit from the dissemination of knowledge (Acemoglu et al. 2016b; Cai et al. 2022). However, these literature focus on the impact of production network on knowledge spillovers **without further analyzing the impact of innovation networks on industry networks and failing to consider the mutually integrated relationship between innovation chains and industrial chains.**



- Unlike these literature, this paper aims to simultaneously examine production and innovation networks, **placing technological spillovers in knowledge flows and product flows within a unified analytical framework** to investigate their mutual integration and transmission effects across industries.

Main Work and Marginal Contributions of This Paper:

- **First, Starting from the real innovation activities at the micro-enterprise level, industry-level innovation network data are generated.** To verify the knowledge spillover effects of technological progress among industries, this paper uses 2.8 million Chinese patent data to construct an inter-industry innovation network through citation relationships.

- **Second, this paper further extends the production network model using innovation network,** proposes a method for measuring technological progress and its knowledge spillover effects under the conditions of production network associations.

- **Third, this paper builds a bridge connecting the production network model and the input-output analysis model,** taking into account the integration of innovation and production networks, while retaining the simplicity of calculation, providing a new perspective for explaining the technological flow and knowledge spillovers among departments.

中国科学院大学
University of Chinese Academy of Sciences

Contents

Reviewing the development process from neoclassical growth theory to endogenous growth theory, the literature related to technological spillovers can be summarized into three directions:

- Emphasizing the externalities and spillover effects of knowledge or skill levels (Arrow, 1962; Romer, 1986);
- Emphasizing the diversification of intermediate products needed in production processes (Romer, 1987; Romer, 1990);
- Emphasizing the improvement of the quality of intermediate products needed in production processes (Grossman & Helpman, 1991; Aghion & Howitt, 1992).

In these three types of research, technological innovation is achieved in two ways: one is the transmission of knowledge, and the other is the transmission of products or innovation investments induced by product differences. **Therefore, this paper reviews the existing literature from the perspectives of production networks and innovation networks.**

1． Technological Spillovers in Production Networks

- From neoclassical economic growth to endogenous economic growth, **technological innovation has progressed from a linear process to a complex interactive process,** and the complementarity between heterogeneous technologies has gradually become an important feature of technological change (Rosenberg, 1982).

  ① However, the neoclassical economic growth considers less the spillover effects

  ② Endogenous growth literature considers multi-department models, but they assume all departments have fixed and identical input structures, a priori excluding the asymmetric inter-department effects of technological.

- **The theoretical analysis suggests that technological progress in an industry can benefit other industries by lowering the prices of intermediate products.** However, this analysis framework based on intermediate product associations has only been inherited and developed with the rise of production network theoretical research in recent years(Acemoglu et al. (2012) .

  ① Along this framework, scholars have further demonstrated that changes in total factor productivity in upstream industries are transmitted to downstream industries through production networks, forming supply-side technological spillovers.

  ② The spillover effects formed by it make industries mutually dependent and promote each other, forming industrial chains.

2． Technological Spillovers in Innovation Networks

- **A large number of empirical studies on input-output analysis have shifted their attention from the connection of intermediate product transactions to the R&D spillover effects。** These spillover effects do not necessarily relate directly to the purchase of goods or services but are tracked through data such as patent citations and industry publications to trace the flow of technology between sectors**However, these studies are not built on a general equilibrium framework, and their micro-foundations remain unclear.**

- **In recent years, some literature has expanded on this.**

  ① Acemoglu et al. (2016b) improved the production network model by combining innovation networks, arguing that a sector's innovation capacity is positively correlated with the knowledge stock composite of other sectors. On this basis,

  ② Cai et al. (2022) included both production and innovation networks in a general equilibrium model in an open economy, suggesting that knowledge accumulation relies not only on the domestic sector but also on the knowledge stock of other countries' sectors.

  ③ ……

3．Literature Review and Improvement in This Paper

Despite the significant development of literature on production and innovation networks, related research still has limitations:

- Due to **the lack of high-quality micro-level data**, systematic measurement research is relatively lacking. Most studies construct spatial weight matrices using geographic distance and spatial adjacency as weights and verify through econometric models. However, this spatial spillover often lacks theoretical basis.
- **Research perspectives are limited.** Existing literature mainly studies production networks as channels for shock transmission, with relatively few in-depth studies on technological innovation from the perspective of production networks.
- **The research sample is limited.** Whether theoretical model research or empirical analysis, they are basically concentrated in developed countries like the United States with relatively rich data, making their research conclusions and findings potentially lacking direct policy guidance significance for developing countries.

中国科学院大学
University of Chinese Academy of Sciences

Contents

1. Inter-Industry Transmission of Technological Progress from the Perspective of Production Networks

The basic assumptions are as follows: there are two types of economic agents in the economy, representative enterprises and representative households.

- **Enterprise Production Behavior：**

Each industry representative enterprise's production function adopts a three-factor input-output model framework, set as a Hicks-neutral technological progress Cobb-Douglas production function,

$$y_i = A_i k_i^{\alpha_i} l_i^{\beta_i} \prod_{j=1}^{N} x_{ij}^{s_{ij}}$$

Maximize their profits by choosing to rent capital, hiring labor, and using intermediate products:

$$max(p_i y_i - r k_i - \omega l_i - \sum_{j=1}^{N} p_j x_{ij})$$

The first-order conditions can be obtained as follows:

$$\frac{p_j x_{ij}}{p_i y_i} = s_{ij}$$

s_{ij}， the expenditure share of intermediate inputs from upstream industry j in the intermediate inputs of industry i, which can be derived from the transpose of the direct consumption coefficient matrix of the input−output table.

1. Inter-Industry Transmission of Technological Progress from the Perspective of Production Networks

The basic assumptions are as follows: there are two types of economic agents in the economy, representative enterprises and representative households.

- **Household Consumption Behavior**

$$u = f(l)\prod_{i=1}^{N} c_i^{b_i}$$

where c_i represents the household's consumption of industry i products, $0 < b_i < 1$ represents the proportion of product i in household consumption expenditure, satisfying$\sum_{i=1}^{N} b_i = 1$. Define $f(l)$ as a decreasing function of labor l, representing the disutility of providing labor.Household income includes wage income and capital income, thus the household's budget constraint equation is:

$$\sum_{i=1}^{N} p_i c_i = \omega l + rk$$

$$\frac{p_i c_i}{b_i} = \frac{p_j c_j}{b_j}$$

The household's optimal condition: $p_i c_i = b_i(\omega l + rk)$

1. Inter-Industry Transmission of Technological Progress from the Perspective of Production Networks

The basic assumptions are as follows: there are two types of economic agents in the economy, representative enterprises and representative households.

- **Inter-Industry Technological Progress Shocks**

Using the equilibrium state profit and utility maximization first-order conditions, as well as the product and factor market clearing conditions, we can obtain the impact of technological changes within an industry on each sector in the economic system through production networks:

$$d\ ln\, y = (I - S)^{-1} d\ ln\, A$$

Define $\mathbf{U} \equiv (\mathbf{I} - \mathbf{S})^{-1}$ and expand the matrix form, the change in department output can be described as:

$$d\ ln\, y_i = d\ ln\, A_i + \sum_{j=1}^{N} \left(u_{ij} - 1_{j=i}\right) \times d\ ln\, A_j$$

The first term represents the technological progress of the industry itself, and the second term represents the sum of the spillover effects of technological progress from related industries.

2. Considering Technological Progress in Innovation Networks and Its Industry Transmission

This paper follows the setting of technological progress in the neoclassical economic growth model, assuming that industry-neutral technological progress is a function of time t. To characterize the trend of technological progress over time, a function combining linear and quadratic terms is introduced. Thus, the technological level A_{it} of industry i in year t is as follows：

$$A_{it} = A_{i0} e^{\delta_{1i} t + \delta_{2i} t^2 + \mu_{it}}$$

In this study, the technological progress of the industry itself spreads through the production network, forming spillover effects on other industries. The size of the spillover effects depends on the strength of the inter-industry connections. Therefore, the functional form of the technological level is modified to:

$$A_{it} = A_{i0} e^{\delta_{1i} t + \delta_{2i} t^2 + \mu_{it}} \prod_{j \neq i}^{N} A_{jt}^{w_{ij}}$$

where w_{ij} indicates whether there is a technological spillover from industry j to industry i and the extent of this spillover, representing the proportion of knowledge from upstream industry j in the knowledge input of industry i, with $w_{ii} = 0$.

$$d\,ln\,A_{it} = \delta_{1i} + d\delta_{2i} t + d\mu_{it} + \sum_{j \neq i}^{n} w_{ij} d\,ln\,A_{jt}$$

University of Chinese Academy of Sciences

2. Considering Technological Progress in Innovation Networks and Its Industry Transmission

$$d\,ln\,A_{it} = \delta_{1i} + d\delta_{2i}t + d\mu_{it} + \sum_{j\neq i}^{n} w_{ij} d\,ln\,A_{jt}$$

Combining like terms and expressing in matrix form, we get:

$$d\,ln\,A_t = (I - W)^{-1}(\Gamma_1 + \Gamma_2 t + u)$$

Substituting this into $d\,ln\,y = (I - S)^{-1} d\,ln\,A$, we obtain:

$$d\,ln\,y = \left(I - S\right)^{-1}(I - W)^{-1}(\Gamma_1 + \Gamma_2 t + u)$$

Defining $\psi \equiv (I - S)^{-1}(I - W)^{-1}$,

$$d\,ln\,y_i = (\delta_{1i} + d\delta_{2i}t + d\mu_{it}) + \sum_{j=1}^{N} \left(\psi_{ij} - 1_{j=i}\right) \times \left(\delta_{1j} + d\delta_{2j}t + d\mu_{ij}\right)$$

The first term in the above equation represents the neutral technological progress of the industry itself, and the second term represents the sum of the neutral technological progress spillover effects of the related industries considering the knowledge spillover effect.

2. Considering Technological Progress in Innovation Networks and Its Industry Transmission

$$d\ln y_i = (\delta_{1i} + d\delta_{2i}t + d\mu_{it}) + \sum_{j=1}^{N} (\psi_{ij} - 1_{j=i}) \times (\delta_{1j} + d\delta_{2j}t + d\mu_{ij})$$

The approximate expansion of ψ_{ij} can be divided into four parts:

$$\psi_{ij} \approx I_{ij} + W_{ij} + \sum_{k=1}^{N} W_{ik}W_{kj} + S_{ij} + \sum_{k=1}^{N} S_{ik}S_{kj}$$

$$+ \sum_{k=1}^{N} S_{ik}W_{kj} + \sum_{k=1}^{N}\sum_{l=1}^{N} S_{il}W_{lk}W_{kj} + \sum_{k=1}^{N}\sum_{l=1}^{N} S_{ik}S_{kl}W_{lj} + \sum_{k=1}^{N}\sum_{l=1}^{N}\sum_{m=1}^{N} S_{il}S_{lk}W_{km}W_{mj}$$

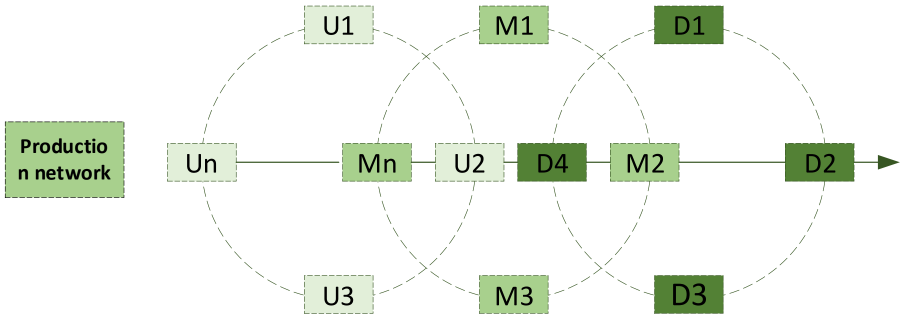
① neutral technological progress ; ②innovation network; ③production network;
④The integration of innovation network and production network

- W_{ij} represents the change in the output growth rate of industry i driven by the spillover effect of industry j through the innovation network;
- S_{ij} represents the change in the output growth rate of industry i driven by the spillover effect of industry j through the production network;
- $W_{ik}W_{kj}$ represents the change caused by industry j first driving industry k through the innovation network spillover effect, and then industry k driving industry $i$through the innovation network spillover effect; $S_{ik}S_{kj}$ represents the change caused by industry j first driving industry k through the production network spillover effect, and then industry k indirectly driving industry i through the production network;
- $S_{ik}W_{kj}$ represents the change caused by industry j first driving industry k through the innovation network spillover effect, and then indirectly driving industry i through the production network.
- Similar effects iterate through the production network and innovation network, continuously spilling over, forming spillover effects such as $S_{ik}S_{kl}W_{lj}$、$S_{il}S_{lk}W_{km}W_{mj}$, and more rounds of spillover effects.

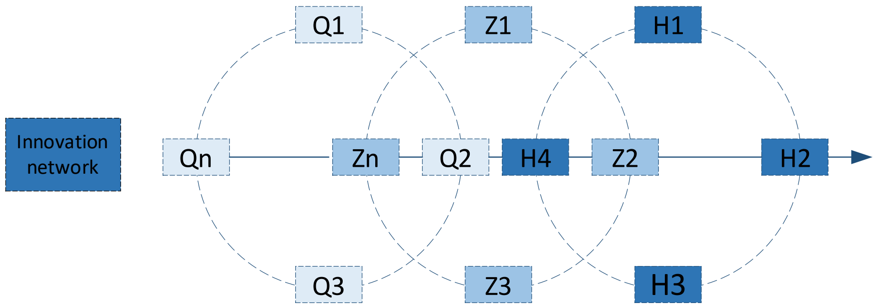
3. Three Modes of Technological Spillover

$$\psi = (I - S)^{-1}(I - W)^{-1} \approx I + W + W^2 + S + S^2 + S^2W + S^2W^2$$

- Firstly, with the further deepening of specialization, the industrial chain gradually lengthens, and under intense competition, multiple enterprises cooperate and form an interactive chain structure (as shown in Figure 1).

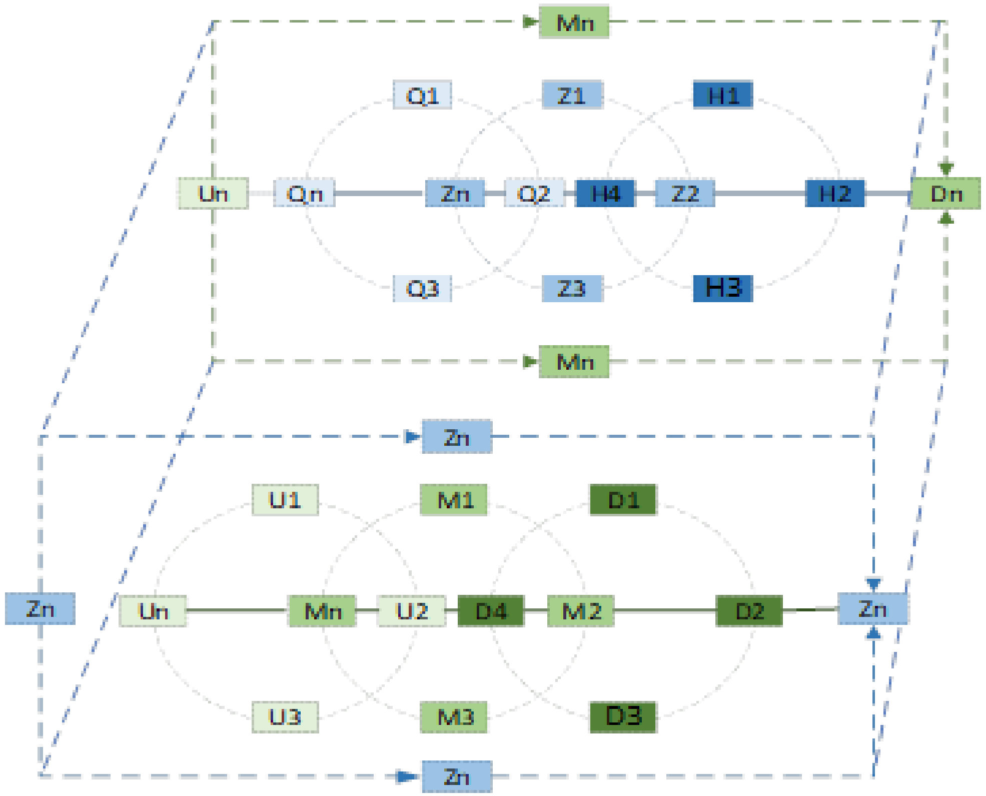


- Secondly, the increase in types of intermediate products in the industrial chain leads to the emergence of new sectors and the formation of new industrial chains. This tightly connects different fields of science and technology, promotes in-depth development in various specialties, pushes scientific ideas from theory into production practice, and extends the industrial chain vertically or horizontally as the national economic cycle expands. This creates an intertwined innovation network among various industries (as shown in Figure 2).



3. **Three Modes of Technological Spillover** $\psi = (I - S)^{-1}(I - W)^{-1} \approx I + W + W^2 + S + S^2 + S^2 W + S^2 W^2$

- Lastly, the innovation chain extends and develops around the industrial chain, and the two become interwoven (as shown in Figure 3).



- **Therefore, this equation reflects the development of social division of labor, where the production network and innovation network both extend and interact with each other, forming an interconnected chain-like structure that continually extends.**

3. Three Modes of Technological Spillover

Based on the formation process and transmission mechanisms of the production network, innovation network, and their integration, this paper summarizes the spillover effects of technological progress into the following three modes:

- **Technological spillover transmitted through the production network can be represented by**

  $$\mathbf{T_1 = S + S^2};$$

- **Technological spillover transmitted through the innovation network can be represented by**

  $$T_2 = W + W^2;$$

- **Technological spillover transmitted through the interaction of the production and innovation networks can be represented by**

  $$T_3 = \psi - I - T_1 - T_2 = SW + SW^2 + S^2W + S^2W^2 + \cdots$$

中国科学院大学
University of Chinese Academy of Sciences

Contents

Data Sources

1. Production Network

The production network is represented by S, where the elements s_{ij} in matrix s_{ij} represent the proportion of intermediate inputs in industry i that come from upstream industry j. This **can be calculated by transposing the direct consumption coefficient matrix of the input-output table.** For this purpose, we use the Chinese input-output tables from the years 2007-2020 as our data source. Since the sector classifications in the input-output tables vary across different years in China, we adjusted these tables to align with the "National Economy Industry Classification Standard (GB/T4754-2017)" (hereinafter referred to as the "Industry Classification").

No.	Sector Name	No.	Sector Name
1	Agriculture, Forestry, Animal Husbandry, and Fishery Products and Services	20	Communication Equipment, Compute and Other Electronic Equipment
2	Coal Mining and Dressing Products	21	Instruments and Meters
3	Petroleum and Natural Gas Extraction Products	22	Other Manufacturing Products and Sc Waste
4	Metal Ore Mining Products	23	Production and Supply of Electricity a Heat
5	Non-metallic Mineral and Other Mining Products	24	Production and Supply of Gas
6	Food and Tobacco	25	Production and Supply of Water
7	Textiles	26	Construction
8	Textile Apparel, Footwear, Leather, Down, and Related Products	27	Wholesale and Retail
9	Wood Processing and Furniture	28	Transportation, Storage, and Postal Services
10	Paper, Printing, and Cultural, Educational, and Sports Goods	29	Information Transmission, Software, a Information Technology Services
11	Petroleum, Coking Products, and Nuclear Fuel Processing Products	30	Finance
12	Chemical Products	31	Real Estate
13	Non-metallic Mineral Products	32	Leasing and Business Services
14	Metal Smelting and Rolling Products	33	Research and Experimental Development
15	Metal Products	34	Comprehensive Technical Services
16	General Equipment	35	Education
17	Special Equipment	36	Culture, Sports, and Entertainment
18	Transportation Equipment	37	Others
19	Electrical Machinery and Apparatus		

2. Innovation Network

This paper measures the degree of knowledge spillover between industries by constructing a patent citation network.

- Patent citation networks not only showcase the dynamic process of technological innovation but are also widely used to understand the connections in knowledge flow across industries, countries, or different types of.
- The data comes from the Patent Citation Database of Listed Companies (CITE), which is a specialized database compiled based on the citation of invention and utility model patents of Chinese listed companies from 1992 to 2020.

Considering that the differences in these networks after standardization are minimal, this paper mainly uses the citation network of authorized invention and utility model patents (2.8 million entries) as the measurement basis for the innovation network.

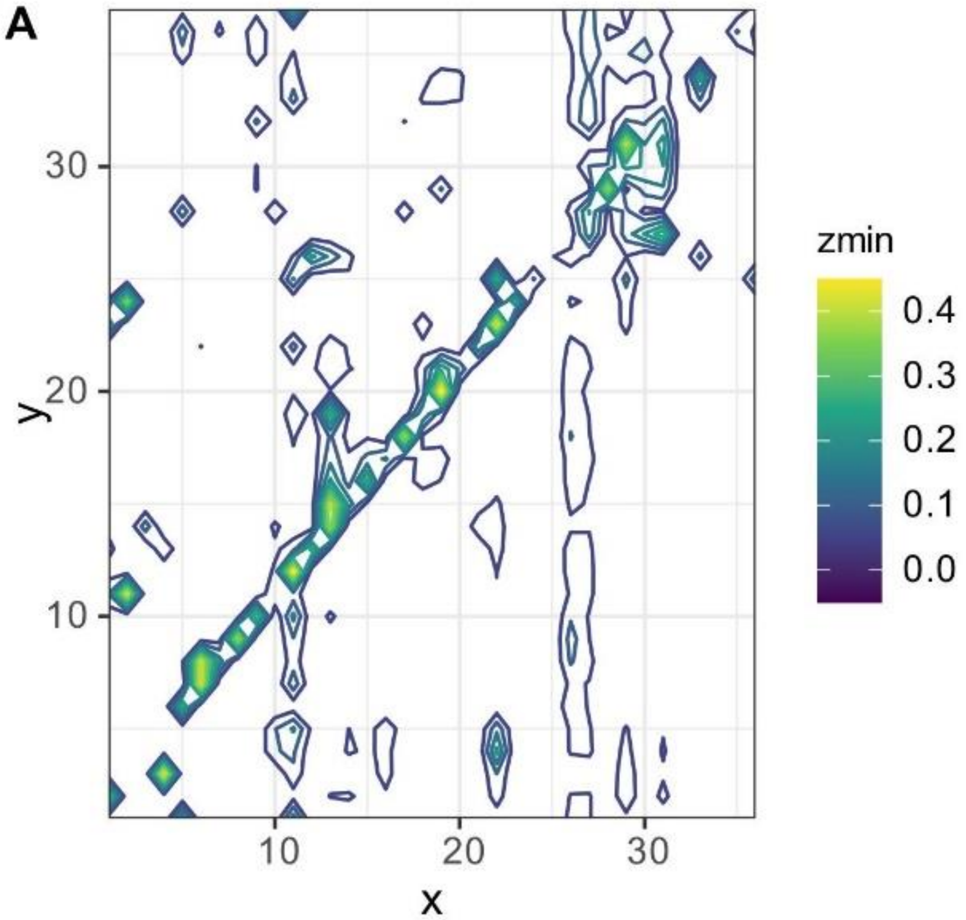
- Knowledge spillover is often continuous, with most patents being quickly cited within a year of publication but continuing to be cited over the next 15-20 years. Therefore, when compiling the innovation network matrix for a certain year, the knowledge accumulation effect from previous years must also be considered.

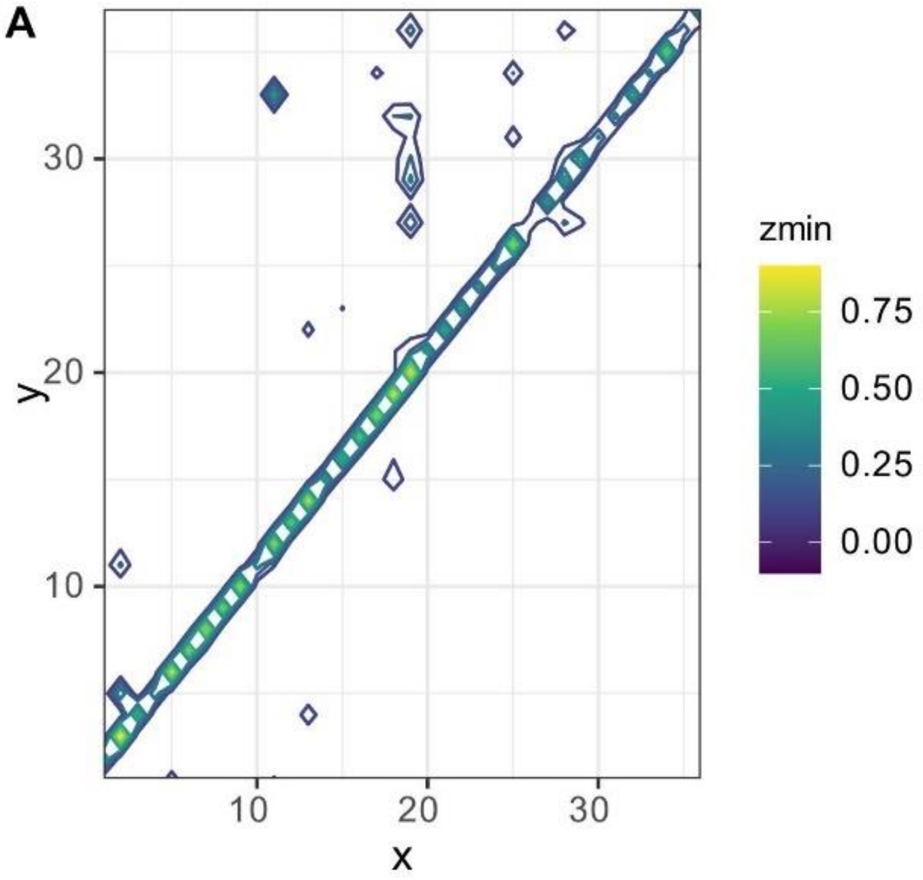
2. Innovation Network

We take the 2020 innovation network as an example. The steps are as follows:

- *First, we construct a patent citation network at the company level based on patent citation information, where the elements represent the number of times one company cites the patents of another company.*
- *Next, we compile the company-level patent citation network into an industry-level network for 2020, according to the "Guidelines for Industry Classification of Listed Companies" issued by the China Association for Public Companies, resulting in 78 industries.*
- *Then, we match this industry network with the sector classification of the input-output table using the "Guidelines for Industry Classification of Listed Companies" and the "National Economy Industry Classification" (GB/T4754-2017), finally merging it into a patent citation network for 37 sectors.*
- *Finally, the innovation network for 2020 should be* $M^{1992}+M^{1993}+\ldots M^{2020}$. *After normalizing the rows and setting the diagonal data to zero, we obtain* W^{2020}.

Data Sources





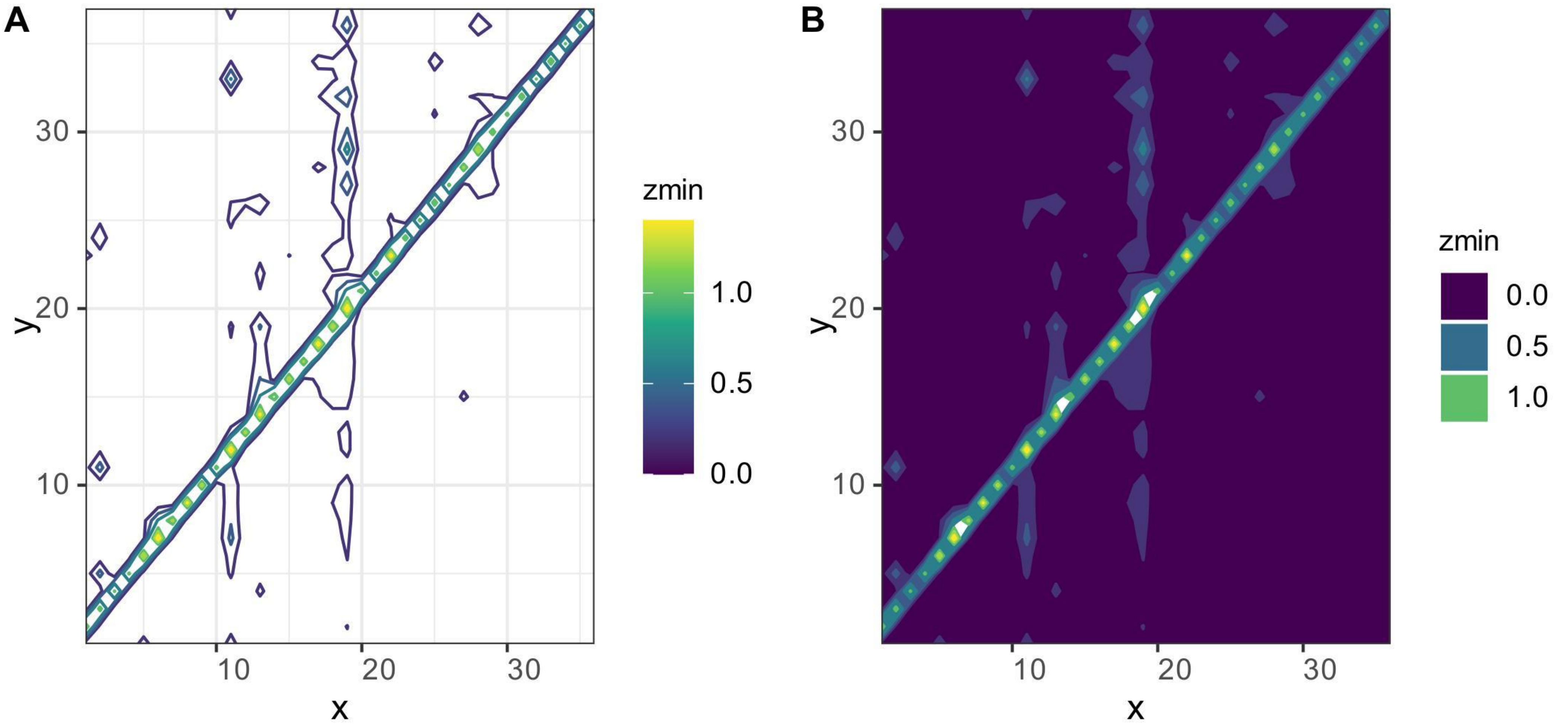
This paper plots the contour maps of the production network and innovation network for 2020.

It is evident that, whether in the production network or the innovation network, most industries have a strong dependency on intermediate inputs or knowledge creation within their own industry, with self-circulation occupying a significant position. This characteristic is even more pronounced in the innovation network, where almost all industries have more than 50% of their patent citations coming from within their own industry.

University of Chinese Academy of Sciences

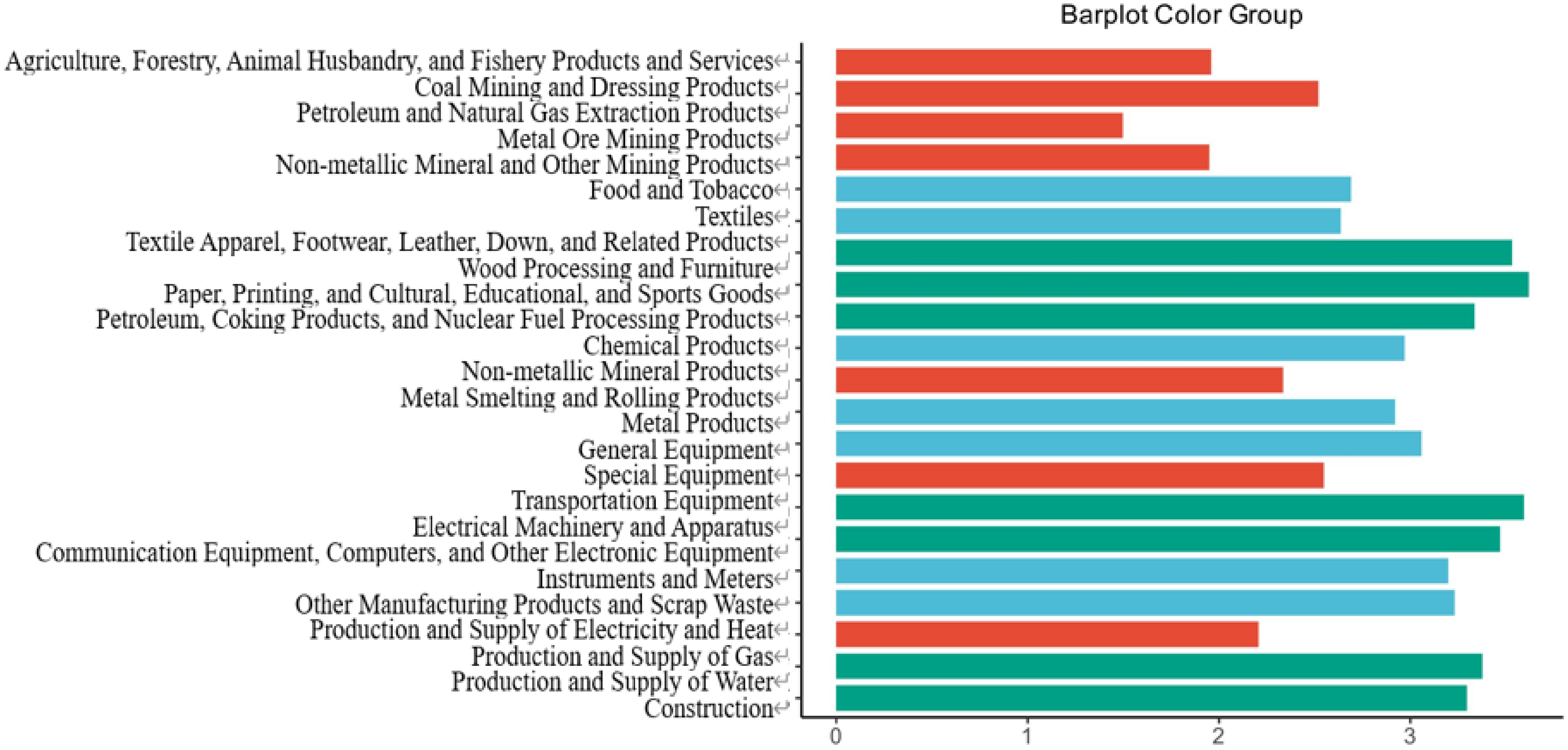
1. $\boldsymbol{\psi} = (\mathbf{I} - \mathbf{S})^{-1}(\mathbf{I} - \mathbf{W})^{-1}$

(1) At the elemental level, ψ_{ij} represents the effect of technological progress in sector j on the growth rate of output in sector i.



1. $\psi = (I - S)^{-1}(I - W)^{-1}$

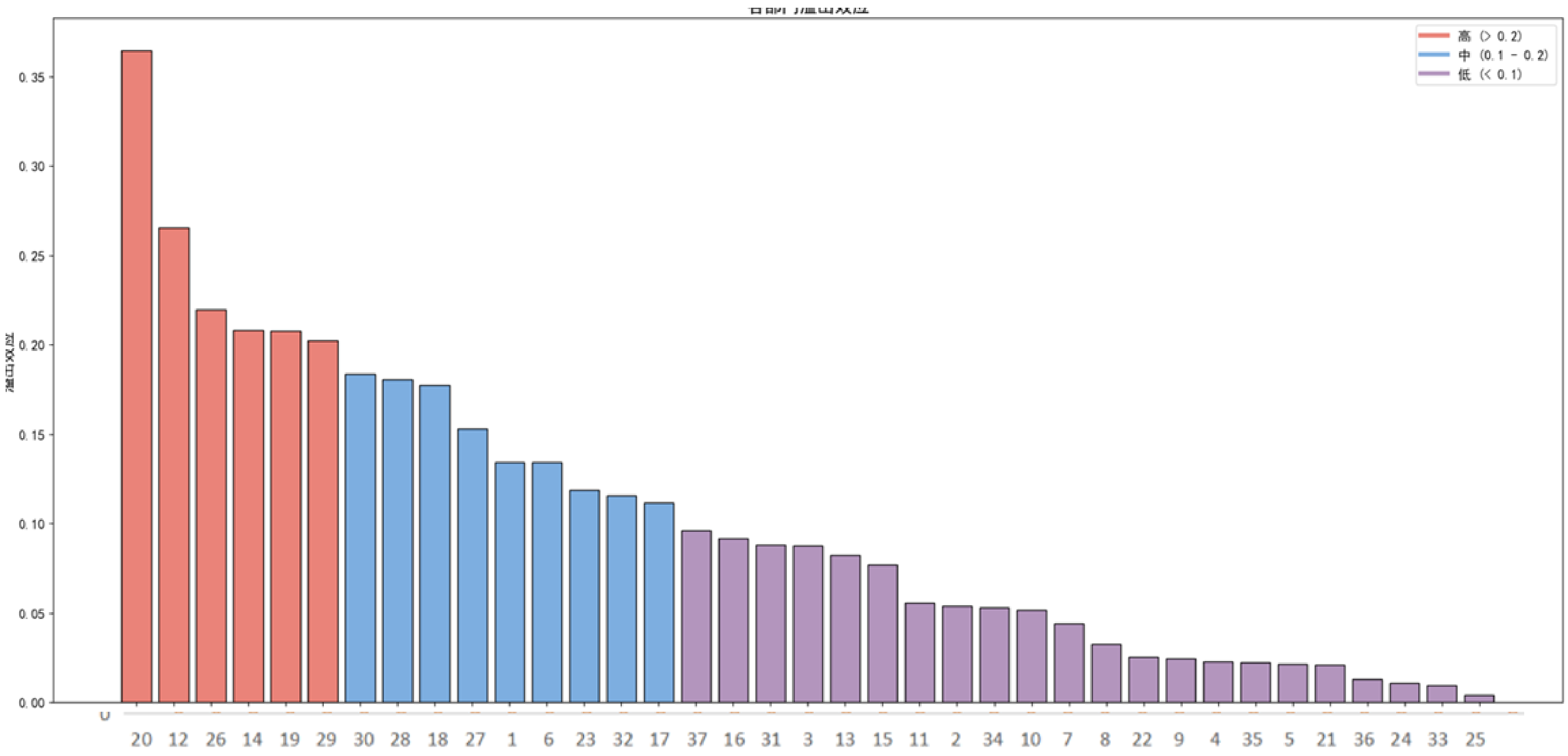
(2) From the perspective of row summation, the economic implication is that if the neutral technological progress of all sectors increases by 1%, it shows the percentage change in the growth rate of a specific sector's output. This can measure which sector can gain more benefits from the production network and innovation network.



Benefits from Network Spillover Effects

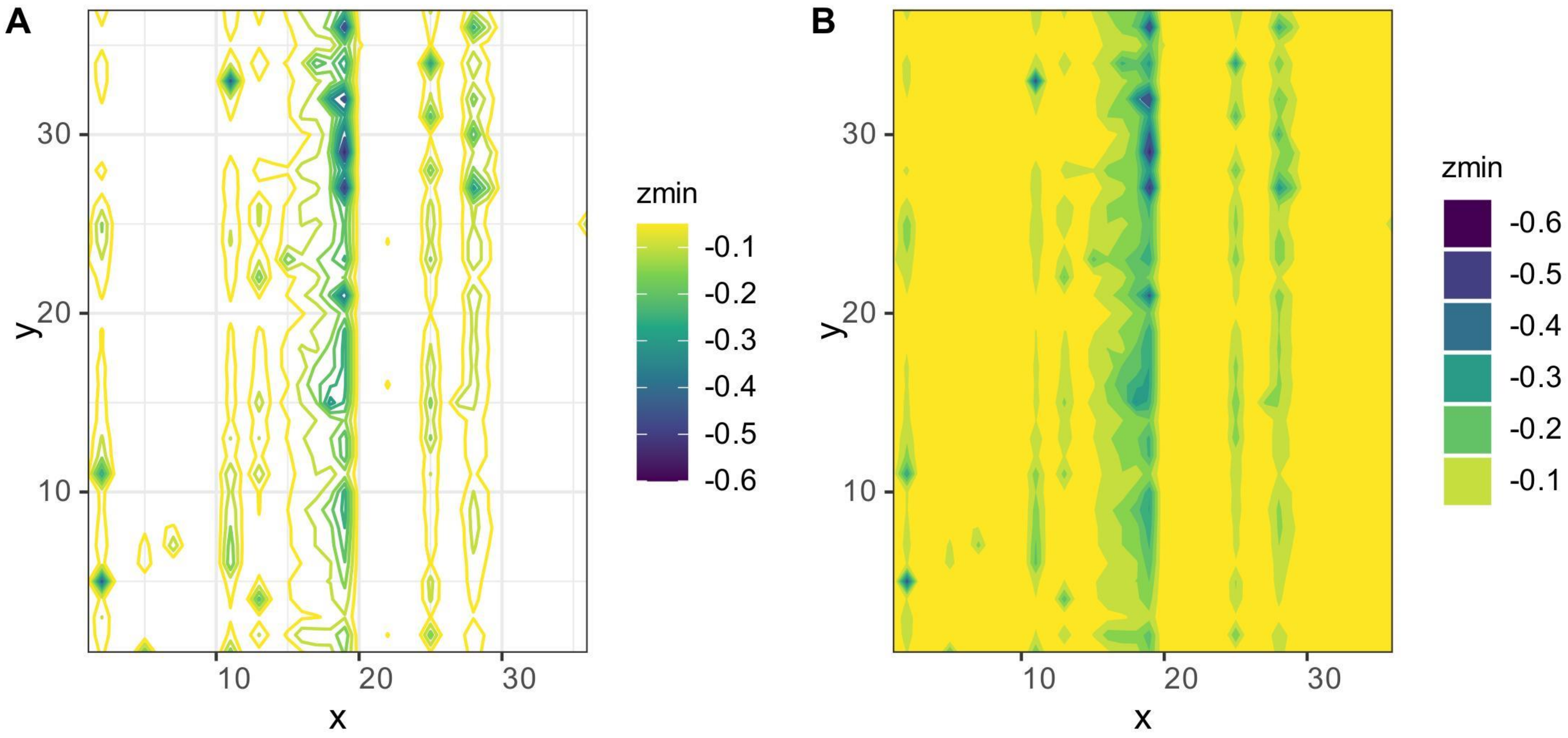
1. $\psi = (\mathbf{I} - \mathbf{S})^{-1}(\mathbf{I} - \mathbf{W})^{-1}$

(3) From the perspective of column summation (weighted sum), the economic implication represents the impact of a 1% increase in the neutral technological progress of a specific sector on overall economic growth (%).



2. Counterfactual Analysis: In the Absence of an Innovation Network

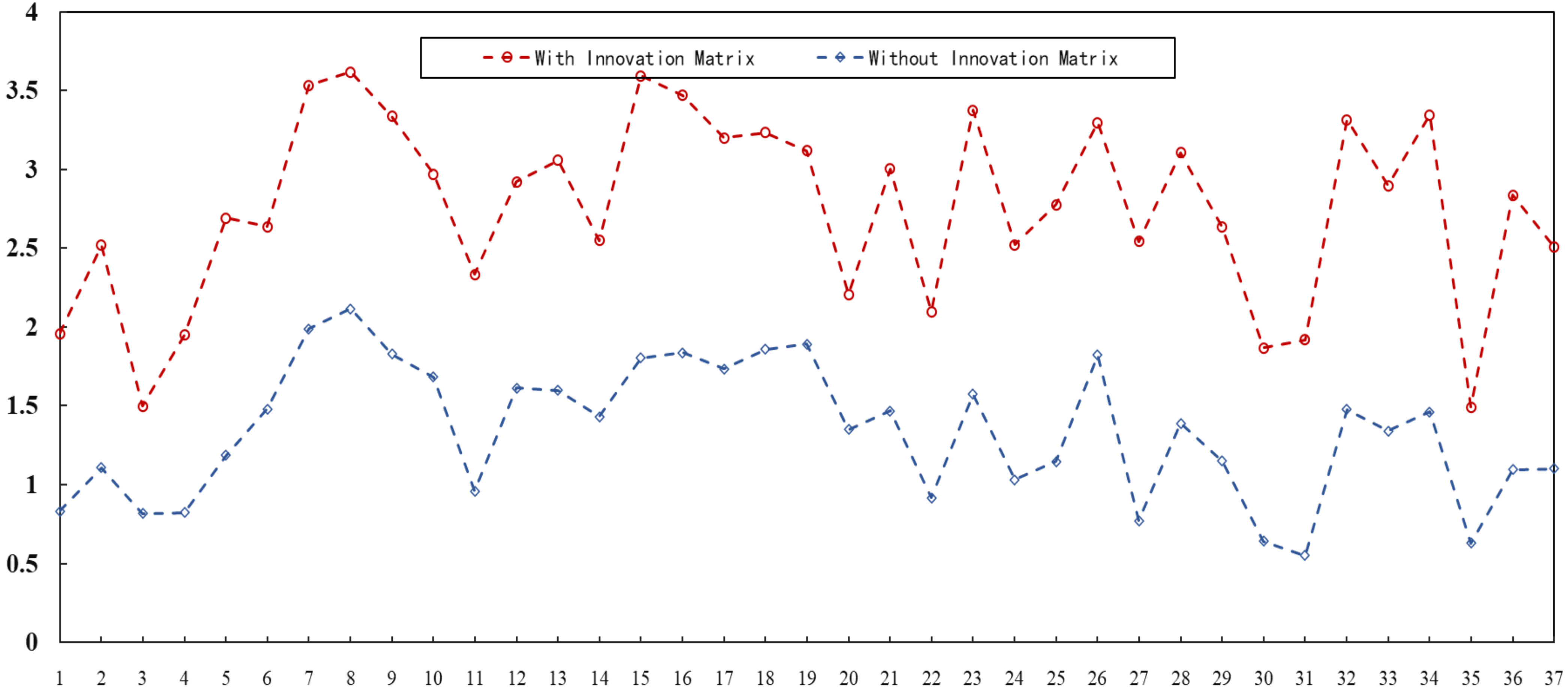
(1) At the elemental level: The technological spillover effects of each sector on other sectors decrease.



2. Counterfactual Analysis: In the Absence of an Innovation Network

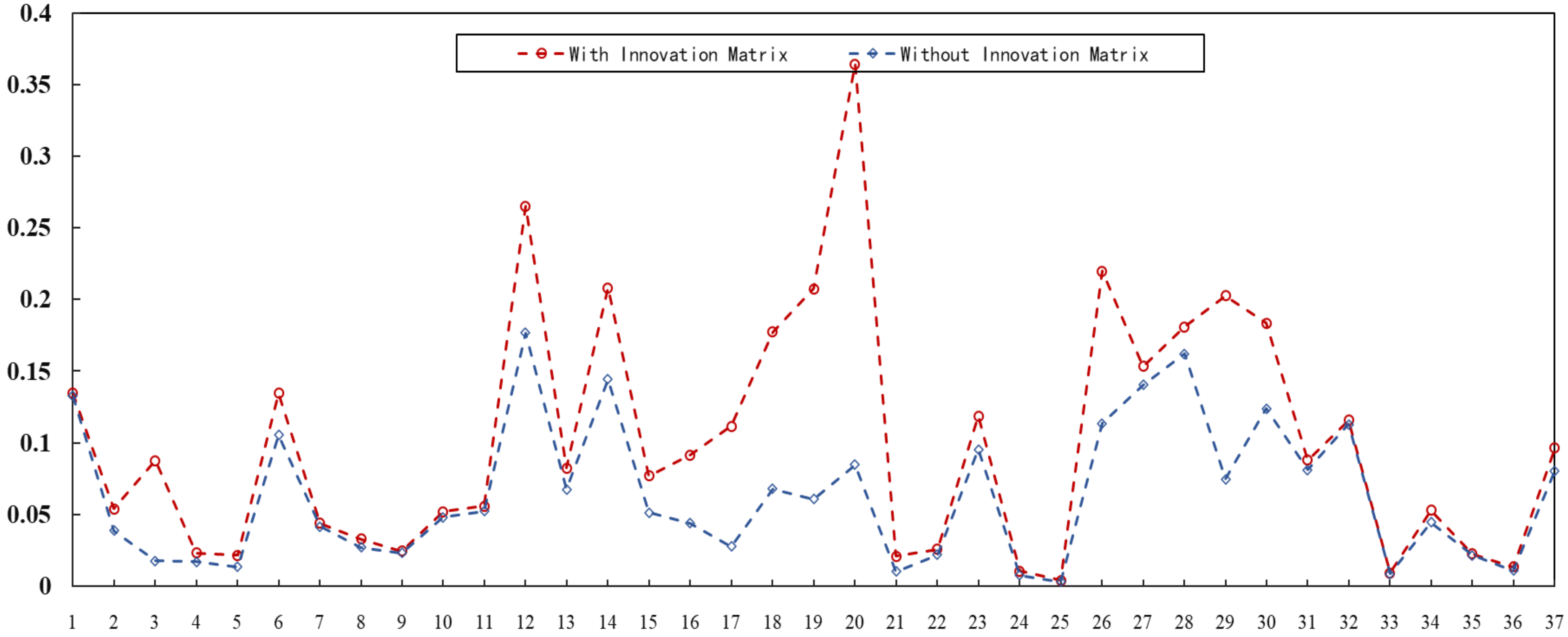
(2) From the perspective of row summation, the losses (%) for each sector are:

the output growth gained by each sector through network spillover effects significantly decreases and exhibits similar magnitudes



2. Counterfactual Analysis: In the Absence of an Innovation Network

(3) Summing along the columns shows that the contribution of each sector to overall economic growth weakens to varying degrees, with the greatest reduction in "Communication Equipment, Computers, and Other Electronic Equipment." This indicates that the innovation network plays an important role in the technological spillover process.

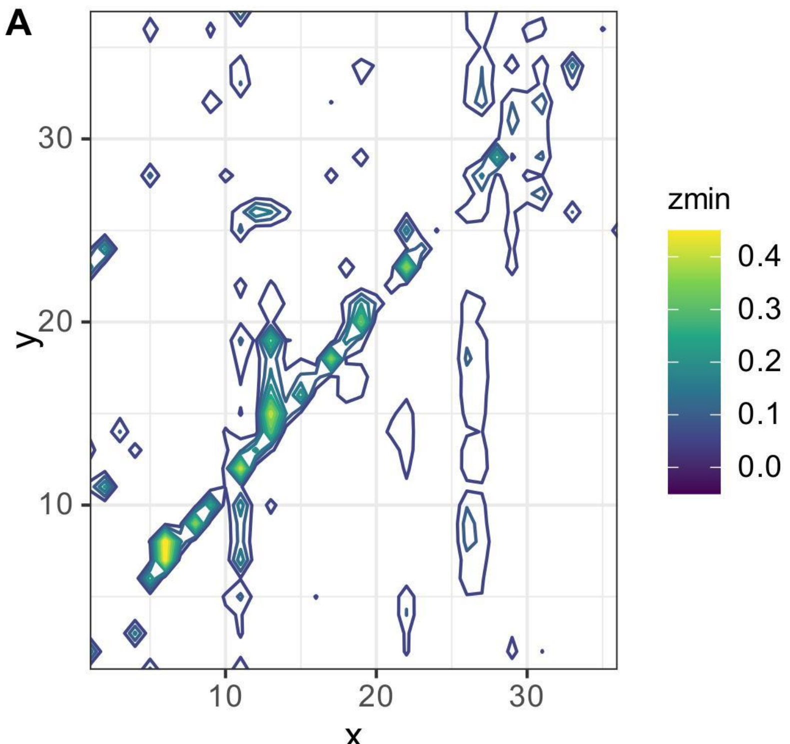


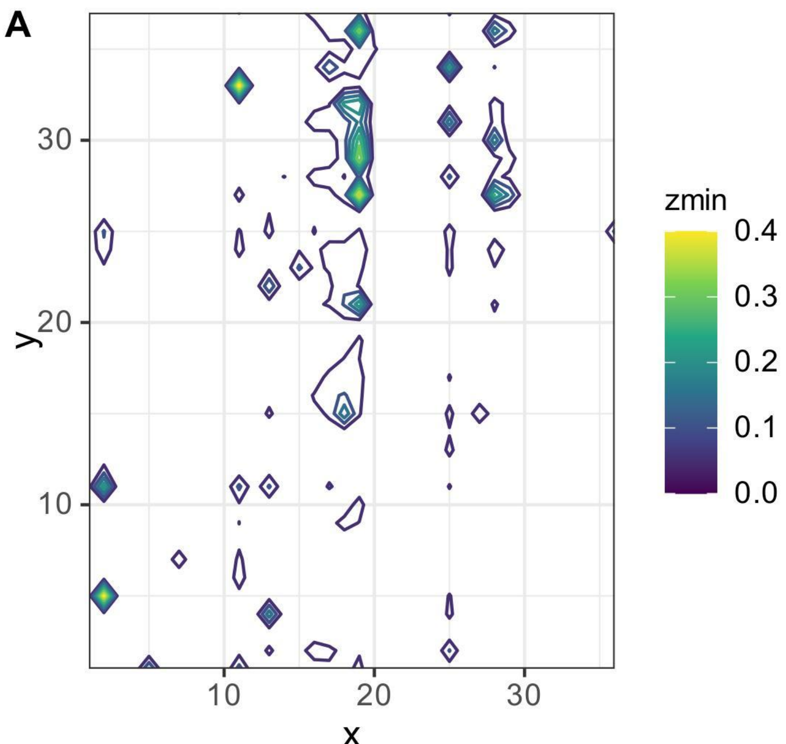
3. Three Modes of Technological Spillovers

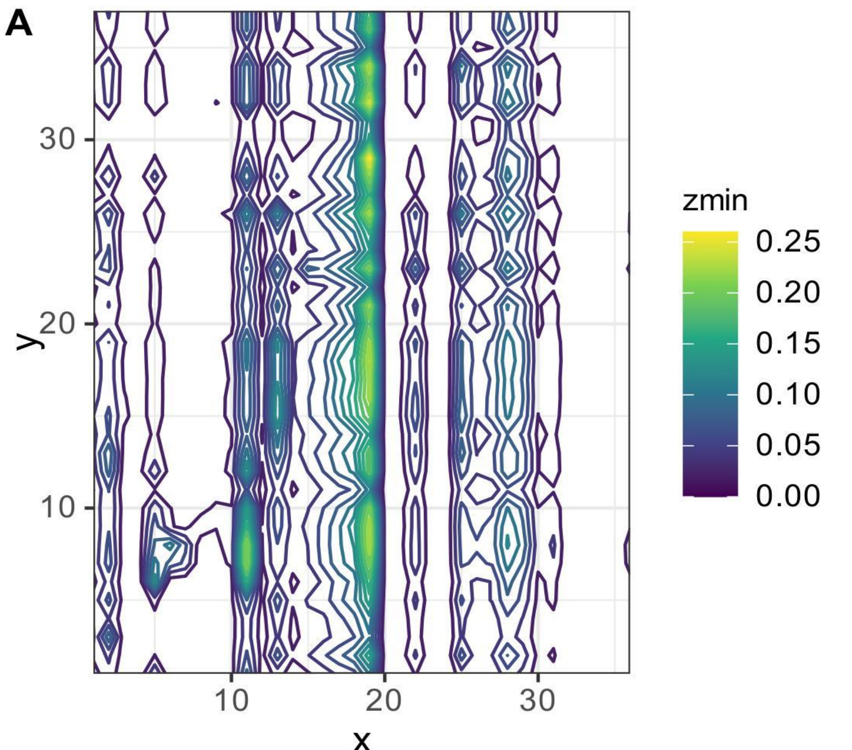
- Technological spillover transmitted through the production network can be represented by $T_1 = S + S^2$;
- Technological spillover transmitted through the innovation network can be represented by $T_2 = W + W^2$;
- Technological spillover transmitted through the interaction of the production and innovation networks can be represented by $T_3 = \psi - I - T_1 - T_2 = SW + SW^2 + S^2W + S^2W^2 + \cdots$

(1) At the elemental level

Technological spillovers transmitted solely through the production network show that most industries have a strong dependency on intermediate inputs within their own sector, with self-circulation playing a significant role. **In contrast, technological spillovers transmitted solely through the innovation network are relatively dispersed, with certain industries such as communication equipment, computers, and electronic equipment manufacturing playing a significant role in the innovation network. The interaction between the production network and the innovation network is more common in technological spillovers across sectors.**





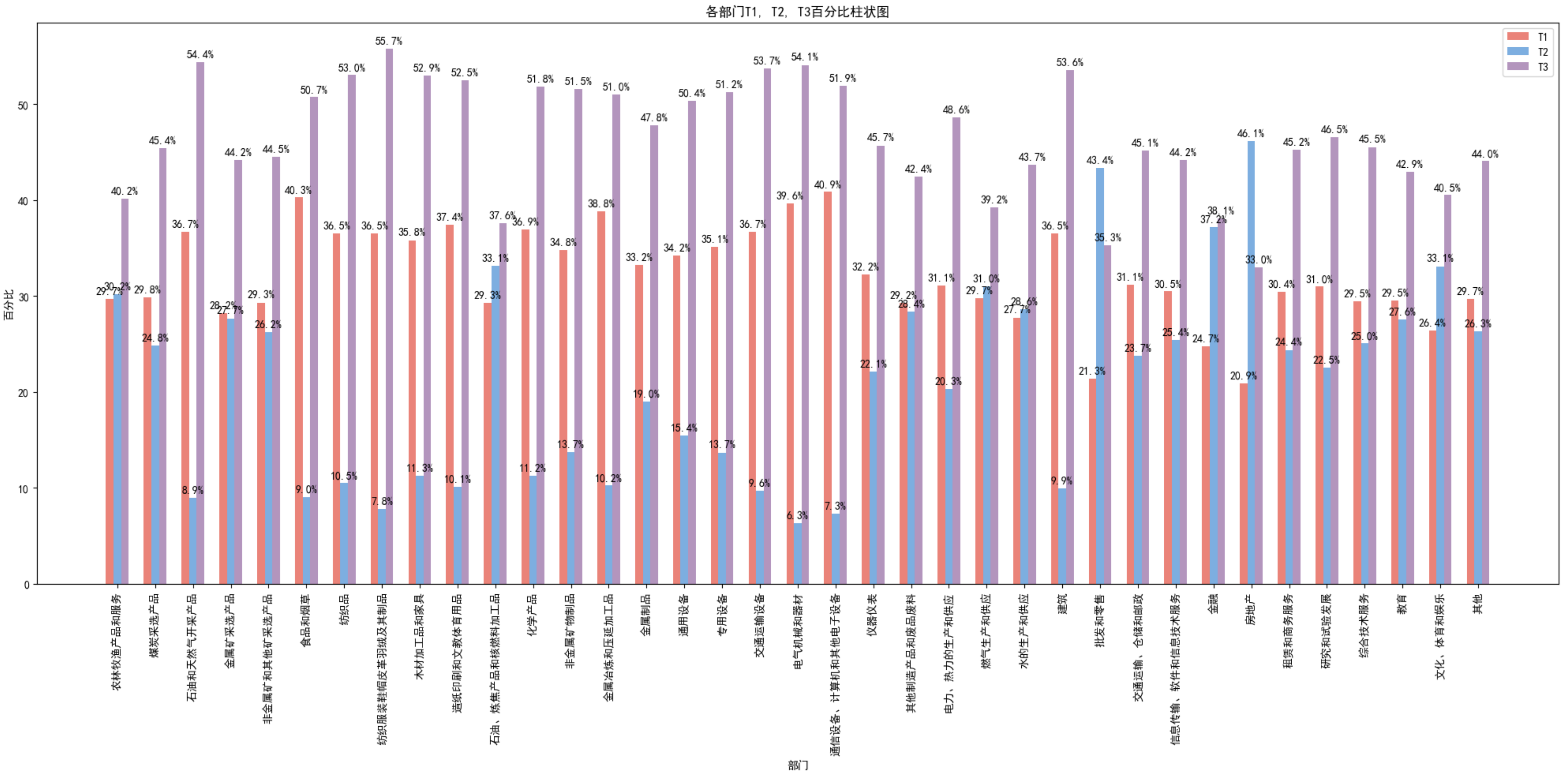


3. Three Modes of Technological Spillovers

(2) From the perspective of row summation

- Technological spillover transmitted through the production network can be represented by $T_1 = S + S^2$;
- Technological spillover transmitted through the innovation network can be represented by $T_2 = W + W^2$;
- Technological spillover transmitted through the interaction of the production and innovation networks can be represented by $T_3 = \psi - I - T_1 - T_2 = SW + SW^2 + S^2W + S^2W^2 + \cdots$

The primary driving force behind the output growth of various sectors is the interaction between the production network and the innovation network (T3).

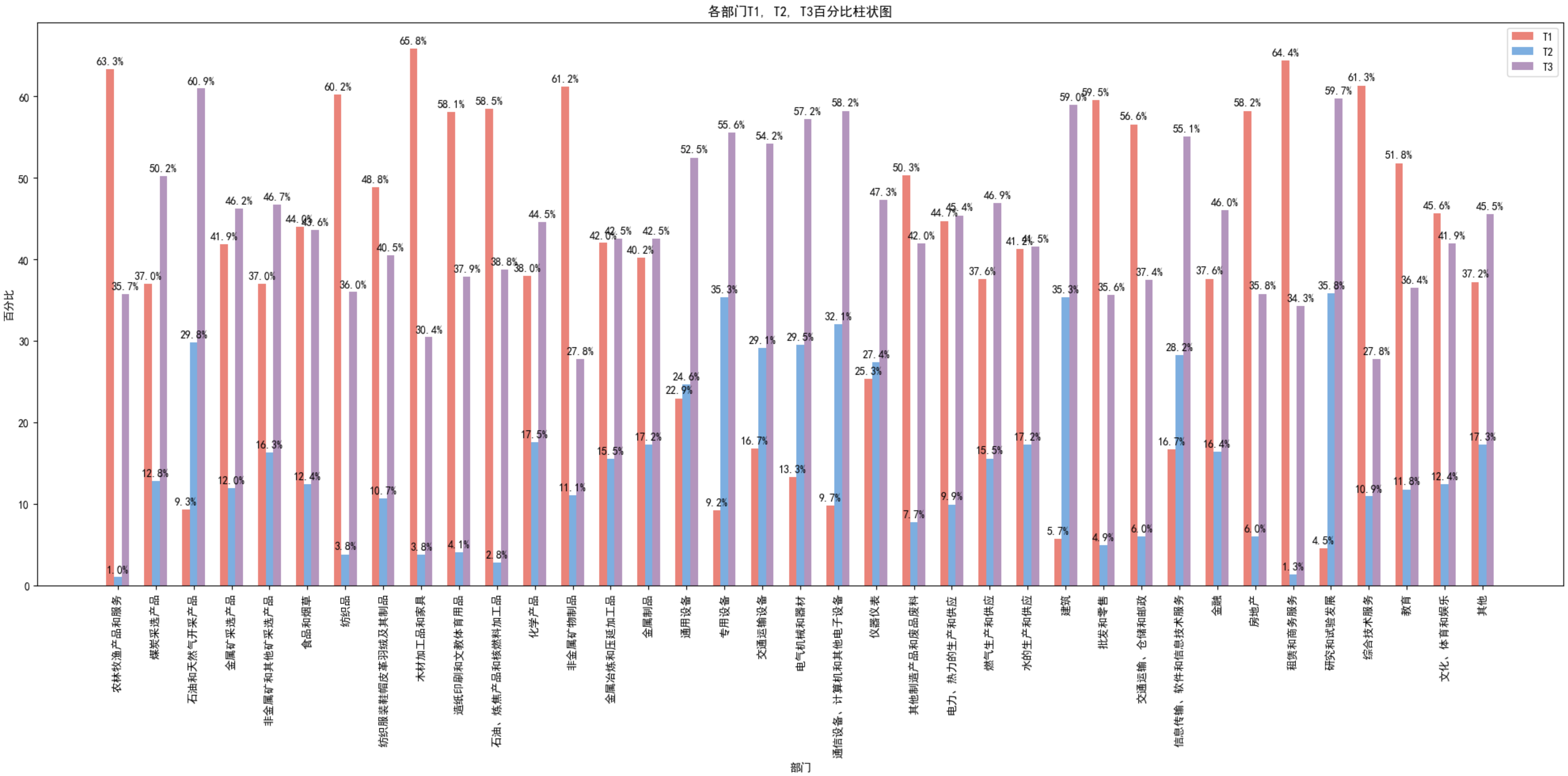


3. Three Modes of Technological Spillovers

(2) From the perspective of row summation

- Technological spillover transmitted through the production network can be represented by $T_1 = S + S^2$;
- Technological spillover transmitted through the innovation network can be represented by $T_2 = W + W^2$;
- Technological spillover transmitted through the interaction of the production and innovation networks can be represented by $T_3 = \psi - I - T_1 - T_2 = SW + SW^2 + S^2W + S^2W^2 + \cdots$

The main channels for technology spillover across various sectors are T1 and T3, followed by T2.



中国科学院大学
University of Chinese Academy of Sciences

Contents

Conclusion

This paper integrates the production network model with the input-output analysis method, placing both knowledge flow spillovers and product flow spillovers within a unified analytical framework. It examines the integration of production and innovation networks and their transmission effects across industries. The main research conclusions include:

- (1) Both production and innovation networks show that most industries heavily depend on intermediate inputs or knowledge creation within their own sectors, with self-circulation playing a significant role. This characteristic is more pronounced in innovation networks, where the proportion of intra-industry patent citations exceeds 50% for almost all industries.
- (2) There are three modes of technological spillovers between industries: technological spillovers through the production network, through the innovation network, and through the integration of both networks.
- (3) The innovation network has a significant transmission effect on technological spillovers. Without considering the innovation network, the growth rates of outputs in various sectors would show a marked decline, and the contribution to economic growth would decrease to varying degrees.
- (4) The primary driving force for the output growth of each sector comes from the interaction between the production and innovation networks. The main mode of technological spillovers for each sector is through the production network and the interaction between the production and innovation networks.


THANK YOU
ADD YOUR TITLE HERE