Technological Innovation in Central Cities and the Development of Modern Industrial Systems in Urban Clusters: A Knowledge-Spillover Economics Perspective

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Abstract

Can the geographical proximity of cities within an urban cluster to the technological-innovation knowledge pool of the central city be effectively converted into a driving force for the development of modern industrial systems? Grounded in the theoretical framework of knowledge-spillover economics, this study examines the impact of technological innovation in central cities on the development of modern industrial systems in urban clusters. The results show that knowledge spillovers generated by central-city technological innovation promote inter-city technology transfer and technological cooperation, reduce imbalances in technological development within urban clusters, alleviate technological rigidity, and thereby advance the development of modern industrial systems in non-central cities. The effect is particularly pronounced in urban clusters at the optimization-and-upgrading development stage and in those located within inland-oriented national strategic layouts. Improvements in digital infrastructure, stronger judicial protection of intellectual property rights, greater government preference for innovation, and a higher degree of fiscal decentralization significantly reinforce the positive effect of central-city technological innovation. The findings provide practical implications for public authorities seeking to implement innovation-driven development strategies.

Keywords: central-city technological innovation; knowledge spillovers; development of modern industrial systems

1. Introduction

The report to the 20th National Congress of the Communist Party of China identified the construction of a modern industrial system as an important task in advancing Chinese modernization. Against a background of deep restructuring in global industrial chains and rapidly changing modes of competition, China's modern industrial system continues to face bottlenecks such as insufficient supply of innovation factors, weak basic innovation capacity, rigid coordination mechanisms, and an inadequate level of industrial-chain modernization (Sheng, 2019; Xu and Xia, 2023). Scientific and technological innovation is a core driver of high-quality industrial development and is therefore crucial to the construction of a modern industrial system. As the spatial carriers of the new development pattern, urban clusters accommodate the dynamic circulation of production, distribution, exchange, and consumption, and serve as open hubs linking supply with demand and domestic with international markets. In this process, modern industrial systems within urban clusters strengthen the micro-foundations of national economic circulation through industrial-chain integration, deeper regional coordination, and stronger supply-chain resilience.

Nevertheless, urban clusters still face problems such as weak coordination, factor misallocation, and industrial homogenization. Central cities, relying on resource endowments and national science-and-technology strategies, often evolve into growth poles, which can lead to an imbalanced spatial distribution of economic activity. Classical theories suggest that the increasing-returns characteristics of technological innovation in central cities may either generate a backwash effect that intensifies spatial polarization (Krugman, 1991) or facilitate the coordination of regional innovation networks through knowledge spillovers (Glaeser et al., 1992; Duranton and Puga, 2004). Under conditions of spatial heterogeneity, therefore, how does technological innovation in central cities affect the development of modern industrial systems in non-central cities within urban clusters? What are the transmission mechanisms and the boundaries of this effect? Answering these questions helps reveal the evolutionary logic of spatial economic systems and provides an empirical basis for innovation strategies aimed at coordinated regional development under the new development pattern.

The literature most closely related to this study falls into two strands. The first focuses on the theoretical construction of modern industrial systems. Existing research has analyzed their theoretical core from multiple dimensions, including industrial characteristics, spatial structure, and coordination among innovation factors (Sheng,

2019; Bai et al., 2022), as well as through systematic frameworks centered on the coordinated evolution of industrial structure, industrial characteristics, and industrial support (Chen et al., 2023). Current construction of China's modern industrial system is constrained by institutional bottlenecks and structural weaknesses (Sheng, 2019; Xu and Xia, 2023). Studies of possible solutions highlight spatial optimization, value-chain upgrading, sectoral restructuring, and the digital economy as an important driving force (Zhao, 2023; Luo et al., 2024; Chen and Song, 2024; Xia and Su, 2024). Yet because modern industrial systems are broad in scope, complex in structure, and dependent on overall coordination, their spatial distribution is necessarily heterogeneous. Most existing measurement studies operate at the national or provincial level, while city-level research is limited, especially systematic measurement based on the industrial endowments of urban clusters. Empirical evidence on development paths for modern industrial systems within urban clusters remains particularly scarce.

The second strand concerns technological innovation in central cities. On the one hand, technological innovation is a core driver of regional economic development, but differences in resource endowments may lead to unequal capacity to acquire and apply new technologies and hence to uneven economic development (Qiu and Zhao, 2013). On the other hand, innovation activity is spatially embedded. Because of internal spatial heterogeneity, there is continuing debate over whether the innovation growth pole of a central city produces backwash or diffusion effects (Ke and Feser, 2010; Chen and Partridge, 2013). New economic geography emphasizes that increasing returns can generate factor agglomeration and backwash effects (Krugman, 1991), potentially weakening coordination across the urban cluster. By contrast, the matching-learning-sharing mechanism emphasized by agglomeration economics points to the opposite pathway (Duranton and Puga, 2004). Geographical proximity lowers the spatial transfer cost of tacit knowledge and facilitates cross-regional exchange of technological factors (Li et al., 2023). Gradient diffusion generated by differences in technological potential can reduce innovation-information asymmetry, generate new infrastructure and business forms, and establish regional pools of technological knowledge (Tang et al., 2019), thereby providing sustained momentum for the modernization of industrial systems in non-central cities.

This theoretical tension implies that central-city technological innovation may simultaneously generate a 'backwash-inhibition' effect and a 'diffusion-promotion' effect. Existing studies mainly examine its influence on industrial upgrading and diversification in urban clusters (Li and Wang, 2021, 2022), without systematically identifying the conditions under which the two mechanisms balance in the development of modern industrial systems.

Relative to prior research, this study makes three contributions. First, it extends research on the spatial effects of central-city technological innovation and on the development of modern industrial systems. Based on knowledge-spillover economics, it constructs a coordination mechanism for innovation networks within urban clusters, identifies the diffusion path of tacit knowledge across multiple spatial nodes and its micro-level transmission channels, and enriches the theoretical discussion of the endogeneity and spatial externalities of central-city innovation while providing new empirical evidence on modern industrial-system development.

Second, the study deepens analysis of the moderating role of institutional factors. Prior research has largely emphasized spatial-layout optimization, value-chain upgrading, and the digital economy, but has devoted less attention to the interaction between an effective market and a proactive government. We develop a moderating framework incorporating digital infrastructure, judicial protection of intellectual property, fiscal decentralization, and government innovation preference, thereby showing how institutional coordination affects the radiation intensity and spillover boundaries of central-city innovation.

Third, the study establishes a link between the deep integration of technological innovation and industrial innovation and the goal of common prosperity. Existing studies focus mainly on the contribution of technological innovation to economic development, while paying less attention to distributional outcomes. We further test whether the deep integration of technological and industrial innovation promotes common prosperity, and examine how technology-diffusion networks may narrow regional wealth gaps and improve the distribution of economic opportunities.

2. Theoretical Analysis and Research Hypotheses

2.1 Central-city technological innovation and the development of modern industrial systems in urban clusters

Technological innovation in central cities can drive the upgrading of industrial structure and the modernization of industrial chains by creating cross-regional innovation-network coordination. It raises total factor productivity in traditional industries, accelerates both vertical extension and horizontal integration of emerging industrial clusters, and thereby supports the reconstruction of modern industrial systems. In essence, this process reallocates innovation factors and recreates value at the spatial scale of the urban cluster, expressed through the coordinated evolution of the real economy, the diffusion of technological innovation, the enabling role of modern finance, and the upgrading of human resources.

First, the deep integration of central-city technological innovation with the real economy can make traditional industrial systems more innovation-oriented and foster new core industries. Innovation therefore empowers high-quality development of the real economy in non-central cities and consolidates the foundation of a modern industrial system. Second, knowledge spillovers promote the widespread application and deep integration of innovation outcomes throughout the urban cluster. External pools of technological knowledge support emerging technological innovation in other cities, improve the regional innovation ecosystem, and promote innovation, upgrading, and modernization in production. Third, technological change improves information search and matching, reduces information asymmetry, raises the spatial allocation efficiency of financial resources, and promotes modern financial markets with diversified financing channels. Fourth, central-city innovation helps create a radiating network for innovative talent, facilitates cross-regional transmission of tacit knowledge, upgrades production technologies and human-capital structures, and improves the organizational allocation of labor between traditional and modern industries.

Hypothesis 1. Technological innovation in central cities significantly promotes the development of modern industrial systems in non-central cities within the same urban cluster.

2.2 Central-city technological innovation, knowledge spillovers, and modern industrial systems

In knowledge-spillover economics, knowledge spillovers occur when proprietary knowledge assets transcend the ownership boundaries of a region or firm and diffuse through industrial-chain linkages, flows of innovation factors, demonstration effects, and related channels. This enables follower firms to obtain part of the technological innovation rent generated by leaders through non-market mechanisms and promotes spontaneous sharing, recombination, and innovation of knowledge within industrial-chain ecosystems (Branstetter, 2005). In the agglomerated environment of sharing, learning, and matching surrounding central-city innovation, firms and industries in non-central cities can gain more effective access to knowledge, information, and technology generated in central cities, accelerating inter-city diffusion and sharing (Duranton and Puga, 2004).

The agglomeration effects of central-city innovation stimulate regional and industrial coordination through cross-regional transfer of knowledge and technology. Knowledge spillovers raise innovation efficiency, promote industrial upgrading and transformation, and support the development of modern industrial systems in non-central cities. At the same time, agglomeration improves the allocation of high-end production factors such as talent, knowledge, and information, further accelerating spillovers. More intensive information exchange, technological cooperation, and resource sharing facilitate communication and collaboration between upstream and downstream industries and firms, narrow technological gaps, strengthen integration across industrial links, and promote technological interaction across sectors.

Geographical proximity to the technological knowledge pool of a central city is manifested mainly in cross-regional technology transfer and technology cooperation. Technology transfer reflects the distribution of benefits from innovation within the urban cluster and gives non-central cities a latecomer advantage. It directly supplements their local stock of technology at relatively low cost, avoids unnecessary duplication of innovation investment, and expands the boundary of the innovation network. The localization of imported technology facilitates human-capital accumulation and learning by doing, enabling cities to move gradually from imitation toward indigenous innovation (Zhang and Qiao, 2016). Through diffusion, industrial specialization, and value redistribution, cross-regional technology transfer promotes a more graduated and coordinated modern industrial system.

Cross-regional technology cooperation, meanwhile, dynamically recombines innovation factors and redistributes value across the spatial scale of the urban cluster, helping to overcome technological rigidity between cities. As core nodes of knowledge production, central cities use technological alliances, joint R&D, and other cooperative arrangements to establish radial innovation-diffusion gradients. The resulting differences in technological potential

generate a transmission mechanism from central to non-central cities. Following the sequence of 'technology gradient - diffusion pressure - absorptive capacity,' these differences create the motive force for diffusion, improve innovation capabilities in non-central cities, and help them build new comparative advantages. Cooperation further strengthens competitiveness through factor integration, risk sharing, and joint standard setting.

Knowledge spillovers also help internalize external technology through capital accumulation, investment, and learning by doing. The free movement of innovation factors and scientific and technological achievements stimulates the exchange of ideas, information, and experience, allowing heterogeneous production and R&D departments in non-central cities to access new knowledge, technologies, and tools (Caballero and Jaffe, 1993). Spillovers can also reduce excessive concentration of innovation factors in central cities, offset diminishing marginal returns created by spatial boundaries, promote common technological progress, and support endogenous growth (Costa and Iezzi, 2004). Heterogeneous cities can therefore use their comparative advantages to share innovation outcomes, strengthen cross-regional innovation networks, coordinate industrial specialization, and build innovative value chains.

Hypothesis 2. Knowledge spillovers generated by technological innovation in central cities promote inter-city technology transfer and technology cooperation, reduce technological-development imbalances and technological rigidity within urban clusters, and thereby advance the development of modern industrial systems in non-central cities.

3. Research Design

3.1 Econometric model

We construct panel data for matched city pairs within urban clusters and empirically estimate the impact of technological innovation in the central city on modern industrial-system development in non-central cities. The baseline model is:

$$Ind_{jt} = \beta_0 + \beta_1 Inno_{it} + \beta_2 Controls_{ijt} + \mu_{ij} + \varphi_t + \theta_i + \varepsilon_{ijt} \quad (1)$$

where i, j, and t denote the central city, a non-central city in the same urban cluster, and year, respectively. Ind_{jt} denotes the level of modern industrial-system development in non-central city j in year t; $Inno_{it}$ denotes technological innovation in central city i in year t; $Controls_{ijt}$ is the set of control variables; μ_{ij} is a city-pair fixed effect; φ_t is a year fixed effect; θ_i is a province fixed effect for the urban cluster; and ε_{ijt} is the random error term. Standard errors are clustered at the city-pair level. The coefficient of primary interest is β_1, which measures the impact of central-city innovation on modern industrial-system development in non-central cities.

3.2 Variable definitions

3.2.1 Development of modern industrial systems

The theoretical and practical meaning of a modern industrial system lies in coordinated development of the real economy, technological innovation, modern finance, and human resources (Liu, 2017). The real economy is the foundation and carrier of the system; upgrading the industrial base and modernizing industrial chains are central to strengthening competitiveness. Technological innovation provides the fundamental driving force; a better innovation environment, sustained innovation inputs, and high-quality outputs support system construction. Modern finance provides circulatory support by improving the level and quality of financial development and the efficiency of resource allocation. Human resources are a key factor, with talent reserves, training systems, and social security supporting technological innovation and industrial transformation. Following Ye and Zhong (2024), and considering data reliability and availability, we construct a composite indicator system with four primary indicators, ten secondary indicators, and 37 tertiary indicators. Principal component analysis (PCA) is applied after standardization to obtain the Modern Industrial System Development Index (Ind).

3.2.2 Technological innovation

Technological innovation is measured from three dimensions - innovation environment, innovation input, and innovation output - so that the index captures the combined development of conditions, resources, and outcomes. After standardization, PCA is used to obtain the Technological Innovation Index (Inno).

Table 1. Indicator System for Modern Industrial-System Development and Technological Innovation

Primary indicator	Secondary indicator	Tertiary indicator	Measurement
Real economy (Reco)	Upgrading of industrial base	Production capacity	GDP growth rate
Real economy (Reco)	Upgrading of industrial base	Development environment	GDP / local general budget expenditure
Real economy (Reco)	Upgrading of industrial base	Traditional infrastructure	Expressway mileage / resident population
Real economy (Reco)	Upgrading of industrial base	Modern infrastructure	Total telecommunications business / GDP
Real economy (Reco)	Upgrading of industrial base	Structural optimization	(Value added of secondary + tertiary industries) / GDP
Real economy (Reco)	Upgrading of industrial base	Endogenous development capacity	Total fixed-asset investment / GDP
Real economy (Reco)	Upgrading of industrial base	Foreign-trade openness	(Imports + exports of goods) / GDP
Real economy (Reco)	Upgrading of industrial base	Pollution-control capacity	Average of industrial solid-waste utilization, harmless waste treatment, and centralized sewage treatment rates
Real economy (Reco)	Modernization of industrial chains	Informationization level	Employment in information transmission, computer services and software / year-end employment
Real economy (Reco)	Modernization of industrial chains	Agricultural modernization	Primary-industry value added / primary-industry employment
Real economy (Reco)	Modernization of industrial chains	Industrial modernization	Secondary-industry value added / secondary-industry employment
Real economy (Reco)	Modernization of industrial chains	Service-sector modernization	Tertiary-industry value added / tertiary-industry employment
Real economy (Reco)	Modernization of industrial chains	Future-industry level	Stock of artificial-intelligence firms
Technological innovation (Tech)	Innovation environment	Government innovation preference	Science expenditure / local general budget expenditure
Technological innovation (Tech)	Innovation environment	Scale of innovation talent	(Finance employment + scientific/technical services & geological-survey employment) / year-end employment
Technological innovation (Tech)	Innovation environment	Innovative firms	Number of firms in scientific research/technical services + information/software/IT services
Technological innovation (Tech)	Innovation environment	Innovation infrastructure	Total postal business / GDP
Technological innovation (Tech)	Innovation input	R&D personnel input	R&D personnel / year-end employment
Technological innovation (Tech)	Innovation input	R&D expenditure input	Intramural R&D expenditure / GDP
Technological innovation (Tech)	Innovation output	Patent applications	Patent applications / resident population
Technological innovation (Tech)	Innovation output	Patent grants	Patent grants / resident population
Modern finance (Dfina)	Financial development level	Financial scale	Year-end loan balance of financial institutions / GDP
Modern finance (Dfina)	Financial development level	Financial entities	Number of entries into the financial industry
Modern finance (Dfina)	Financial development level	Financial talent	Financial-sector employment / resident population
Modern finance (Dfina)	Financial development quality	Financial efficiency	Year-end loan balance / year-end deposit balance
Modern finance (Dfina)	Financial development quality	Financial competition	1 - HHI (Herfindahl-Hirschman Index of branches)
Modern finance (Dfina)	Financial development quality	FinTech	FinTech development level
Modern finance (Dfina)	Financial development quality	Financial openness	Contracted foreign investment in current year / GDP
Human resources (Popr)	Talent reserves	Higher-education input	Number of regular higher-education institutions
Human resources (Popr)	Talent reserves	Higher-education training	Number of students enrolled in regular higher-education institutions
Human resources (Popr)	Talent reserves	Labor-force level	Year-end employment in organizations

Primary indicator	Secondary indicator	Tertiary indicator	Measurement
Human resources (Popr)	Talent training	Education expenditure input	Education expenditure / local general budget expenditure
Human resources (Popr)	Talent training	Higher-education quality	Full-time university teachers / university students
Human resources (Popr)	Social security	Health care	Hospital and health-center beds / resident population
Human resources (Popr)	Social security	Social security	Basic pension-insurance participants for urban employees / resident population
Human resources (Popr)	Social security	Cultural facilities	Public-library books per 100 residents

3.2.3 Moderating variables

(1) Digital infrastructure (Dige). Digital infrastructure promotes industrial digitalization and the industrialization of digital technologies and thereby supports modern industrial-system development. It is proxied by the frequency of digital-economy-related terms in provincial government work reports.

(2) Judicial protection of intellectual property rights (Kno). Effective judicial protection provides an institutional environment and legal safeguards for innovation. It is measured by the number of completed local intellectual-property judicial cases per capita.

(3) Government innovation preference (Govinno). Local government preference for innovation influences fiscal and industrial-policy priorities. It is measured by the ratio of science and technology expenditure to local general budget revenue.

(4) Fiscal decentralization (Fiscal). Fiscal decentralization affects local public expenditure choices and government competition. It is measured by local general budget expenditure per capita.

3.2.4 Control variables

At the city-pair level, we control for: the economic-development gap (Lgap), measured by the ratio of average nighttime lights in the non-central city to those in the central city; the human-capital gap (Hgap), measured by the ratio of university students per 10,000 residents; the government-intervention gap (Fgap), measured by the ratio of local general budget expenditure as a share of GDP; the government-governance gap (Ggap), measured by the ratio of employment in public administration and social organizations to year-end employment; and the social-consumption gap (Cgap), measured by the ratio of total retail sales of consumer goods to GDP.

3.3 Data sources and sample selection

City-level data are drawn from the China City Statistical Yearbook for 2008-2023. Data on the stock of artificial-intelligence firms and firm entry are obtained from business-registration databases; digital-infrastructure data are compiled from annual government work reports; judicial protection of intellectual property rights is based on the China Judgments Online database accessed through PKULaw; and patent applications and grants are obtained from the Chinese Research Data Services Platform. The study covers seven urban clusters containing nine national central cities: the Pearl River Delta, Yangtze River Delta, Beijing-Tianjin-Hebei, Middle Reaches of the Yangtze River, Chengdu-Chongqing, Guanzhong Plain, and Central Plains urban clusters. These clusters span different regional development gradients and both coastal and inland national strategic layouts. We construct matched panel data linking each central city with non-central cities in the same cluster. For Beijing-Tianjin-Hebei and Chengdu-Chongqing, which each contain two central cities, separate pairings are built for each central city. Because the concept of urban clusters was formally proposed in 2006, the baseline sample covers 2007-2022. Missing values are supplemented by interpolation where appropriate, and all continuous variables are winsorized at the 1% tails.

Table 2. Descriptive Statistics

Variable	Definition	N	Mean	SD	Min	Median	Max
Ind	Modern industrial-system development	2456	-0.009	0.953	-1.253	-0.293	3.725

Variable	Definition	N	Mean	SD	Min	Median	Max
Inno	Technological innovation	2456	-0.009	0.933	-1.179	-0.279	3.741
Dige	Digital infrastructure	2403	8.752	7.874	0	6	36
Kno	IPR judicial protection	2212	0.056	0.067	0.003	0.031	0.371
Govinno	Government innovation preference	2456	0.039	0.026	0.008	0.032	0.142
Fiscal	Fiscal decentralization	2456	0.741	0.413	0.135	0.709	2.165
Lgap	Economic-development gap	2456	0.404	0.354	0.042	0.297	1.862
Hgap	Human-capital gap	2456	0.377	0.430	0.029	0.211	2.559
Fgap	Government-intervention gap	2456	1.131	0.497	0.391	1.059	2.862
Ggap	Government-governance gap	2456	2.019	0.938	0.545	1.823	5.106
Cgap	Social-consumption gap	2456	0.921	0.218	0.476	0.899	1.544

3.4 Stylized facts

Table 3 reports differences in central-city technological innovation and modern industrial-system development in non-central cities across urban clusters. The Pearl River Delta, Yangtze River Delta, and Beijing-Tianjin-Hebei clusters rank clearly above the other clusters on both dimensions. When the sample is classified by development gradient and national strategic layout, clusters in the optimization-and-upgrading stage and those following a coastal development strategy outperform clusters in the development-and-expansion stage and inland-oriented clusters.

Table 3. Differences across Urban Clusters

Urban cluster / category	N	Central-city innovation	Modern industrial-system development in non-central cities
Pearl River Delta	128	1.401	1.529
Yangtze River Delta	592	0.518	0.671
Beijing-Tianjin-Hebei	248	0.281	0.221
Middle Reaches of the Yangtze River	464	-0.295	-0.273
Chengdu-Chongqing	448	-0.387	-0.583
Guanzhong Plain	160	-0.628	-0.752
Central Plains	416	-0.405	-0.386
Optimization-and-upgrading stage	1880	0.131	0.138
Development-and-expansion stage	576	-0.467	-0.488
Coastal strategic layout	968	0.574	0.669
Inland strategic layout	1488	-0.389	-0.449

4. Empirical Results

4.1 Baseline regressions

Table 4 presents the baseline results. Column (1) reports a univariate regression with city-pair, year, and province fixed effects. Columns (2)-(6) sequentially add the economic-development, human-capital, government-intervention, government-governance, and social-consumption gaps. The coefficient on central-city technological innovation is positive and statistically significant at the 1% level in every specification. This indicates that technological innovation in

central cities generates spillovers that promote modern industrial-system development in non-central cities. The conclusion remains robust after accounting for other potential influences, supporting Hypothesis 1.

Table 4. Baseline Regression Results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Inno	0.025*** (0.008)	0.026*** (0.008)	0.026*** (0.008)	0.025*** (0.008)	0.025*** (0.007)	0.025*** (0.007)
Lgap		0.157 (0.181)	0.157 (0.181)	0.200 (0.185)	0.228 (0.181)	0.215 (0.179)
Hgap			0.031 (0.052)	0.034 (0.052)	0.040 (0.050)	0.041 (0.051)
Fgap				-0.122*** (0.044)	-0.117*** (0.044)	-0.118*** (0.044)
Ggap					0.053*** (0.013)	0.055*** (0.013)
Cgap						-0.059 (0.096)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City-pair FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2456	2456	2456	2456	2456	2456
R^2	0.949	0.949	0.949	0.949	0.950	0.950

*Notes: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors clustered at the city-pair level are in parentheses. Unless otherwise stated, subsequent regressions include control variables and year, city-pair, and province fixed effects.*

4.2 Endogeneity

4.2.1 Instrumental-variable estimation

Unobserved factors and reverse causality may still affect the results. Following Bai and Zhang (2021), we use terrain flatness as an instrument for technological innovation. Topography is exogenous to the economic system. In terms of relevance, flatter terrain directly affects the layout of urban transport networks and thereby the agglomeration of innovation factors and industrial activity within central cities, which in turn influences technological innovation. In terms of exogeneity, terrain flatness is an inherent geographical characteristic that changes little over short periods and is unlikely to directly determine the development of modern industrial systems in non-central cities. The inclusion of city-pair, year, and province fixed effects and the city-pair controls also absorbs historical characteristics, urban location, and features of the contemporary economic environment.

Because terrain flatness is cross-sectional, following Duflo and Pande (2007) we interact terrain flatness - measured as the inverse of terrain relief - with a time variable and use the interaction as an instrument for central-city technological innovation in the fixed-effects panel model. Table 5 shows that the instrument is significantly positive in the first stage, while the coefficient on the core explanatory variable is significantly positive in the second stage. The first-stage F statistic exceeds conventional thresholds. The Kleibergen-Paap rk LM statistic rejects under-identification at the 1% level, confirming instrument relevance. To further assess exogeneity, following Yang et al. (2025) we examine whether time-invariant terrain flatness in the central city affects the average level of modern industrial-system development in non-central cities over the sample period. Column (3) shows no significant effect, supporting the exogeneity assumption. The baseline conclusion therefore remains robust after IV estimation.

Table 5. Instrumental-Variable Estimation

Variable	Central-city innovation: first stage	Modern industrial system: second stage	Exogeneity test
IV	0.018*** (0.004)		

Variable	Central-city innovation: first stage	Modern industrial system: second stage	Exogeneity test
Inno		0.808*** (0.243)	-0.034 (0.125)
First-stage F	23.763		
Under-identification test	15.240 <p=0.000>		
Weak-IV test	18.025 [16.380]		
Observations	2456	2456	154

Notes: The under-identification test uses the Kleibergen-Paap rk LM statistic; angle brackets report its p-value. The weak-IV test uses the Kleibergen-Paap rk Wald F statistic; square brackets show the Stock-Yogo weak-ID critical value at the 10% level.

4.2.2 Double machine learning

We further apply the double machine learning (DML) approach of Bodory et al. (2022) for causal inference. Relative to conventional methods, DML is advantageous in variable selection and model specification. Machine-learning algorithms and regularization automatically select an optimal subset from a high-dimensional pool of controls, improving estimation accuracy, while flexible screening helps control potential confounders affecting modern industrial-system development. DML also mitigates the 'curse of dimensionality' caused by redundant controls and reduces omitted-variable bias. Table 6 reports the results. Columns (1)-(3) use LASSO for prediction with a 1:4 sample split and sequentially include first-, second-, and third-order terms of the control variables. The estimated coefficient on Inno remains positive and significant at the 1% level. Replacing LASSO with gradient boosting in columns (4)-(6) produces the same conclusion. Thus, the findings remain robust after addressing endogeneity with DML.

Table 6. Double Machine Learning Causal Inference

Variable	LASSO (1)	LASSO (2)	LASSO (3)	Gradient Boosting (4)	Gradient Boosting (5)	Gradient Boosting (6)
Inno	0.028*** (0.007)	0.027*** (0.007)	0.027*** (0.007)	0.028*** (0.008)	0.051*** (0.012)	0.154*** (0.016)
First-order controls	Yes	Yes	Yes	Yes	Yes	Yes
Second-order controls	No	Yes	Yes	No	Yes	Yes
Third-order controls	No	No	Yes	No	No	Yes
Observations	2456	2456	2456	2456	2456	2456

Robust standard errors are shown in parentheses.

4.3 Robustness checks

To strengthen the reliability of the baseline findings, we conduct robustness checks by lagging the core explanatory variable by one period, allowing for city-specific time trends, changing the sample regression window, replacing the measurement of the core variables, and excluding the influence of contemporaneous policies. The main conclusions remain unchanged across these tests. Detailed results are retained by the authors and are available upon request.

4.4 Heterogeneity analysis

Because urban clusters differ in resource endowments, regional development gradients, and national strategic positioning, the knowledge-spillover effect of central-city technological innovation may be heterogeneous. We therefore conduct subsample analyses by development stage and strategic layout.

4.4.1 Heterogeneity by development gradient

Urban clusters are divided into an optimization-and-upgrading stage and a development-and-expansion stage. As shown in columns (1) and (2) of Table 7, technological innovation in central cities significantly promotes modern industrial-system development in non-central cities within clusters at the optimization-and-upgrading stage, but the effect is not statistically significant in the development-and-expansion stage. One possible explanation is that the former group contains stronger central-city innovation capacity and more sub-central cities - such as provincial capitals and sub-provincial cities - with favorable resource endowments and relatively strong innovation capabilities. This enhances

the spillover function of the central-city innovation growth pole. By contrast, central cities in the development-and-expansion stage have weaker innovation capacity and have not yet fully realized their potential as innovation growth poles. The positive estimated coefficient nevertheless suggests that their growth-pole function is strengthening, highlighting the importance of building spatial governance systems around core innovation poles.

4.4.2 Heterogeneity by national strategic layout

We further divide urban clusters into coastal and inland strategic layouts. Columns (3) and (4) of Table 7 show that central-city technological innovation significantly promotes modern industrial-system development in non-central cities of inland clusters, while the effect is not significant in coastal clusters. Coastal clusters benefited earlier from national opening-up policies, favorable geography, and comparative advantages in resource endowments, and their modern industrial systems have already reached a relatively mature stage. By contrast, policy targeting and the strategic shift toward inland regions have improved digital foundations and institutional conditions there, strengthened the radiating effect of central-city innovation growth poles, and promoted both modern industrial systems and coordinated regional development. This result illustrates the important role of a proactive government in coordinating regional development.

Table 7. Heterogeneity Analysis

Variable	Optimization & upgrading	Development & expansion	Coastal	Inland
Inno	0.023*** (0.008)	0.017 (0.013)	0.011 (0.008)	0.023** (0.010)
Observations	1880	576	968	1488
R^2	0.954	0.839	0.946	0.907

5. Further Analysis

5.1 Mechanism tests

The preceding results show that central-city technological innovation produces spillover effects that promote modern industrial-system development in non-central cities. To identify the channels, we construct the following mechanism model based on equation (1) and apply a two-step mediation approach:

$$Me_{jt} = \gamma_0 + \gamma_1 Inno_{it} + \gamma_2 Controls_{ijt} + \mu_{ij} + \varphi_t + \theta_i + \varepsilon_{ijt} \quad (2)$$

Me_{jt} denotes the mechanism variable, and γ_1 measures the effect of central-city technological innovation on that mechanism. All other variables are defined as in the baseline model.

The theoretical analysis predicts that central-city innovation generates knowledge spillovers through technology transfer, reducing technological-development imbalances and supporting modern industrial-system development in non-central cities. We measure this channel using the number of patent transfers from the central city to the non-central city, normalized by population. Column (1) of Table 8 shows that central-city innovation significantly increases inter-city technology transfer within the urban cluster.

Central-city innovation may also catalyze technology-cooperation networks. Knowledge sharing and complementarity within such cooperation accelerate the efficient flow of knowledge, ease technological rigidity in non-central cities, and provide sustained momentum for industrial modernization. Using the number of jointly developed patents between central and non-central cities, normalized by city population, we find a significant positive effect in column (2). Together, the two mechanism tests support Hypothesis 2.

We then decompose the modern industrial system into the real economy, technological innovation, modern finance, and human resources. Columns (3)-(6) show that central-city innovation significantly promotes the real economy, technological innovation, and human-resource development in non-central cities, with the largest effect on technological innovation, while the effect on modern finance is not statistically significant. These results provide further evidence for the knowledge-spillover mechanism. The strong effect on the real economy also highlights the importance of deep integration between technological and industrial innovation.

Table 8. Mechanism Tests

Variable	Technology transfer	Technology cooperation	Real economy	Technological innovation	Modern finance	Human resources
Inno	0.010*** (0.004)	0.012** (0.006)	0.020*** (0.007)	0.040*** (0.014)	0.009 (0.007)	0.013** (0.006)
Observations	2456	2456	2456	2456	2456	2456
R^2	0.558	0.529	0.956	0.877	0.906	0.899

5.2 Moderating effects

5.2.1 Digital infrastructure

Under China's digital-power strategy, local governments have introduced measures to improve digital infrastructure, expand data-resource supply, and promote both industrial digitalization and digital industrialization. Stronger digital infrastructure supports modern industrial-system development, creates better conditions for the transfer and cooperation of innovation activities, and improves the efficiency of information search and matching. We therefore interact digital infrastructure with central-city innovation (Inno × Dige) and add the interaction to equation (1). Column (1) of Table 9 shows a significantly positive interaction coefficient. This indicates that digital-infrastructure development strengthens the positive effect of central-city technological innovation on modern industrial-system development in non-central cities and reveals an important role for the digital economy in integrating technological and industrial innovation.

5.2.2 Judicial protection of intellectual property rights

A sound judicial system for intellectual-property protection provides an institutional environment and legal safeguards for innovation and the construction of modern industrial systems. In the era of big data, data elements can empower industrial modernization, but uncertain data-property rights may undermine the market order for data transactions. Stronger judicial protection helps clarify the ownership of data rights and the boundaries of circulation and transactions, while also encouraging the creation, application, and protection of technological achievements. We interact IPR judicial protection with central-city innovation (Inno × Kno). Column (2) of Table 9 reports a significantly positive coefficient, showing that stronger judicial protection reinforces the spillover effect of central-city innovation and facilitates the deep integration of technological and industrial innovation.

5.2.3 Government innovation preference

Within an institutional arrangement combining a proactive government with an effective market, government support for innovation is important for modern industrial-system development. Fiscal policies involving local projects, financial support, and subsidies for innovative talent can stimulate firm innovation. Government innovation preference reflects attention to the institutional mechanisms, hard and soft environments, and financial support needed to protect innovation. Because both technology transfer and technology cooperation depend on such institutions and on support for funding and talent, we interact government innovation preference with central-city innovation (Inno × Govinno). Column (3) of Table 9 shows a significantly positive coefficient, indicating that stronger government preference for innovation amplifies the role of central-city technological innovation in non-central cities.

5.2.4 Fiscal decentralization

Within China's central-local fiscal arrangements, greater fiscal decentralization can improve the efficiency of local public expenditure, increase flexibility in allocating fiscal resources, and provide public goods more effectively for modern industrial-system development. Greater fiscal autonomy may also stimulate local innovation incentives and entrepreneurship and strengthen responsibility for expenditure decisions. It allows local governments to make better use of information advantages and regional governance capacity and to design fiscal policies adapted to local conditions, increasing the precision and efficiency with which fiscal expenditure supports industrial modernization (Li and Yang, 2018). We interact fiscal decentralization with central-city innovation (Inno × Fiscal). Column (4) of Table 9 shows a significantly positive coefficient, indicating that fiscal decentralization further strengthens the positive effect of central-city innovation.

Table 9. Moderating-Effect Analysis

Variable	(1) Digital infrastructure	(2) IPR protection	(3) Gov. innovation preference	(4) Fiscal decentralization

Variable	(1) Digital infrastructure	(2) IPR protection	(3) Gov. innovation preference	(4) Fiscal decentralization
Inno	-0.034*** (0.011)	0.005 (0.008)	-0.020 (0.013)	-0.052*** (0.015)
Inno × Dige	0.005*** (0.001)			
Dige	0.004** (0.002)			
Inno × Kno		0.215* (0.120)		
Kno		-1.254*** (0.435)		
Inno × Govinno			1.022*** (0.339)	
Govinno			1.902*** (0.700)	
Inno × Fiscal				0.088*** (0.020)
Fiscal				0.331*** (0.114)
Observations	2403	2212	2456	2456
R^2	0.953	0.952	0.952	0.954

5.3 Extended analysis: economic consequences for common prosperity

A further question is whether the modern industrial-system development induced by central-city technological innovation, and the resulting deep integration of technological and industrial innovation, contributes to common prosperity. Following Chen et al. (2021), we construct a common-prosperity indicator system with 25 secondary indicators under the primary dimensions of development, sharing, and sustainability, and use PCA after standardization to obtain a composite index for non-central cities. We then add the interaction Inno × Ind to the baseline model. The estimated interaction coefficient is significantly positive, indicating that as technological innovation in central cities rises, the positive contribution of modern industrial-system development to common prosperity in non-central cities becomes stronger. In other words, deeper integration of technological and industrial innovation helps advance common prosperity. The complete indicator system and regressions are retained by the authors because of space limitations.

6. Conclusions and Policy Implications

Against the backdrop of accelerated global industrial-chain restructuring and a reshaping of competitive patterns, deep integration between technological innovation and industrial innovation is not only a strategic choice for gaining an advantage in global scientific and technological competition and capturing opportunities from future industrial change; it is also a key path toward cultivating new growth poles and raising total factor productivity. The spatial organization of economic activity is an important determinant of technological innovation. Promoting innovation in central cities and developing modern industrial systems within urban clusters can therefore strengthen industrial-chain resilience and support the new development pattern.

Using matched city-pair data for urban clusters from 2007 to 2022, this study examines how technological innovation in central cities affects modern industrial-system development in non-central cities. The results show that innovation-generated knowledge spillovers promote inter-city technology transfer and technological cooperation, alleviate technological rigidity, reduce imbalances in technological development, and thereby advance modern industrial-system development in non-central cities. The effect is stronger for clusters at the optimization-and-upgrading stage and for those in inland-oriented national strategic layouts. Better digital infrastructure, stronger judicial protection of intellectual property, stronger government innovation preferences, and greater fiscal decentralization further reinforce the role of central-city innovation growth poles. Extended analysis also indicates that the resulting development of modern industrial systems contributes to common prosperity.

First, policy should build an integrated innovation-space governance system combining ‘core innovation poles - network channels - field ecosystems’ to optimize the topology and raise the capacity of innovation factors within urban clusters. Central-city innovation should be connected to a gradient transmission mechanism linking growth poles,

diffusion axes, and hinterlands. Top-level institutional design should strengthen central-city nodes and market integration while creating coordinated innovation networks and better allocation of innovation factors. Differentiated development plans should be tailored to the characteristics of individual urban clusters, with greater emphasis on coordination among clusters.

Second, policy should strengthen digital transformation and judicial protection of intellectual property in the deep integration of technological and industrial innovation. Digital-technology innovation should support cross-regional industrial digitalization and the digital transformation of industrial chains. A judicial protection system matched to the innovation system should clarify concepts, property-right attributes, and protection rules for emerging innovation, especially data elements, and establish a city-cluster-specific framework for protecting technological innovation.

Third, the proactive government should play a stronger role in coordinating innovation resources and organizing collective action while allowing the market to remain central in resource allocation. Within the unified framework of central-local administrative reform, governments should improve incentive mechanisms for local strategic decisions on technological and industrial innovation, deepen fiscal-decentralization reform in the high-quality integration of urban clusters, grant appropriate fiscal autonomy to local governments, and at the same time strengthen constraints on investment preferences and accountability.

Fourth, a pathway should be constructed through which the deep integration of technological and industrial innovation advances common prosperity. Technological innovation should raise total factor productivity and reduce marginal costs, thereby promoting economic and social development and material well-being. Industrial innovation should upgrade employment structures and create a digitally enabled inclusive innovation ecosystem that expands opportunities and inclusive growth. The integration of technological and industrial innovation should penetrate major livelihood sectors such as health care, elderly care, and employment. Long-term mechanisms are needed to ensure that innovation addresses social needs, improves welfare, serves relatively poor and low-income groups, and supports shared development.

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