Analysis of the Spillover Effect of Technological Progress in the Perspective of the Fusion of Production Networks and Innovation Networks

Li Chuan

Abstract: Studying technological innovation from the perspective of production networks and scientifically measuring the spillover effects of technological progress among industries are crucial for accurately identifying the driving forces behind economic growth. Unlike existing literature, this paper combines the production network model with input-output analysis, placing technological spillovers in knowledge flows and product flows within a unified analytical framework. It examines the integration of production networks and innovation networks and their transmission effects across industries. Specifically, this paper starts from the real innovation activities at the micro-enterprise level, using 2.8 million Chinese patent data to construct an inter-industry innovation network through citation relationships. Based on this network, the paper builds a bridge connecting the production network model and the input-output analysis model, taking into account the integration of innovation networks and production networks. It proposes a method for measuring technological progress and its spillover effects under network association conditions, helping to clearly understand the growth model and driving sources of China's economy under the industrial chain division system. The research conclusions are as follows: (1) Both production and innovation networks show a strong dependence on intermediate inputs or knowledge creation within the industry itself, occupying an important position in self-circulation. (2) Without considering the innovation network, the output growth rate of various departments would significantly decline, and their contribution to economic growth would also decrease to varying degrees. (3) There are three modes of technological spillovers among industries: spillovers transmitted only through production networks, only through innovation networks, and through the interaction of production networks and innovation networks. (4) The primary driving source of output growth and the transmission driver of its spillover effects in various departments are the interactions between production and innovation networks. The conclusions of this paper help accurately judge the driving sources of China's economic growth and provide a reference for the deployment of innovation and industrial chains.

Keywords: Production network; Innovation network; Input-output analysis; Innovation chain

1.Introduction

Traditional neoclassical economic growth theories assume that technological progress among economic entities is independent of each other and based on this assumption, measure total factor productivity. The evolution of production networks has broken this assumption of independent technological progress. With the continuous deepening of production division, the links between economic entities have gradually strengthened, and production links have also become important channels for knowledge spillovers and endogenous technological sources. In the asymmetric input-output relationship network, shocks from micro-departments or market heterogeneous entities will not offset each other when aggregated, but will form significant impacts at the macro level. (Xi Yuanjie et al. 2024; Wang Yong et al. 2022). In recent years, a series of studies on production networks have recognized that the association of intermediate inputs is an important mechanism for productivity shocks to be transmitted and affect economic growth (Acemoglu et al. 2016; Liu Weigang 2022; Liu Weilin et al. 2023). They have provided a theoretical foundation for the circular spillover of technological progress and attempted to develop corresponding model tools and accounting methods. 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.

However, this logic does not correspond to real economic activities because there are not only product trading relationships among industries but also the dissemination of knowledge and information. 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. In many cases, the impact of the former on productivity is even greater than the latter (Verspagen 1997; Harada 2018). To this end, 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 changes in production network structures on knowledge spillovers without further analyzing the impact of innovation networks on industry networks and failing to consider the mutually integrated and symbiotic 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.

Specifically, the main work and marginal contributions of this paper are as follows: 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 data, proposes a method for measuring technological progress and its knowledge spillover effects under the conditions of production network associations, helping to clearly understand the growth model and driving sources of China's economy under the industrial chain division system. 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. The remaining structure of this paper is arranged as follows: the second part reviews the literature; the third part establishes the theoretical model connecting production and innovation networks; the fourth part introduces data sources and processing procedures; the fifth part presents empirical estimation results; finally, the main conclusions and policy implications are provided.

2.Literature Review

Reviewing the development process from neoclassical growth theory to endogenous growth theory, the literature related to technological spillovers can be summarized into three directions: (1) emphasizing the externalities and spillover effects of knowledge or skill levels (Arrow, 1962; Romer, 1986); (2) emphasizing the diversification of intermediate products needed in production processes (Romer, 1987; Romer, 1990); (3) 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.

2.1 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). However, the neoclassical economic growth framework incorporates technological progress as a production factor into the production function, considering less the spillover effects of technological progress among economic entities. Although endogenous growth literature considers multi-department models, they assume that all departments have fixed and identical input structures, a priori excluding the asymmetric inter-department effects of technological changes (Grossman & Helpman, 1991). Some literature includes knowledge spillover effects (Arrow, 1962), but the spillover mechanism mainly uses social capital stock or human capital as the channel, paying less attention to the important role of intermediate products as knowledge transmission carriers. 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. For example, Acemoglu et al. (2012) proposed that in a production network system, the association and interaction of intermediate inputs are important mechanisms for productivity shocks to be transmitted and affect macroeconomic fluctuations. 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 (Acemoglu et al. 2016a; Baqaee et al. 2018; Liu Weilin et al. 2023). Some literature also examines the impact of embedded technologies in intermediate products on enterprise productivity and the mechanism of action from a micro perspective (Xie Qian et al. 2021; Liu Weigang 2022). The cyclical flow of intermediate products is the core characteristic of production networks. The spillover effects formed by it make industries mutually dependent and promote each other, forming industrial chains.

2.2 Technological Spillovers in Innovation Networks

In addition to examining knowledge spillovers from the perspective of production networks, innovation networks have gradually become a research hotspot. The creation of knowledge in one sector requires the use of knowledge from other sectors (Wang Yong et al. 2022; Xi Yuanjie et al. 2024). 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 (Meyer 2002; Nomaler and Verspagen 2008; Montresor and Vittucch Marzetti 2009; Düring and Schnabel 2000; Gehringer 2012). Additionally, R&D data are also linked to the production network reflected in the input-output tables to depict the R&D spillover effects among departments

(Zhu Pingfang et al., 2016; Sun Xiaohua et al., 2012; Keller 1997; Mohnen 1997; Meyer 2002). These empirical studies have successfully revealed the importance of technological flow between departments in promoting economic growth. 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. 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, 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. Additionally, Cai and Li (2019) and Zhu (2020) argued that innovation networks could disseminate knowledge, combining with international trade and endogenous growth for further expansion. However, these literatures mainly discuss the mechanism under the abstract form of production networks, making it difficult to directly match with real empirical characteristics.

2.3 Literature Review and Improvement in This Paper

Despite the significant development of literature on production and innovation networks, related research still has limitations: (1) 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. Some literature constructs spatial weight matrices based on intermediate product usage but ignores the technological spillovers transmitted through knowledge among industries. To this end, this paper extends the data level by constructing an innovation network from micro patent data. (2) 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. Although production networks have been studied as transmission channels, with the earliest shock types being technological changes, and have now extended to various shock types such as fiscal, monetary, trade openness policies, and natural disasters (Qi Yingfei et al. 2020; Chen Guojin et al. 2024; Fadinger et al. 2022; Ozdagli et al. 2023; Barrot et al. 2016). However, there are not many systematic studies on technological diffusion in production networks and the relationship between its endogenous changes and technological innovation. Therefore, this paper embeds the innovation network into the production network model, proposing a method for measuring technological progress and its knowledge spillover effects under production network association conditions, helping to clearly understand the growth model and driving sources of economic growth. (3) 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.

3. Model Setting and Theoretical Analysis

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

Based on Acemoglu et al. (2016a), combined with the research needs of this paper, the basic assumptions are as follows: there are two types of economic agents in the economy, representative enterprises and representative households. All enterprises use capital, labor, and intermediate inputs for production, with the output used for intermediate input and private consumption. Representative households provide labor to enterprises to earn wages and spend all their disposable income on consumption.

3.1.1 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, i.e., industry i produces department output by renting capital, hiring labor, and using intermediate products. Its form is as follows:

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

where y_i represents the output level of industry i,$A_i$represents the technological level of industry i. $k_i$and l_i represent the capital and labor input of industry i, respectively; x_{ij} represents the intermediate inputs from industry j used by industry α_i, β_i, and $s_{ij}$are the output elasticities of capital, labor, and intermediate inputs, respectively. The price of each industry product is represented by p_i , and enterprises maximize their profits by choosing to rent capital, hiring labor, and using intermediate products:

$$max(p_i y_i - r k_i - \omega l_i - \sum_{j=1}^{N} p_j x_{ij}) \tag{2}$$

Under the condition of profit maximization, the relative elasticity of factor inputs equals the expenditure share of that factor. The first-order conditions can be obtained as follows:

$$\frac{p_j x_{ij}}{p_i y_i} = s_{ij} \tag{3}$$

$$\frac{r k_i}{p_i y_i} = \alpha_i \tag{4}$$

$$\frac{\omega l_i}{p_i y_i} = \beta_i \tag{5}$$

where s_{ij}represents 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.

3.1.2Household Consumption Behavior

Assuming the utility function of representative households is:

$$u = f(l) \prod_{i=1}^{N} c_i^{b_i} \tag{6}$$

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:

$$\sum_{i=1}^{N} p_i c_i = \omega l + r k \tag{7}$$

Where$l$ and k represent the total labor and capital provided by the household, and ω and r represent the wage and interest, respectively. The clearing condition of the capital market is that the total capital supply of the household equals the total demand for capital from industry sectors; simultaneously, the clearing condition of the labor supply market is that the household's labor supply equals the total demand for labor from industry sectors. The household's optimal condition:

$$\frac{p_i c_i}{b_i} = \frac{p_j c_j}{b_j} \tag{8}$$

$$p_i c_i = b_i(\omega l + rk) \tag{9}$$

Assuming wages \omega and capital interest r are constants, the first-order condition of labor supply is:

$$-\frac{f^{'}(l)}{f(l)} = \frac{\omega}{\omega l + rk} \tag{10}$$

3.1.3. 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:

$$d\,ln\,y = (I - S)^{-1} d\,ln\,A \tag{11}$$

where $dlny$ and $dlnA$ represent the vectors composed of $d\,ln\,y_i$ and $d\,ln\,A_i$, respectively. S is the matrix composed of s_{ij}, and I is the identity matrix. Therefore, the output change of industry i is jointly influenced by the technological progress of its own industry and related industries. Define $U \equiv (I - S)^{-1}$ and expand the matrix form, the change in department output can be described as:

$$d\,ln\,y_i = d\,ln\,A_i + \sum_{i=1}^{N} \left(u_{ij} - 1_{j=i}\right) \times d\,ln\,A_j \tag{12}$$

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.

3.2 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 levelA_{it} of industry i in year t is as follows:

$$A_{it} = A_{i0} e^{\delta_{1i} t + \delta_{2i} t^2 + \mu_{it}} \tag{13}$$

where δ_{1i} and δ_{2i} are parameters to be estimated, and μ_{it} is the random disturbance term of the technological level. 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:

$$A_{it} = A_{i0} e^{\delta_{1i} t + \delta_{2i} t^2 + \mu_{it}} \prod_{j \neq i}^{N} A_{jt}^{w_{ij}} \tag{14}$$

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 $w_{ii} = 0$. Taking the logarithm of both sides of equation (14) and differentiating, we obtain:

$$d\,ln\,A_{it} = \delta_{1i} + d\delta_{2i}t + d\mu_{it} + \sum_{j\neq i}^{n} w_{ij} d\,ln\,A_{jt} \tag{15}$$

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

$$d\,ln\,A_t = (I - W)^{-1}(\Gamma_1 t + \Gamma_2 t^2 + u) \tag{16}$$

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

$$d\,ln\,y = (I - S)^{-1}(I - W)^{-1}(\Gamma_1 t + \Gamma_2 t^2 + u) \tag{17}$$

Defining $\psi \equiv (I - S)^{-1}(I - W)^{-1}$, the matrix form can be expanded, and the change in sector output can be described as:

$$d\,ln\,y_i = (\delta_{1i} + d\delta_{2i}t + d\mu_{it}) + \sum_{j=1}^{N}\left(\psi_{ij} - 1_{j=i}\right) \times (\delta_{1j} + d\delta_{2j}t + d\mu_{ij}) \tag{18}$$

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. In equation (18), ψ_{ij} represents the change in the output growth rate of industry i after the unit neutral technological progress of industry j, through the complex iterative effect of the production network and innovation network. To clarify its meaning, equation (19) reports the approximate expansion of the expression of ψ_{ij}, where 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.

$$\psi_{ij} \approx I_{ij} + W_{ij} + \sum\nolimits_{k=1}^{N} W_{ik}W_{kj} + S_{ij} + \sum\nolimits_{k=1}^{N} S_{ik}S_{kj} + \sum\nolimits_{k=1}^{N} S_{ik}W_{kj}$$
$$+ \sum\nolimits_{k=1}^{N}\sum\nolimits_{l=1}^{N} S_{il}W_{lk}W_{kj} + \sum\nolimits_{k=1}^{N}\sum\nolimits_{l=1}^{N} S_{ik}S_{kl}W_{lj} + \sum\nolimits_{k=1}^{N}\sum\nolimits_{l=1}^{N}\sum\nolimits_{m=1}^{N} S_{il}S_{lk}W_{km}W_{mj} \tag{19}$$

3.3 Three Modes of Technological Spillover

According to equation (19), $\psi = (I - S)^{-1}(I - W)^{-1} \approx I + W + W^2 + S + S^2 + SW + SW^2 + S^2W + S^2W^2$, 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. From a theoretical perspective:

Firstly, with technological progress, market expansion, and diversification of demand, the functions undertaken by economic entities increasingly tend toward specialization. The complete industrial process, from raw material production, intermediate goods manufacturing, to final product manufacturing and consumption, is divided among upstream, midstream, and downstream enterprises. 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).

Lastly, the innovation chain extends and develops around the industrial chain, and the two become interwoven. On one hand, the innovation chain is the value-adding foundation for each link of the industrial chain. Each existing link of the industrial chain can derive an innovation chain and embed it into the main chain of the industrial chain, driving innovation in other links and enhancing the overall value of the industrial chain. On the other hand, the innovation chain uses the industrial chain as a carrier. Enterprises in the same industry or upstream and downstream enterprises share information and knowledge during the development of new products, jointly constructing vertical and horizontal cooperation networks (as shown in Figure 3).

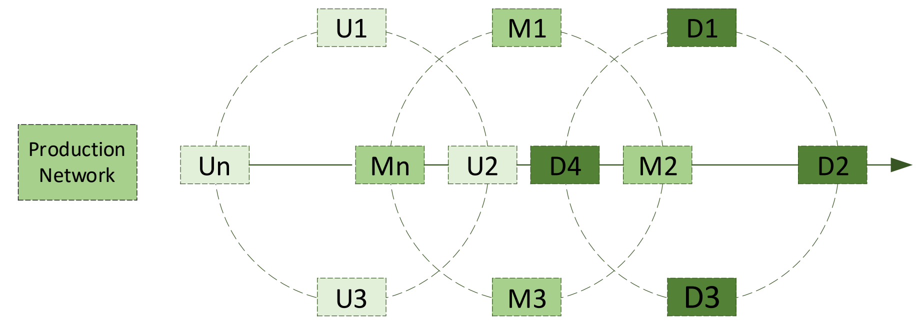


Figure 1 Schematic diagram of the production network

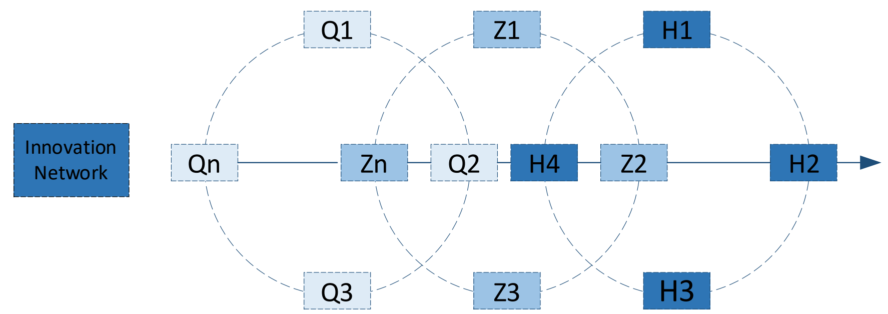


Figure 2 Schematic diagram of the innovation network

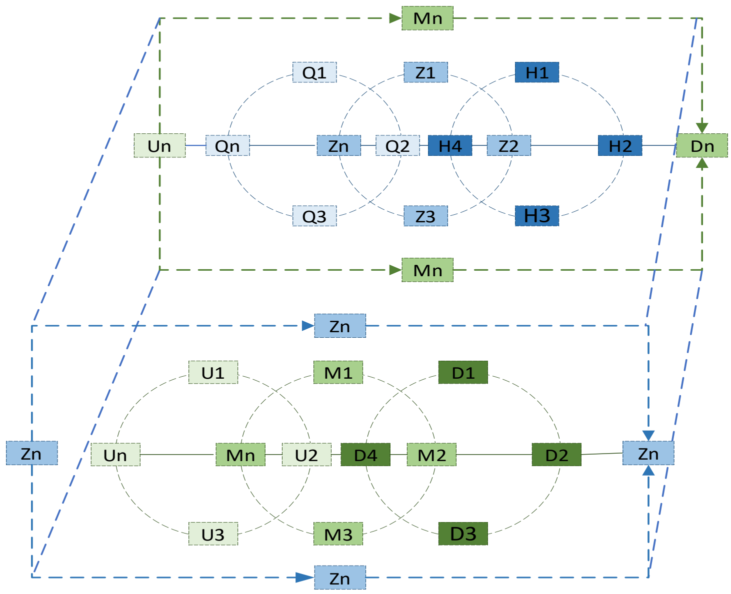


Figure 3 Schematic diagram of the convergence of production and innovation networks

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: ① Technological spillover transmitted through the production network can be represented by $T_1 = S + S^2$; ② Technological spillover transmitted through the innovation network can be represented by $T_2 = W + W^2$; ③ Technological spillover transmitted through the interaction of the production and innovation networks can be represented by $T_3 = \psi - I - T_1 - T_2 = SW + SW^2 + S^2W + S^2W^2 + \cdots$.

Thus, the spillover effect of technological progress can be expressed as the sum of these three network effects. Based on these three network modes, we can classify and judge the modes of technological spillover in various industries in China. This can help provide references for "deploying innovation chains around the industrial chain and arranging the industrial chain around the innovation chain."

4. Data Sources

The empirical analysis in this paper involves two sets of data: production network data and innovation network data.

4.1 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"). This involved splitting or merging different sectors in the input-output tables of various years to ensure consistency in the number of sectors and accounting scope, ultimately standardizing the input-output tables to 37 sectors, as shown in Table 1. Additionally, since this paper focuses on how Chinese economic sectors leverage the advantage of the large domestic market to achieve technological progress transmission and spillover through production and innovation networks, it is necessary to exclude imported intermediate inputs. Currently, the National Bureau of Statistics has published non-competitive input-output tables for 2017, 2018, and 2020. We adjusted the competitive input-output tables for other years to non-competitive ones based on the import proportions.

Table 1: Sector Classification Standards

No.	Sector Name	No.	Sector Name
1	Agriculture, Forestry, Animal Husbandry, and Fishery Products and Services	20	Communication Equipment, Computers, 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 Scrap Waste
4	Metal Ore Mining Products	23	Production and Supply of Electricity and 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, and 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		

4.2 Innovation Network

The innovation network is represented by W, where the elements w_{ij} in matrix W indicate 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. This paper measures the degree of knowledge spillover between industries by constructing a patent citation network, which represents the innovation network. Patent citation refers to a patent being cited by applicants or examiners of subsequent patents, indicating a technological connection between the two patents. The number of patent citations is a core indicator of patent quality. If a patent cites previous patents, it can be inferred that the patent uses the knowledge contained in those earlier patents. The patent citation network can demonstrate the dynamic process of technological innovation and is widely used to understand the connections in knowledge flow among industries, countries, or different types of technology (Ernst, 2003; Choi & Park, 2008). The data used in this paper come from the Patent Citation Database of Listed Companies (CITE), which is a specialized database compiled based on the citation information of invention and utility model patents of Chinese listed companies from 1992 to 2020. The original data mainly come from Google Patent, including various situations such as company name matching, patent self-citation, and company name changes.

Based on this database, we compiled annual innovation networks between industries from 1992 to 2020 according to the application or authorization year of the cited patents. The compiled innovation networks include the following types: the citation network of invention patent applications for each year, the citation network of authorized invention patents for each year, the citation network of authorized utility model patents for each year, and the citation network of both authorized invention and utility model patents. Considering that the differences after standardizing these networks are not significant, the subsequent analysis in this paper mainly uses the citation network of authorized invention and utility model patents as the basis for measuring the innovation network. The innovation networks for each year are denoted as M^{1992}、$M^{1993}\cdots\cdots M^{2020}$; the elements M_{ij}^{t} represent the number of times patents in industry i in year t cite patents in industry j. However, knowledge spillover often has a lasting effect, as shown in the cumulative probability graph of the time intervals between patent publication and citation (Figure 4). Most patents are quickly cited within a year of publication, but they continue to be cited over the next 15-20 years. Therefore, when compiling the innovation network matrix for a given year, it is necessary to consider the cumulative effect of prior knowledge. Based on the actual data characteristics, this paper constructs the innovation network matrix for each year as the sum of the network matrices for that year and all previous years.

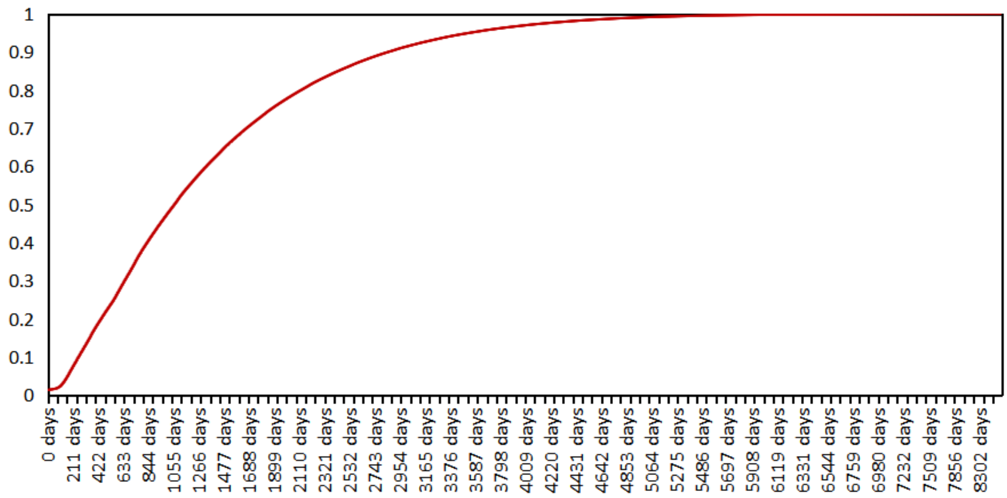


Figure 4: Cumulative Probability of Patent Citation Intervals

To illustrate the process, 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 $M^{1992} + M^{1993} + \cdots M^{2020}$. After normalizing the rows and setting the diagonal data to zero, we obtain W^{2020}.

This paper plots the contour maps of the production network and innovation network for 2020, as shown in Figure 5. 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.

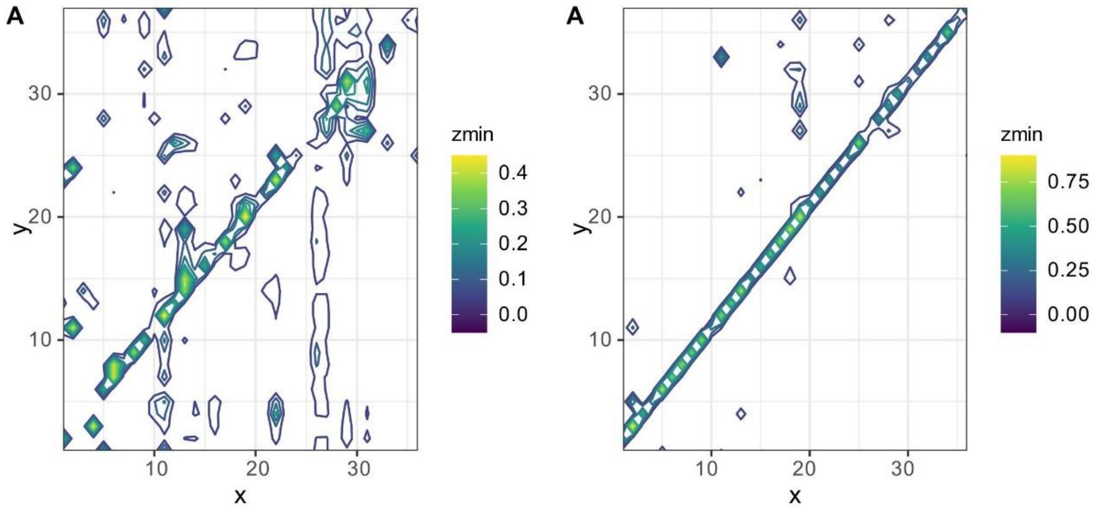


Figure 5: Contour Maps of the Production Network and Innovation Network

5. Empirical Analysis

In this section, we will verify the asymmetrical shocks described in the theoretical and model sections by measuring the inter-sectoral spillover effects of technological progress.

5.1 Analysis of Inter-sectoral Spillover Effects of Technological Progress

By calculating $\psi = (I - S)^{-1}(I - W)^{-1}$,this paper constructs an inter-sectoral technological spillover effect matrix, revealing the complex interaction relationships between industries. Each element ψ_{ij} in the matrix represents the change in the output growth rate of industry i driven by a unit of neutral technological progress in industry j.The contour map of matrix ψ is shown in Figure 6. The main conclusions are as follows:

The diagonal elements of the matrix are generally greater than 1, indicating that the neutral technological progress in each sector is enhanced through the iterative effects of the production and innovation networks. The five sectors with the highest diagonal elements are "Chemical Products," "Communication Equipment, Computers, and Other Electronic Equipment," "Textiles," "Transportation Equipment," and "Production and Supply of Electricity and Heat," with diagonal values of 1.56, 1.56, 1.53, 1.49, and 1.48, respectively. This shows that these sectors not only achieve technological progress within their own sector but also gain additional output growth rates of 0.56, 0.56, 0.53, 0.49, and 0.48 units through network effects. Conversely, sectors such as "Research and Experimental Development," "Education," and "Metal Ore Mining Products" have smaller network effects from their own technological progress.

The off-diagonal elements of the matrix are generally smaller, indicating that the mutual influence between industries is relatively limited. However, certain industries play a key driving role in the economic system, showing higher off-diagonal element values. For example, the impact value of the "Food and Tobacco" sector on the "Agriculture, Forestry, Animal Husbandry, and Fishery Products and Services" sector is 0.54. Additionally, some industries not only have a significant impact on their own output but also broadly drive multiple other industries. For instance, "Communication Equipment, Computers, and Other Electronic Equipment" not only significantly boosts its own output but also has a strong driving effect on multiple other industries. This multidimensional economic linkage indicates that certain industries act as key nodes in the entire economic system, with their output changes triggering chain economic reactions. It is worth noting that the mutual influence between some industries is small, as reflected by the lower element values in the matrix. For example, the "Production and Supply of Water" sector has a low impact value on most other industries, indicating a strong independence in economic activities. Overall, the matrix analysis shows that while each industry's self-growth effect is significant, several key industries play an important linkage role in the economic system, driving the development of other related industries through their output changes. This analysis provides important insights for understanding the complex interaction relationships in the economic system, aiding in the formulation of precise economic policies and industry development strategies. By studying these linkage effects, we can better identify key drivers in the economic system, optimize resource allocation, and promote coordinated overall economic growth.

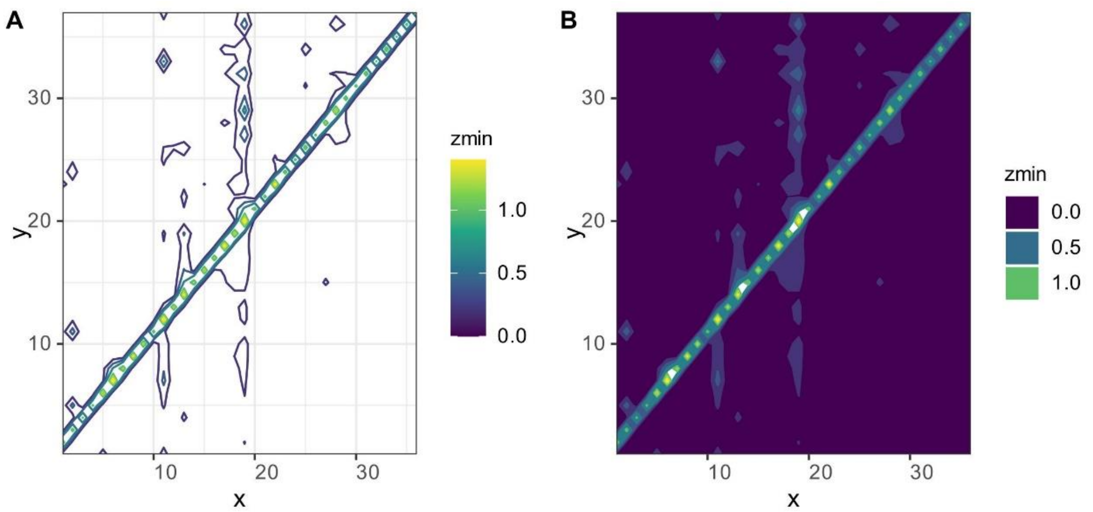


Figure 6: Contour Map of Matrix

5.2 Industry Distribution of Network Spillover Effects

Based on the inter-sectoral technological spillover effect matrix constructed in this paper, summing along the rows gives the change in the output growth rate of a sector when each sector achieves a unit of neutral technological progress. This can be used to measure the benefits each sector gains through network spillover effects. As shown in Figure 7, sectors such as "Textiles, Textile Apparel, Footwear, Leather, Down, and Related Products," "Metal Products," and "General Equipment" benefit the most from overall technological progress. These sectors are most significantly driven by the network spillover effects from other sectors. "Petroleum and Natural Gas Extraction Products," "Education," "Finance and Real Estate" gain relatively less from overall technological progress, indicating that the output growth in these sectors mainly relies on their own technological progress. This analysis provides important insights for understanding the benefit differences of various sectors in overall technological progress, helping to formulate more precise economic policies and industry development strategies, optimize resource allocation, and promote coordinated overall economic growth.

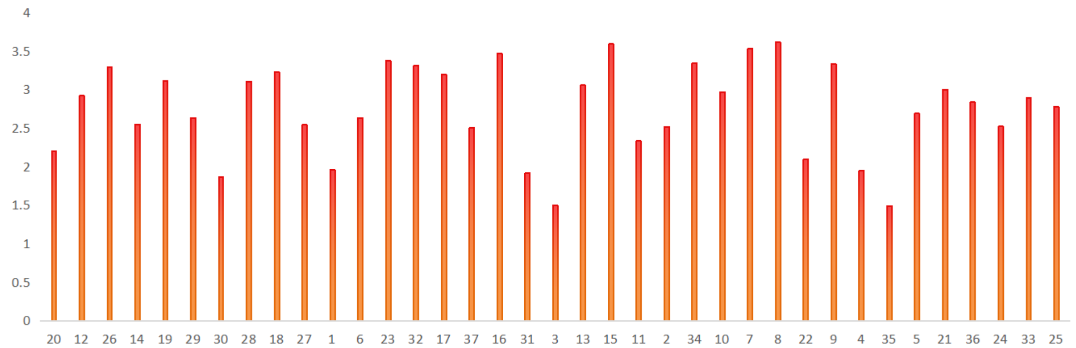


Figure 7: Benefits from Network Spillover Effects

Summing the technological spillover matrix columns based on total output weight can reveal the key role and contribution of technological progress in different sectors to overall economic growth, as shown in Figure 8. Among all sectors, the technological spillover effect of "Communication Equipment, Computers, and Other Electronic Equipment" is the largest, indicating its technological progress has the greatest driving effect on overall economic growth. This shows that technological progress in this sector not only significantly increases its own output but also drives the development of other industries through strong spillover effects, highlighting its core position in the modern economy. "Chemical Products," "Construction," "Metal Smelting and Rolling Products," and "Electrical Machinery and Apparatus" also have significant driving effects on overall economic growth. Innovations and progress in these sectors can be widely applied to various industries, generating substantial economic effects. Sectors such as "Agriculture, Forestry, Animal Husbandry, and Fishery Products and Services," "Textile Apparel, Footwear, Leather, Down, and Related Products," "Transportation Equipment," and "Information Transmission, Software, and Information Technology Services" play a moderate driving role in overall technological progress, indicating their central role in the economic system. Their technological progress not only benefits their own development but also positively impacts other related industries. Sectors like "Production and Supply of Water," "Production and Supply of Gas," and "Other Manufacturing Products and Scrap Waste" have a smaller driving effect on overall economic growth from technological progress, possibly because their technological progress is mainly absorbed within the sector or has limited spillover effects.

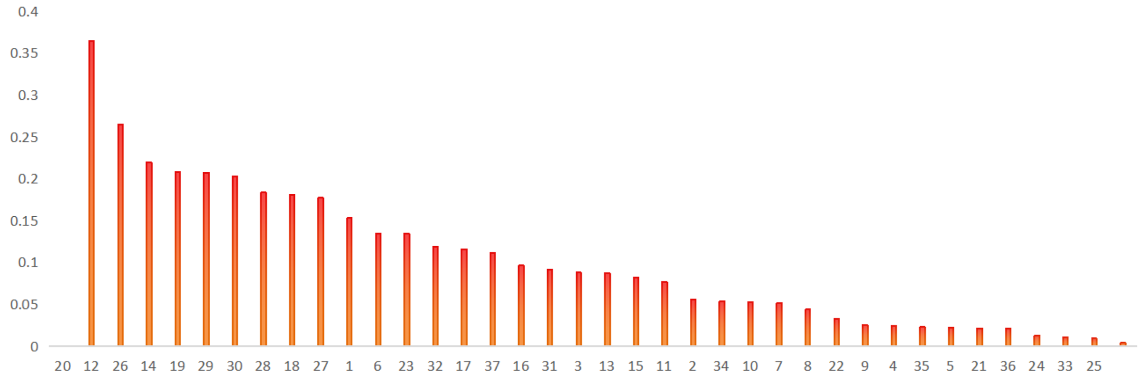


Figure 8: Analysis of Network Spillover Effects by Sector

5.3 Counterfactual Analysis Without Innovation Networks

Unlike existing literature, this paper considers the innovation network and its interaction with the production network. Therefore, we conduct a counterfactual analysis of the spillover effects of technological progress in each sector without the innovation network. At the element level, the results are shown in Figure 9. The technological spillover effects of each sector on other sectors decrease. Summing along the rows shows that the output growth gained by each sector through network spillover effects significantly decreases and exhibits similar magnitudes (as shown in Figure 10). 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.

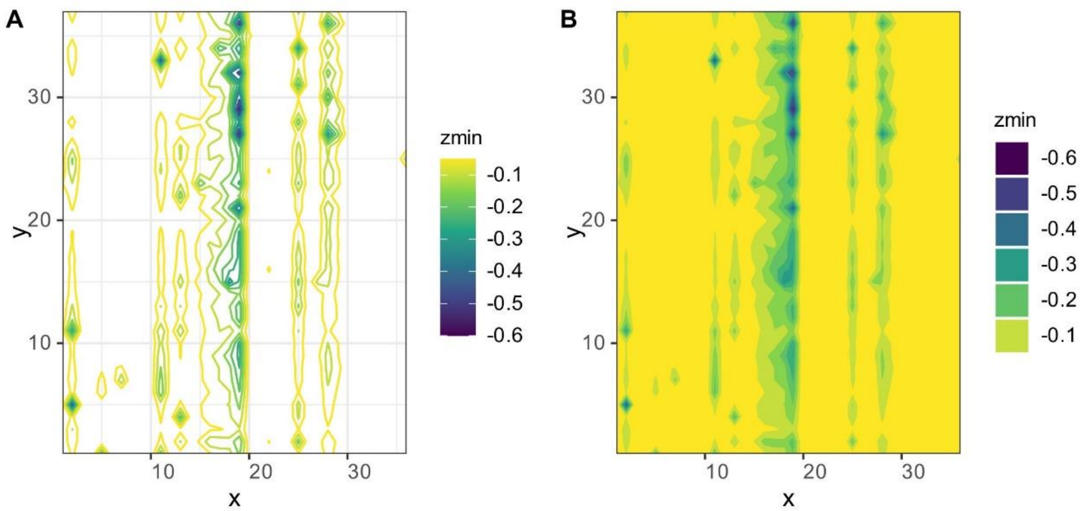


Figure 9: Changes in Elements of Matrix ψ Without the Innovation Network

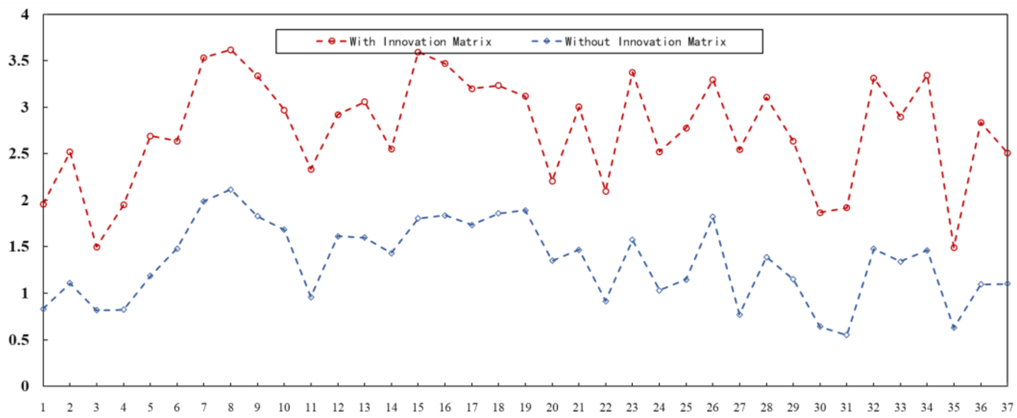


Figure 10: Benefits from Network Spillover Effects with and without the Innovation Network

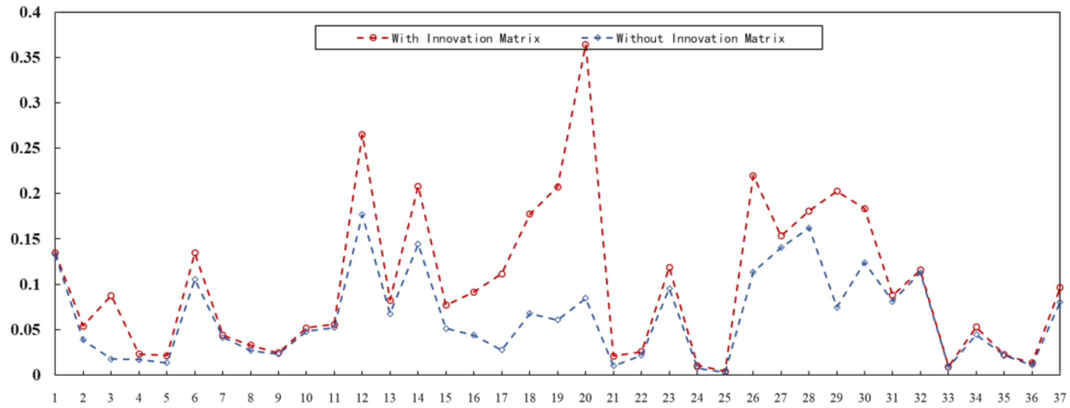
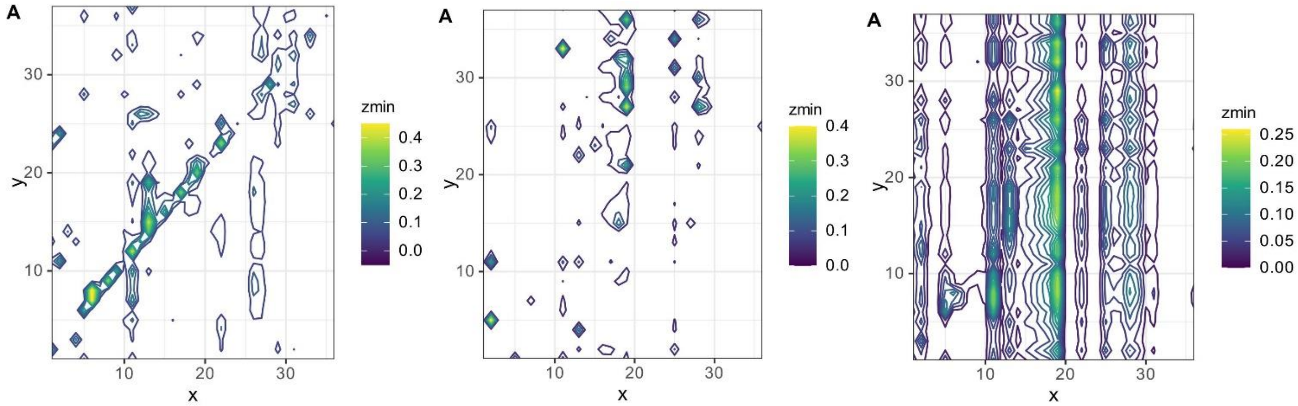


Figure 11: The technological spillover among departments with and without an innovation network.

5.4 Transmission Modes of Technological Spillover Effects

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: ①Technological spillover transmitted through the production network. ②Technological spillover transmitted through the innovation network. ③Technological spillover transmitted through the interaction of the production and innovation networks.

These transmission modes can be calculated using the previous formulas to derive matrices. Figure 12 shows the contour maps of the matrices for the three technological spillover transmission modes at the element level. It is clear that the technological spillover transmitted only through the production network and only through the innovation network is relatively dispersed. Although there are varying degrees of technological spillover between sectors, they mainly exist on the diagonal or in key industries. The technological spillover transmitted through the interaction of the production and innovation networks is more widespread and comprehensive, with significant spillover effects between almost all sectors. This indicates that sectors form a tightly interconnected network through the interaction of the production and innovation networks. Summing these three technological spillover modes along the rows and columns, as shown in Tables 2 and 3, reveals that the primary driver of output growth in each sector is the interaction of the production and innovation networks. The main mode of technological spillover in each sector is through the production network and the interaction of the production and innovation networks.



(a) Production Network (b) Innovation Network (c) Interaction of Production and Innovation Networks

Figure 12: Element-level Contour Maps of the Three Technological Spillover Transmission Modes

Table 2: Row-wise Summation of the Three Technological Spillover Modes

NO.	Total Spillover Effects	T1	T2	T3
1	1.96	0.58	0.59	0.79
2	2.52	0.75	0.62	1.14
3	1.50	0.55	0.13	0.81
4	1.95	0.55	0.54	0.86
5	2.69	0.79	0.71	1.20
6	2.64	1.06	0.24	1.34
7	3.53	1.29	0.37	1.87
8	3.62	1.32	0.28	2.02
9	3.34	1.19	0.38	1.77
10	2.97	1.11	0.30	1.56
11	2.33	0.68	0.77	0.88
12	2.92	1.08	0.33	1.51
13	3.06	1.06	0.42	1.58
14	2.55	0.99	0.26	1.30
15	3.59	1.19	0.68	1.72
16	3.47	1.19	0.54	1.75
17	3.20	1.12	0.44	1.64
18	3.23	1.18	0.31	1.74
19	3.12	1.23	0.20	1.69
20	2.21	0.90	0.16	1.15
21	3.00	0.97	0.66	1.37
22	2.10	0.61	0.59	0.89
23	3.38	1.05	0.69	1.64
24	2.52	0.75	0.78	0.99
25	2.78	0.77	0.79	1.21

26	3.30	1.20	0.33	1.77
27	2.54	0.54	1.10	0.90
28	3.11	0.97	0.74	1.40
29	2.63	0.80	0.67	1.16
30	1.87	0.46	0.69	0.71
31	1.92	0.40	0.88	0.63
32	3.31	1.01	0.81	1.50
33	2.90	0.90	0.65	1.35
34	3.34	0.98	0.84	1.52
35	1.49	0.44	0.41	0.64
36	2.84	0.75	0.94	1.15
37	2.51	0.74	0.66	1.10

Table 3: Column-wise Summation of the Three Technological Spillover Modes

NO.	Total Spillover Effects	T1	T2	T3
1	0.09	0.05	0.00	0.03
2	0.05	0.02	0.01	0.02
3	0.08	0.01	0.02	0.05
4	0.02	0.01	0.00	0.01
5	0.02	0.01	0.00	0.01
6	0.09	0.04	0.01	0.04
7	0.03	0.02	0.00	0.01
8	0.02	0.01	0.00	0.01
9	0.01	0.01	0.00	0.00
10	0.04	0.02	0.00	0.01
11	0.04	0.02	0.00	0.02
12	0.21	0.08	0.04	0.09
13	0.06	0.03	0.01	0.02
14	0.16	0.07	0.03	0.07
15	0.06	0.02	0.01	0.02
16	0.07	0.02	0.02	0.04
17	0.10	0.01	0.03	0.05
18	0.15	0.02	0.04	0.08
19	0.18	0.02	0.05	0.10
20	0.32	0.03	0.10	0.19
21	0.02	0.00	0.00	0.01
22	0.02	0.01	0.00	0.01
23	0.09	0.04	0.01	0.04
24	0.01	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00
26	0.11	0.01	0.04	0.07
27	0.10	0.06	0.00	0.03
28	0.12	0.07	0.01	0.05
29	0.17	0.03	0.05	0.09

30	0.14	0.05	0.02	0.06
31	0.05	0.03	0.00	0.02
32	0.08	0.05	0.00	0.03
33	0.00	0.00	0.00	0.00
34	0.03	0.02	0.00	0.01
35	0.00	0.00	0.00	0.00
36	0.01	0.00	0.00	0.00
37	0.03	0.01	0.01	0.02

6. Conclusions and Policy Recommendations

6.1 Conclusions

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.

6.2 Policy Recommendations

(1) Break down the interest barriers and institutional obstacles between departments to promote the construction of a unified national market, fully leveraging the network spillover effects brought by industrial division and cooperation.

(2) Enhance the governance capacity for cross-industry and cross-departmental coordination, deepen the integration and cooperation of upstream, midstream, and downstream sectors of the industrial chain, ensure the stable and smooth operation of supply chains, and promote cost reduction and efficiency improvement from the perspective of the entire industrial chain to provide continuous momentum for high-quality economic growth.

(3) Relying on internal circulation, promote the deep integration of the industrial chain and innovation chain, enhance China's independent innovation capabilities, and strengthen the endogenous power and reliability of internal circulation. The government should encourage the creation of self-reliant, controllable industrial chain collaborative innovation consortia, establish multi-field integrated innovation platforms, enhance technological communication and

collaboration within and between chains, and encourage leading enterprises to act as "chain owners," utilizing their coordination and vertical integration capabilities along the industrial chain, supporting enterprises in jointly tackling core technologies and components on the basis of vertical and horizontal collaboration.

References

[1] Acemoglu, D., Akcigit, U., Kerr, W. R., 2016b. Innovation Network [J/OL]. Proceedings of the National Academy of Sciences, 113(41): 11483-11488. DOI:10.1073/pnas.1613559113.

[2] Acemoglu, D., Akcigit, U., Kerr, W., 2016a. Networks and the Macroeconomy: An Empirical Exploration [J/OL]. NBER Macroeconomics Annual, 30: 273-335. DOI:10.1086/685961.

[3] Acemoglu, D., Carvalho, V. M., Ozdaglar, A., et al., 2012. The Network Origins of Aggregate Fluctuations [J/OL]. Econometrica, 80(5): 1977-2016. DOI:10.3982/ECTA9623.

[4] Aghion, P., & Howitt, P. (1992). A Model of Growth through Creative Destruction. Econometrica 60(2), 323-351.

[5] Arrow, K. J. (1962). The Economic Implications of Learning by Doing. Review of Economic Studies, 29(3), 155-173.

[6] Baqaee, D. R., Farhi, E., 2018. Macroeconomics with Heterogeneous Agents and Input-Output Networks [M/OL]. National Bureau of Economic Research [2024-05-22]. https://www.nber.org/papers/w24684. DOI:10.3386/w24684.

[7] Barrot, J. N., Sauvagnat, J., 2016. Input Specificity and the Propagation of Idiosyncratic Shocks in Production Networks *[J/OL]. The Quarterly Journal of Economics, 131(3): 1543-1592. DOI:10.1093/qje/qjw018.

[8] Cai, J., Li, N., Santacreu, A. M., 2022. Knowledge Diffusion, Trade, and Innovation across Countries and Sectors [J/OL]. American Economic Journal: Macroeconomics, 14(1): 104-145. DOI:10.1257/mac.20200084.

[9] Chen, Guojin, Liu, Yuanyue, Ding, Saijie, et al., 2024. Macroeconomic Tail Risks, Production Networks, and Industry Output [J/OL]. Management World, 40(2): 28-52.

[10] Chen, Y., Li, S., 2014. Research of Innovation Diffusion on Industrial Networks [J/OL]. Mathematical Problems in Engineering, 2014: 1-7. DOI:10.1155/2014/629279.

[11] Düring, B., & Schnabel, U. 2000. "R&D Spillovers and Input-Output Analysis: Evidence from German Manufacturing Industries." Economic Systems Research, 12(1), 1-23.

[12] Fadinger, H., Ghiglino, C., Teteryatnikova, M., 2022. Income Differences, Productivity, and Input-Output Networks [J/OL]. American Economic Journal: Macroeconomics, 14(2): 367-415. DOI:10.1257/mac.20180342.

[13] Gehringer, A. 2012. "Technological Spillovers from Foreign Direct Investment in Central and Eastern Europe: Evidence from the Czech Republic." Economic Systems, 36(4), 654-666.

[14] Gonçalves, E., Borges Ferreira Neto, A., 2016. Intersectoral Flows of Technological Knowledge in Emerging Countries: An Input-Output Analysis [J/OL]. CEPAL Review, 2016(118): 139-155. DOI:10.18356/db371779-en.

[15] Grossman, G. M., & Helpman, E. (1991). Innovation and Growth in the Global Economy. MIT Press.

[16] Harada, T., 2018. A Model of Intersectoral Flow of Technology Using Technology and Innovation Flow Matrices [J/OL]. Economic Systems Research, 30(2): 238-251. DOI:10.1080/09535314.2018.1423545.

[17] Keller, W., 1997. Technology Flows Between Industries: Identification and Productivity Effects [J/OL]. Economic Systems Research, 9(2): 213-219. DOI:10.1080/09535319700000015.
[18] Liu, Weigang, 2022. Changes in the Structure of Production Inputs and Enterprise Innovation: An Analysis Based on the Endogenization of Production Networks [J]. Economic Research Journal, 57(4): 50-67.
[19] Liu, Weilin, Cheng, Qian, Yu, Yongze, 2023. Network Effects of Technological Progress in Chinese Industries from the Perspective of Dual Circulation Technology Spillovers: Calculations of Total Factor Productivity Growth and Transmission in Global Production Networks [J/OL]. Management World, 39(5): 38-59.
[20] Meyer, M. 2002. "Tracing Knowledge Flows in Innovation Systems Using Patent Citations." Research Policy, 31(6), 797-811.
[21] Meyer, M., 2002. Tracing Knowledge Flows in Innovation Systems [J]. Scientometrics, 54(2): 193-212.
[22] Mohnen, P., 1997. Introduction: Input–Output Analysis of Interindustry R&D Spillovers [J/OL]. Economic Systems Research [2024-05-22].
[23] Montresor, S., & Vittucci Marzetti, G. 2009. "Innovation Clusters in Technological Systems: A Network Analysis of 15 OECD Countries for the Mid-1990s." Industry and Innovation, 15(3), 321-346.
[24] Nomaler, Ö., & Verspagen, B. 2008. "Knowledge Flows and Innovation Networks in European Union Countries: An Application of Social Network Analysis." Research Policy, 37(10), 1717-1735.
[25] Ozdagli, A. K., Weber, M., 2023. Monetary Policy through Production Networks: Evidence from the Stock Market [M/OL]. Rochester, NY (2023-10-06) [2024-05-22].
[26] Qi, Yingfei, Yuanfei, L, 2020. Departmental Allocation of Fiscal Expenditure and the Upgrading of China’s Industrial Structure: An Analysis Based on the Production Network Model [J]. Economic Research Journal, 55(4): 86-100.
[27] Romer, P. M. (1986). Increasing Returns and Long-Run Growth. Journal of Political Economy, 94(5), 1002-1037.
[28] Romer, P. M. (1987). Growth Based on Increasing Returns Due to Specialization. American Economic Review, 77(2), 56-62.
[29] Romer, P. M. (1990). Endogenous Technological Change. Journal of Political Economy, 98(5), S71-S102.
[30] Semitiel-García, M., Noguera-Méndez, P., 2012. The Structure of Inter-Industry Systems and the Diffusion of Innovations: The Case of Spain [J/OL]. Technological Forecasting and Social Change, 79(8): 1548-1567. DOI:10.1016/j.techfore.2012.04.010.
[31] Sun, Xiaohua, Zheng, Hui, 2012. Measurement and Comparison of R&D Spillover Effects among Manufacturing Industries Based on the Input-Output Method [J]. Science Research Management, 33(2): 79.
[32] Verspagen, B., 1997. Measuring Intersectoral Technology Spillovers: Estimates from the European and US Patent Office Databases [J/OL]. Economic Systems Research, 9(1): 47-65. DOI:10.1080/09535319700000004.
[33] Wang, Yong, Huang, Yuxuan, Han, Boyu, 2022. Research Progress on Production Networks and Vertical Structures [J]. Economic Dynamics, (3): 123-138.

[34] Xi, Yuanjie, Han, Song, 2024. Technological Innovation from the Perspective of Production Networks: A Literature Review [J/OL]. Industrial Economics Review, (2): 5-25.
[35] Xie, Qian, Liu, Weigang, Zhang, Pengyang, 2021. Embedded Technology in Imported Intermediate Goods and Enterprise Productivity [J/OL]. Management World, 37(2): 66-80, 6, 22-23. DOI:10.19744/j.cnki.11-1235/f.2021.0020.
[36] Zhu, Pingfang, Xiang, Gede, Wang, Yongshui, 2016. Research on R&D Spillover Effects among Chinese Industrial Sectors [J]. Economic Research Journal, 51(11): 44-55.