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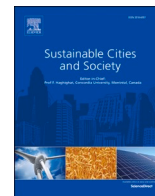
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Digital infrastructure construction and urban industrial chain resilience: Evidence from the “Broadband China” strategy

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ABSTRACT

Effective governance of industrial chain resilience (ICR) is crucial for urban sustainability, and the development of digital infrastructure provides actionable pathways to achieve this goal. However, limited attention has been paid to the influence of digitalization efforts on ICR. Utilizing panel data from 271 Chinese cities spanning 2009 to 2021, this study adopts the “Broadband China” strategy as a proxy and employs a staggered Difference-in-Differences model combined with machine learning algorithms to evaluate the impacts of digital infrastructure construction (DIC) on urban ICR. The results show that: (1) DIC significantly drives urban ICR. This conclusion shows strong reliability, as it is confirmed by extensive robustness checks. (2) Heterogeneity analysis indicates stronger effects of DIC on eastern cities, non-resource-based cities, and cities with high industrial agglomeration. The positive impact exhibits sustained growth in the eastern region yet gradual attenuation in the central region. (3) Mechanism analysis reveals that DIC improves ICR by bridging the digital divide, fostering digital human capital and elevating innovation quality. These findings provide critical insights for formulating policies to strengthen digital infrastructure development and enhance urban ICR.

1. Introduction

Uncertain events can lead to unpredictable disruptions and damage to both ecological and social systems. “Resilience” describes the ability of a system to return to its original state after being disturbed, a concept that originated in physics and was later applied in the industrial economy (Martin, 2012). In the digital era, the deep integration of the industrial chains has become inevitable. Various factors, including global industrial dynamics, natural disasters, geopolitical tensions, trade disputes, and major public health emergencies, can pose threats to the stability of industrial chains (Das et al., 2022; Shen & Sun, 2023). Industrial chain resilience (ICR) refers to the capacity to recover and reconstruct from potential sudden risks (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009; Yang & Liu, 2024; Zhao et al., 2024). Specifically, when encountering internal and external shocks, the industrial chain can swiftly mitigate disruptions and adaptively adjust to new conditions, ultimately restoring operational equilibrium (Yan, 2025). Maintaining the stability of the industrial chain is fundamental to the high-quality development of national industries, as well as a critical

safeguard for the stable functioning of the real economy and long-term economic growth. The United Nations’ Sustainable Development Goal (SDG) 11 highlights the importance of inclusiveness, safety, and resilience in creating sustainable cities, offering guidance for strengthening urban ICR. In the context of globalization and the increasing interdependence of regional economies, ICR has emerged as a strategic pillar of national competitiveness.

Digital infrastructure serves as a critical conduit for the dissemination of economic and social information, underpinning the transformation of conventional industries towards informatization, digitization, and intelligentization (Gong et al., 2023; Yi et al., 2024). The deep integration of digital technology with the industrial chains accelerates the digital transformation of industries, improves the transparency of production processes, optimizes resource allocation, and drives changes within industrial chains (Ivanov et al., 2021; Srinivasan & Swink, 2018). SDG 9 advocates for the construction of resilient infrastructure, the promotion of inclusive and sustainable industries, and the fostering of innovation. Digital infrastructure construction (DIC) serves as a fundamental pillar for developing digital technology and

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advancing digital economy. The broadband network acts as an essential public infrastructure, strategically contributing to China's economic and social progress while playing a vital role in the digital infrastructure landscape. In August 2013, China launched the "Broadband China" strategy (BCS) to accelerate the deployment of digital infrastructure, expand broadband coverage, improve the digital industry ecosystem (Hong et al., 2023), and speed up the adoption of cutting-edge technologies (Kangmin et al., 2023). As digital infrastructure continues to expand, it is imperative to explore the impact of DIC on ICR and to identify effective strategies for achieving sustainable social development.

Current research evaluating DIC in China focuses on economic progress, green development, and social welfare. Regarding economic progress, digital infrastructure is crucial for promoting the digital upgrading of industries and fostering new business models. DIC enhances adaptability, resilience to risks, and transformation within the industrial chain (Yang & Liu, 2024). It also supports both radical and incremental innovation in enterprises (Liu & Ju, 2023) and facilitates breakthroughs in core technologies (Yuan & Chao, 2024). Additionally, DIC can mitigate improper resource allocation in enterprises by lowering information costs and eliminating market barriers (Jin et al., 2024), and facilitate the unimpeded inter-regional flow of capital (Liu et al., 2024a). DIC is injecting momentum into cities' green transformation (Qin et al., 2024). Specifically, DIC can improve carbon emission efficiency (Yu & Hu, 2024) and support low-carbon development (Ding et al., 2024) by upgrading its industrial structure and increasing investment in cutting-edge technologies. As a new form of digital infrastructure, smart facilities can produce positive externalities and effectively reduce environmental pollution (Yi et al., 2024). Furthermore, DIC can improve the environmental performance of enterprises by encouraging them to lower pollution emissions through enhanced oversight, technological innovation, and optimized management practices (He et al., 2024). However, due to capital concentration and the incentive to consume fossil fuels, DIC may lead to increased carbon emissions (Che et al., 2024). In terms of social welfare, DIC can affect household consumption behavior by developing the consumer internet (Zhang et al., 2024a). DIC can also improve the use of medical services, enhance human health, and promote health equity (Liu et al., 2024b). In addition, DIC can reduce urban-rural income inequality (Li et al., 2024), and foster regional inclusive growth (Song et al., 2024).

Extensive studies have examined DIC from various perspectives; however, there remains a gap in research assessing its impact from the resilience perspective. As emphasized by Ma and Zhang (2024), integrating resilience into sustainable development frameworks is critical for urban development. The escalating frequency of global uncertainties highlights the growing need for stress resistance in industrial chains. Therefore, it is imperative to intensify the discourse on ICR within the context of digital infrastructure development to identify practical strategies for enhancing industrial stability and promoting resilient urban economic growth.

This paper treats the BCS as a quasi-natural experiment and aims to evaluate the impact of DIC on ICR using a staggered DID approach integrated with machine learning techniques. The study's main contributions lie in three critical aspects. First, this paper expands the research field of DIC. Unlike previous studies that primarily focused on digital industrialization (Yang & Liu, 2024), enterprise digital transformation (Sun et al., 2025), and public data openness (Yan, 2025), our study focuses on digital infrastructure. This study simultaneously addresses a research gap since existing studies on DIC primarily emphasize economic resilience (Ma & Zhang, 2024). In addition, from the perspective of the policy of DIC, existing research has largely focused on the impact of the BCS on innovation (Liu & Ju, 2023), low-carbon growth (Qin et al., 2024; Yu & Hu, 2024), and social development (Li et al., 2024; Liu et al., 2024b), yet has scarcely explored its role in enhancing resilience. Second, this paper investigates how DIC enhances ICR, aiming to unpack the theoretical "black box" underlying this relationship. Existing studies

have focused on DIC's transmission mechanisms via industrial structure and government governance (Ding et al., 2024; He et al., 2025; Yan, 2025). This paper explores the mechanisms of DIC's impact by considering the digital divide, digital human capital, and innovation quality. Third, this paper conducts an in-depth heterogeneity analysis across multiple dimensions, including urban location, resource endowment, and industrial agglomeration levels. Notably, it further examines both the short-term and long-term effects of urban location through a dynamic analysis framework. These insights offer crucial theoretical and empirical benchmarks with a policy foundation to enhance ICR, supporting SDGs 9 and 11 achievements via DIC-driven strategies. The research framework is illustrated in Fig. 1.

2. Policy context and theoretical hypothesis

2.1. Policy context

Broadband networks function as the principal conduit for the dissemination of economic and social information. The BCS acts as a key cornerstone in building a digital China and establishing the country as a leading networked nation. In 2013, the Chinese government promulgated the Broadband China Strategy and Implementation Plan and subsequently approved batches of 120 pilot cities (city clusters) in the years 2014, 2015, and 2016. According to the 2023 China Broadband Development White Paper, as of September 2023, over 140 million households have gigabit broadband access. The total length of optical cable has reached 63.097 million kilometers, and a total of 1.08 billion Fiber-to-the-Home ports have been established and activated. The 53rd Statistical Report on Internet Development in China, released by the China Internet Network Information Center, indicates that as of December 2023, there are 1.092 billion internet users in China, with an internet penetration rate of 77.5%.

The BCS aims to create a nationwide high-speed broadband network to expand coverage, enhance access capabilities, promote information technology use, strengthen network security, and improve the industry chain networks. By facilitating the simultaneous integration of major affiliated institutions and enterprises in the industry chain into high-speed networks, the BCS reinforces the convergence between networks and traditional industries. This integration enhances the transmission and flow of information and knowledge among cities and supports the development of new industries (Jin et al., 2024).

2.2. Theoretical hypothesis

2.2.1. Digital infrastructure construction and ICR

Digital infrastructure is the foundation for the digital transformation of cities and businesses. Digital transformation can restructure existing industrial chains, making them more secure, stable, and efficient (Huang

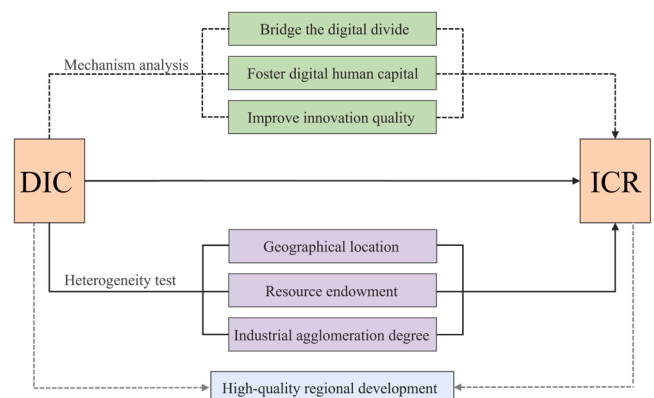


Fig. 1. Research framework.

& Tsai, 2022). First, digital infrastructure induces transformations in corporate assets (Kyllingstad et al., 2021) and speeds up information exchange and technological spillovers across regions (Zhao et al., 2022). Second, DIC can drive the transformation of traditional industries, accelerate industrial digitization, promote factor flow, and enhance technological efficiency (Ahn, 2020) and resource allocation efficiency (Hu et al., 2023). As digital infrastructure expands and digital industrialization progresses, it supports the upgrading of industrial structures and improves crisis management efficiency (He et al., 2024). Thus, Hypothesis 1 is proposed:

H1: DIC can significantly promote urban ICR.

2.2.2. Digital infrastructure construction, digital divide, and ICR

The COVID-19 crisis has highlighted the critical importance of broadband access, intensifying the urgency of bridging the digital divide. The digital divide is increasingly recognized as a determining factor for digital competencies (Aydin, 2021). It is pervasive across regions (Wang et al., 2021), leading to disparities in access to information and communication technologies. Bridging this divide depends on the provision of digital infrastructure.

Narrowing the digital divide lessens the digital technology gap between regions and diminishes the effects of information asymmetry on the industrial chain. First, digital technology can accelerate the integration of regional production factors, stimulate entrepreneurial activities within urban areas, transform economic development models (Zhao & Weng, 2024), and increase inclusivity in economic endeavors. Second, the mitigation of information asymmetry enables enterprises to make precise forecasts, which influence upstream and downstream companies to adjust inventory management, production plans, and supply chain strategies. Third, the Industrial Internet facilitates information sharing, enables real-time monitoring, and supports intelligent decision-making (Zhang et al., 2024b). Fourth, establishing digital infrastructure strengthens the integration of the Internet with sectors such as healthcare, logistics, and education (Zhang et al., 2024a), thus accelerating industrial convergence and reducing industry divide. Accordingly, Hypothesis 2 is proposed:

H2: DIC promotes urban ICR by bridging the digital divide.

2.2.3. Digital infrastructure construction, digital human capital, and ICR

Human capital is a key factor in the efficient functioning of organizations and plays a decisive role in strategic management and maintaining competitive advantage within organizations (Czarniewski, 2014). As a channel for information and knowledge capital, Internet infrastructure overcomes spatial and temporal constraints in information transmission, promoting knowledge accumulation and innovation convergence (Tang et al., 2021), and accelerating digital human capital accumulation.

Digital infrastructure alone cannot drive innovation; it requires the support of human capital (Osei, 2024). First, the digitization of human resource management involves integrating digital technologies into human resource practices (Veenendaal & Bondarouk, 2015). Technological advancements, such as recruitment software and automated management tools, have improved the efficiency and decision-making processes in human resources (Pea-Assounga & Sibassaha, 2024). Second, due to the heavy reliance of modern enterprises on digital infrastructure and technology, there is a risk of operational value chain collapse in the event of software or system failures (Gao et al., 2022). Consequently, the role of digital technology professionals in repairing and upgrading software and platforms is indispensable. Third, according to the theory of endogenous growth (Romer, 1994), digital human capital equips the workforce with advanced technical skills and innovative abilities. These competencies boost productivity and foster innovation, enabling enterprises to adapt more rapidly to new technologies and market environments. Fourth, digital human capital promotes knowledge flow and spillovers, fosters industrial chain integration, and enables the efficient allocation of resources, thereby strengthening the

ability to withstand external shocks (Zhou & Qi, 2023). Considering the analysis above, Hypothesis 3 is proposed:

H3: DIC promotes urban ICR by promoting digital human capital aggregation.

2.2.4. Digital infrastructure construction, innovation quality, and ICR

Digital infrastructure enables cross-field and cross-regional innovation cooperation. Digital collaboration methods enhance both the diversity and depth of innovation. Digitization extends the boundaries of innovation possibilities, empowering companies to achieve economies of scale and allocate surplus capital towards cutting-edge innovation with high technological content and substantial research and development expenditures (Cong et al., 2021). Additionally, digital transformation can address challenges in enterprise innovation by improving access to information and speeding up knowledge flow, which enhances the quality of innovation (Yu et al., 2019; Zhuo & Chen, 2023).

Technological innovation can accelerate knowledge integration, enhance organizational efficiency, fortify and optimize the stability of the industrial chain (Yang & Liu, 2024). The innovation quality, unlike the innovation quantity that measures technological innovation performance, signifies the actual technological impact and economic value, reflecting the effectiveness and competitiveness of innovation (Higham et al., 2021; Lanjouw & Schankeman, 2004; Zhao et al., 2023). Furthermore, the theories of innovation promotion and open innovation suggest that digital infrastructure allows enterprises to effectively integrate and utilize external and internal knowledge resources during the innovation process, thereby improving innovation quality. Ongoing cutting-edge innovation and technological advancements by upstream and downstream enterprises can enhance the resilience of the supply chain (Wei et al., 2024). Given the analysis presented above, Hypothesis 4 is proposed:

H4: DIC promotes urban ICR by elevating innovation quality.

3. Model and variables

3.1. Model

Following Xiao et al. (2024), this study constructs a staggered DID model incorporating the phased rollout and gradual implementation characteristics of the BCS program, specified as follows:

$$ICR_{it} = \alpha + \beta_1 did_{it} + \beta_2 Control_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (1)$$

where ICR_{it} denotes the urban ICR level; did_{it} is a dummy variable representing the core explanatory variable, indicating whether city i was selected as a BCS pilot city in year t ; $Control_{it}$ represents a series of control variables; β_1 serves as the DID estimator, quantifying the impact of the BCS on ICR; α is the constant term; μ_i describes the fixed effect of city; η_t represents the annual fixed effect that accounts for the time trend; ε_{it} is the random disturbance term.

3.2. Variables and data

3.2.1. Dependent variable

Considering the availability and scientific rigor of data from prefecture-level cities, and drawing on the work of Li and Rong (2022), this study employs the entropy evaluation method (Yi et al., 2024) to assess ICR through the lenses of adaptive resistance and transformative adaptability. Adaptive resistance emphasizes the industrial chain's capacity to endure disruptions and maintain its existing production structure and functions (Li & Rong, 2022). Transformative adaptability highlights the industrial chain's proactive ability to adjust to evolving circumstances and optimize dynamic resource allocation, with the goal of achieving sustainable development and competitive growth (Chen et al., 2025). Transformative adaptability is measured by the annual patent application volume of each prefecture-level city, while adaptive

resistance is represented by the Industrial Diversity Index (*Indiv*). The estimation model of *Indiv* is as follows:

$$Indiv_{it} = 1 / HHI = 1 / \sum S_i^2 \tag{2}$$

where HHI denotes the Herfindahl-Hirschman Index, and a smaller HHI value indicates a higher level of industrial diversification; S_i represents the proportion of the output value of the i industry in the gross regional product.

3.2.2. Independent variable

This paper utilizes the BCS as a proxy for DIC development. The core independent variable (*did*) represents whether city i was selected as a BCS pilot city in year t . The BCS was unveiled in August 2013, with lists of pilot cities disclosed in successive batches in 2014, 2015, and 2016. Considering the delayed effects of policy influence, 2014 is designated as the initial impact year. If city i is designated as a pilot city in year t , it is assigned a value of 1; otherwise, it is assigned a value of 0.

3.2.3. Control variables

Based on relevant studies (Kangmin et al., 2023; Liao & Liu, 2024; Muhammad & Hoffmann, 2024; Wan et al., 2024; Yi et al., 2024), this study includes the following control variables: Economic development level (GDP) is assessed through the logarithm of the per capita GDP. Regional financial size (Fsize) is measured by the ratio of institutional deposits and loan balances to GDP. Residential consumption level (Consump) is measured by the ratio of the total retail sales of consumer goods to the GDP. Population density (Pop) is measured by the logarithm of population density. The degree of government intervention (Gov) is expressed as the ratio of the local government’s general budget expenditures to GDP. The degree of foreign trade dependence (Dep) is denoted by the city’s total annual imports and exports of goods as a percentage of GDP. Urbanization level (Urb) is calculated by taking the urban resident population as a percentage of the total resident population at the year-end. Education level (Edu) is represented by the ratio of the education expenditure to total government expenditure. The logarithm of paved road area per capita and the logarithm of public library stock pertain to transport infrastructure (Rode) and urban innovation atmosphere (Culture), respectively.

3.2.4. Data specification

Given the implementation timeline of the BCS policies and data availability, we utilize data from 271 prefecture-level cities in China, covering the period from 2009 to 2021. The data is sourced from the China City Statistical Yearbook, the CNRDS database, the China Urban Construction Statistical Yearbook, and statistical yearbooks of provinces and prefecture-level cities. Missing data were filled through mean imputation and linear interpolation. Table 1 presents the statistical descriptions of variables.

Table 1
Descriptive statistics of variables.

Symbol	Obs	Mean	Std. Dev.	Min	Max
<i>ICR</i>	3523	0.035	0.073	0.001	0.992
<i>did</i>	3523	0.211	0.408	0	1
<i>Dep</i>	3523	0.187	0.299	0.000	2.491
<i>Urb</i>	3523	0.560	0.153	0.185	1
<i>Rode</i>	3523	2.771	0.433	0.438	4.096
<i>Culture</i>	3523	7.374	1.044	4.159	12.100
<i>Pop</i>	3523	5.745	0.937	1.603	7.882
<i>GDP</i>	3523	10.671	0.627	4.595	13.056
<i>Fsize</i>	3523	2.450	1.210	0.588	21.302
<i>Consump</i>	3523	0.377	0.108	0.026	1.013
<i>Edu</i>	3523	0.177	0.040	0.010	0.356
<i>Gov</i>	3523	0.195	0.105	0.043	1.485

4. Result analysis

4.1. Baseline regression

Table 2 summarizes the regression results, offering empirical estimates of the impact of the BCS on ICR. To address the potential serial correlation and heteroskedasticity, robust standard errors are employed, clustered at the city level. After accounting for time and city fixed effects and including control variables, the coefficients of *did* changed in magnitude, but their positive effects on ICR remain significant. The benchmark regression results indicate that DIC significantly enhances ICR. Hypothesis 1 is supported. This underscores the vital role of digital infrastructure in enhancing the agility and responsiveness of the industrial chain network. Digital infrastructure boosts information dissemination and resource sharing efficiency through network effects. Additionally, it reduces the costs associated with information retrieval, communication, and transactions, leading to greater market transparency and efficiency.

4.2. Parallel trend test

A satisfactory parallel trend test indicates that the treatment group and the control group did not exhibit significant differences in ICR before being designated as the BCS pilot cities. This is crucial for ensuring the reliability of the DID estimation results. Following Beck et al. (2010), a series of dummy variables were incorporated into the benchmark model to verify the parallel trends, as shown in Eq. (3):

$$ICR_{it} = \alpha + \sum_{k \geq -5} \theta_k D_{it}^k + \beta_2 Control_{it} + \mu_i + \eta_t + \varepsilon_{it} \tag{3}$$

where D_{it}^k represents the BCS pilot city; the variable k denotes the effects of the BCS in the preceding k periods ($-k$) and the subsequent k periods ($+k$). In this study, the BCS shock is established in the year 2014. Data was collected for the 5 years ($k_{min} = -5$) preceding the policy shock and the subsequent 7 years ($k_{max} = +7$), with the 1st year preceding the policy shock ($k = -1$) designated as the baseline period. As depicted in Fig. 2, the 95% confidence intervals of coefficients for all pre-pilot policy periods include zero, indicating the treatment and control groups had similar trends in ICR before the BCS impact, thereby meeting the parallel trends prerequisite.

Traditional parallel trend tests may introduce bias and distortion in estimation and inference (Roth et al., 2023). Therefore, this paper adopts sensitivity analysis (Rambachan & Roth, 2023) to test the deviations from the parallel trend assumption. We construct a robust confidence interval for the causal effect by determining the maximum deviation from the parallel trend (\bar{M}). Fig. 3 displays robust confidence sets for the treatment effect from the +2 period to the +5 period using different values of \bar{M} . Examining each panel in Fig. 3, we identify the “breakdown value” for a significant effect. This interval is wider than the confidence interval in Fig. 2. These findings indicate that the effect of the

Table 2
Baseline regression results.

	(1)	(2)	(3)	(4)
<i>did</i>	0.0574*** (4.8150)	0.0272*** (3.9134)	0.0180*** (3.2169)	0.0231*** (4.3172)
<i>_cons</i>	0.0232*** (12.1943)	0.0296*** (20.1507)	-0.4081*** (-6.8179)	0.1077 (0.7814)
Control			YES	YES
City FE		YES		YES
Year FE		YES		YES
obs	3523	3523	3523	3523
R ²	0.1031	0.7705	0.5196	0.8060

Note: (1) * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; (2) t-statistics in parentheses; (3) The following tables are the same.

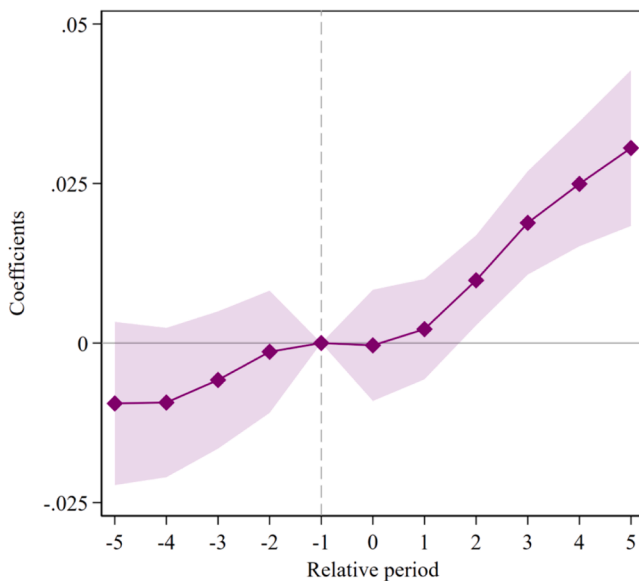


Fig. 2. Parallel trend test.

BCS on ICR remains robust even with a larger violation of parallel trends than observed. Furthermore, to address the heterogeneous treatment effects in regression results, we followed Sun and Abraham (2021) by applying “interaction-weighted” estimators to reduce potential bias. Fig. 4 plots the estimated results, which align with the trends of the treatment effects depicted in Fig. 2, confirming the robustness of our core finding.

4.3. Robustness test

4.3.1. Double dual machine learning

Double dual machine learning (DDML) has since been widely applied in causal inference (Chernozhukov et al., 2018). By combining machine learning with causal inference methods, DDML exhibits increased robustness against model misspecification and high-dimensional data (Wen et al., 2024). It does not require prior knowledge of covariate functional forms (Zhang et al., 2024a) and effectively mitigates model misspecification with nonlinear data (Yang et al., 2020). We use the random forest (RF) algorithm with a sample split ratio of 1:4. Additionally, the lasso algorithm is applied to reduce potential bias from the DDML model and improve result robustness. Table 3 indicates that the estimated coefficients stay significant in both models, and this significance persists after excluding the impact of the COVID-19 outbreak (columns 3 and 4). The results provide further evidence that DIC contributes to the improvement of urban ICR.

4.3.2. Placebo test

To further mitigate potential interference from random factors related to the selection of pilot cities, this study conducts a placebo test (Liu et al., 2024b). In implementing the placebo test, cities are randomly selected from the full sample to construct a pseudo-treatment group, while the remaining cities form the placebo control group. This resampling procedure is iterated 1000 times to enhance the robustness of the placebo test. As depicted in Fig. 5, the estimated coefficients (solid line) and p-values (points) of the pseudo-treatment group approximately conform to a zero-centered normal distribution. The majority of p-values exceed 0.1 (dotted line), demonstrating that these coefficients lack statistical significance. Therefore, it supports the significant impact of DIC on ICR from an alternative perspective.

4.3.3. PSM-DID

This study utilizes the propensity score matching (PSM) method to

reduce the potential impact of sample selection bias in model estimation. Control variables are used as matching criteria to pair cities with similar characteristics across treatment and control group cities. To ensure robust matching outcomes, four propensity score methods are applied: 1:1 nearest neighbor matching (NNM), caliper matching (CM), caliper nearest neighbor matching (CNNM), and kernel matching (KM). Table 4 demonstrates that all estimated coefficients are statistically significant. These findings further confirm the positive effect of DIC on enhancing urban ICR.

4.3.4. Removal of policy interference

To evaluate the robustness of the core finding and the BCS’s net effect on ICR, we consider the impact of other policy pilots within the study’s scope. Specifically, we evaluate the effects of three policies implemented between 2009 and 2021: Free Trade Zone Pilots (FTZ), the Low-Carbon City Pilot strategy (LCCP), and the National Big Data Comprehensive Pilot Zone (BDCCP). Table 5 demonstrates that the estimated coefficients are statistically significant at the 1% level, regardless of whether these policies are considered individually or collectively. These results further validate that DIC has a substantial and tangible impact on ICR.

4.3.5. Goodman-Bacon decomposition test

Owing to the staggered release of the BCS’s pilot cities, heterogeneous treatment effects across different treatment groups or temporal variations may result in unreliable regression outcomes. We employ the Goodman-Bacon (2021) approach to conduct decomposition to assess the bias in staggered DID estimates with two-way fixed effects. Fig. 6 shows the decomposition result, indicating that few unreasonable treatment groups (Later T vs. Earlier C) exist. Therefore, inappropriate treatment effects are exceedingly rare and do not significantly interfere with the core findings.

4.3.6. Other robustness tests

This study conducts additional robustness checks on the baseline regression by adjusting model specification, mitigating endogeneity, and removing outliers. First, given that ICR is a censored variable with a lower bound of zero, we use a Tobit model to enhance the robustness of the core finding. Second, to address endogeneity concerns in the baseline regression, we adopt a one-period lag structure for both the independent variable and the control variables. Third, we winsorize all continuous variables at the 1% and 99% quantiles to reduce the influence of outliers. Table 6 presents the results of these tests, showing that the coefficients of *did* and *L.did* consistently remain significant at the 1% level. Based on the preceding analysis, we conclude that DIC positively impacts ICR, and this finding demonstrates robustness across alternative specifications.

5. Heterogeneity analysis

5.1. City location

Given China’s vast territory, cities across the country vary in economic conditions, infrastructure, topography, and population distribution. According to the principles of new economic geography (Krugman, 1991), these disparities may cause uneven effects of digital infrastructure development on ICR across regions. To account for such regional differences, we categorize the sample cities into eastern, central, and western regions based on their geographic location and re-estimate the regression analysis for each subsample. The results, shown in columns (1) to (3) of Table 7, indicate that the impact of the BCS on ICR is most pronounced in eastern cities, followed by central cities. In contrast, no statistically significant effect is observed in western cities. The digital government in central and eastern cities is well-developed, enabling these regions to use digitalization for industrial chain transformation and upgrading, thus enhancing their resilience to external shocks.

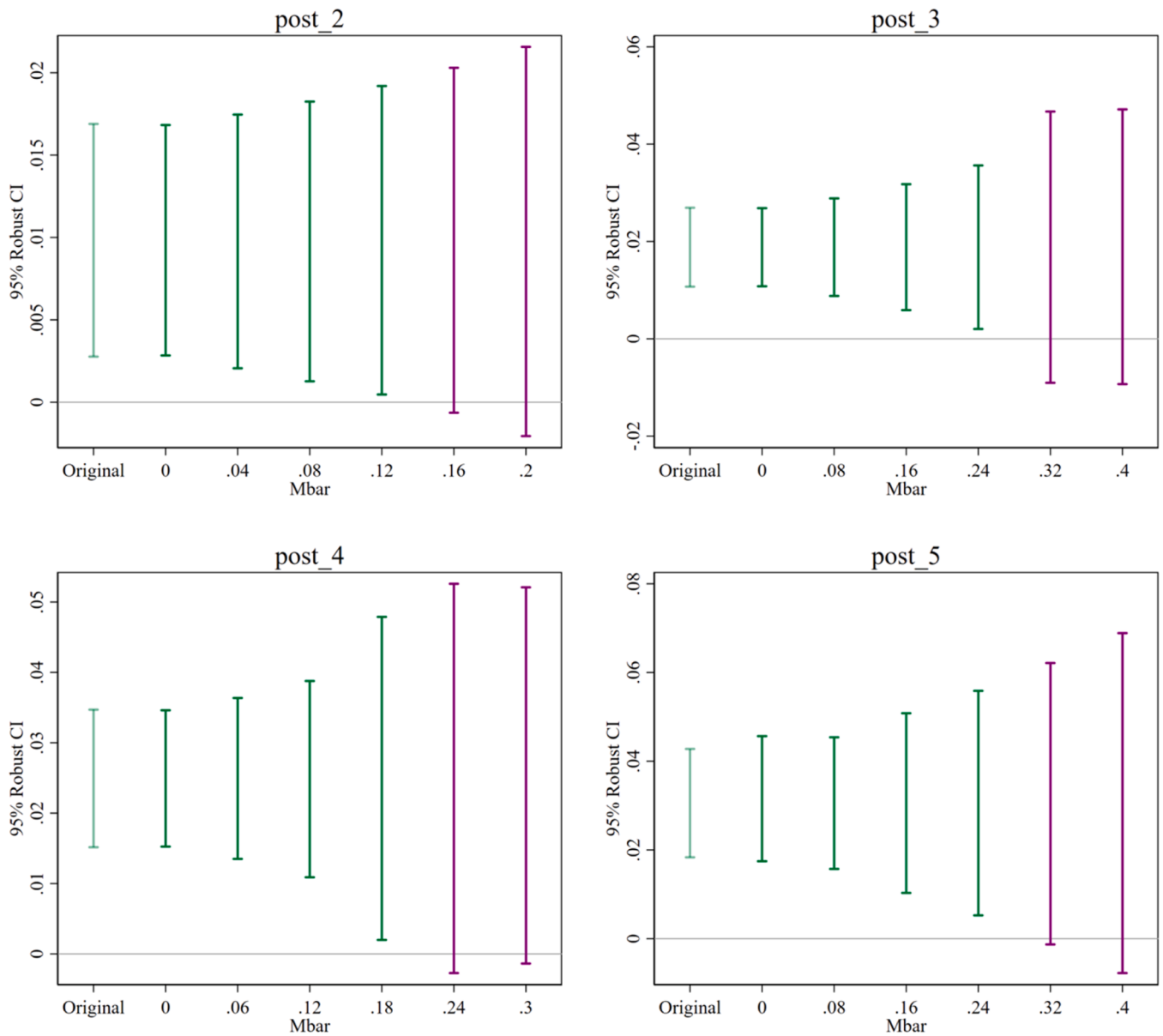


Fig. 3. Sensitivity analysis.

The establishment of digital infrastructure is a long-term process, and its sustainable effects require a certain time frame for comprehensive evaluation (Xiao et al., 2024). Drawing on Xu et al. (2024), we further analyze the dynamic impacts of DIC on the resilience of industrial chains in different regions. As depicted in Fig. 7, the enhancement of ICR by the BCS demonstrates significant dynamic regional heterogeneity. Following a policy shock, improvements in ICR first become apparent in the central region, followed by the eastern region. The short-term and long-term differences indicate that policy implementation further enhances the positive impact of the BCS on ICR in the eastern region over time. In contrast, although the positive impact on the central region persists, it weakens progressively. This trend may stem from the eastern region's entrenched economic strengths, which allow it to adapt rapidly to national policies and mobilize resources for industrial development, thereby establishing a cumulative advantage.

5.2. Resource endowment

Resource-based cities are heavily reliant on resources and typically have a narrow industrial structure, in contrast to non-resource-based

cities, which generally feature a diversified economic structure. Based on the principles of resource dependence theory (Pfeffer & Salancik, 1978), this distinction may lead to varying impacts of DIC on ICR. Following the classification in the Circular on the National Sustainable Development Plan for Resource-based Cities (2013–2020), we categorize the sample into resource-based and non-resource-based cities. A comparison of columns (4) and (5) in Table 7 shows that the BCS significantly impacts the ICR in non-resource-based cities. This disparity stems from differences in cities' ability to withstand risks, influenced by their resource endowments (Liu et al., 2024c). Resource-based cities rely more on natural resources, resulting in less industrial diversity compared to non-resource-based cities. Non-resource-based cities also show higher digital governance, with superior government efficiency and more advanced digitization. Consequently, non-resource-based cities demonstrate greater efficacy in enhancing infrastructure and strengthening urban resilience relative to resource-based cities.

5.3. Urban industrial agglomeration degree

Industrial agglomeration involves the geographical clustering of

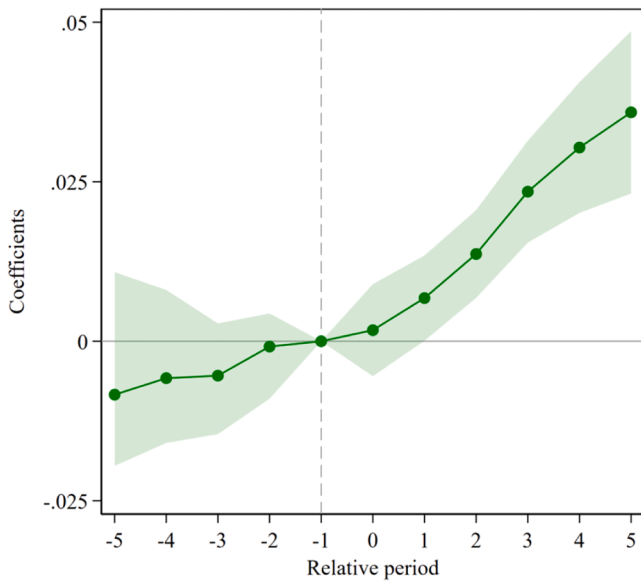


Fig. 4. Parallel trend test (Sun & Abraham, 2021).

Table 3 The results of DDML.

	(1)	(2)	(3)	(4)
	RF	Lasso	RF	Lasso
<i>did</i>	0.0069*** (3.3389)	0.0298*** (9.8487)	0.0071*** (3.3167)	0.0282*** (9.0772)
Control	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
obs	3523	3523	2981	2981

Note: z-statistics in parentheses.

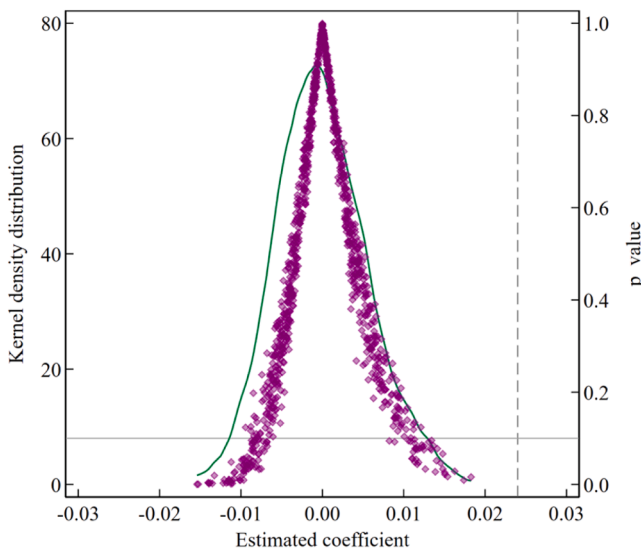


Fig. 5. Results of the Placebo test.

upstream and downstream enterprises within an industry that share interdependent relationships in the industrial chain. As emphasized by Porter’s cluster theory (Porter, 1990), this agglomeration can encourage inter-industry connections, facilitate resource exchange, and enhance regional competitiveness. Accordingly, we quantify the degree of industrial agglomeration by calculating the ratio of employed individuals

Table 4 The results of PSM-DID.

	(1) NNM	(2) CM	(3) CNNM	(4) KM
<i>did</i>	0.0138*** (4.4948)	0.0107*** (3.1577)	0.0068* (1.7705)	0.0092*** (2.8246)
_cons	0.1973 (1.4487)	0.1140 (1.3477)	-0.0143 (-0.3427)	-0.0330 (-0.9065)
Control	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
obs	1875	3274	2549	3115
R ²	0.8307	0.8003	0.8099	0.7936

Table 5 The results of controlling for other policy effects.

	(1) FTZ	(2) LCCP	(3) BDGP	(4) collective
<i>did</i>	0.0222*** (4.2499)	0.0228*** (4.3363)	0.0240*** (4.3387)	0.0227*** (4.2791)
_cons	0.1002 (0.7385)	0.0974 (0.6931)	0.0794 (0.6194)	0.0642 (0.4962)
Control	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
obs	3523	3523	3523	3523
R ²	0.8104	0.8080	0.8083	0.8145

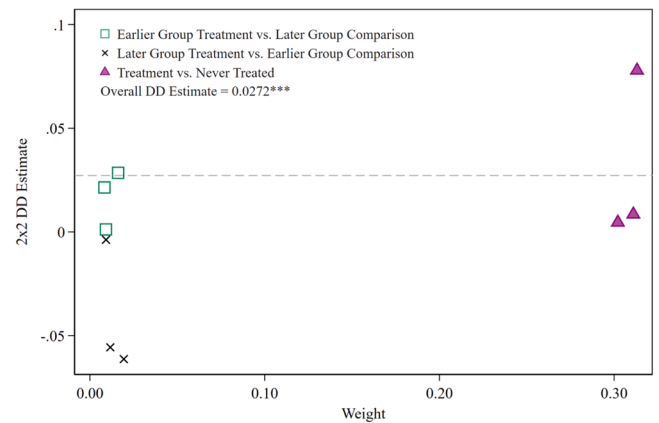


Fig. 6. Bacon decomposition diagram.

Table 6 The results of other robustness tests.

	(1) Tobit model	(2) one-period lag	(3) winsorized
<i>did</i>	0.0231*** (10.4769)		0.0174*** (4.1985)
<i>L.did</i>		0.0244*** (4.3605)	
_cons	0.3877*** (9.0960)	-0.1089 (-0.7394)	0.0436 (0.4504)
Control	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES
obs	3523	3252	3523
R ²		0.8294	0.8570

to unit area (Ciccone, 2002). Based on the average value, we categorize the degree of urban industrial agglomeration into high and low. Columns (6) and (7) in Table 7 present the regression results for cities with divergent agglomeration levels. The results indicate that in

Table 7
The results of heterogeneity effect.

	Geographical location			Resource endowment		Industrial agglomeration degree	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
<i>did</i>	0.0428*** (4.0265)	0.0163*** (3.6857)	0.0026 (0.4606)	0.0326*** (4.2162)	0.0027 (1.6198)	0.0251*** (4.1063)	0.0132* (1.8360)
<i>_cons</i>	-1.3102** (-2.1173)	0.2688*** (2.7546)	-0.0066 (-0.1703)	0.4290* (1.8446)	-0.0577** (-2.0489)	0.1207 (0.6768)	0.0617 (0.6861)
Control	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
obs	1521	1001	1001	2106	1417	2925	598
R ²	0.8396	0.7709	0.8268	0.8213	0.7723	0.8115	0.8213

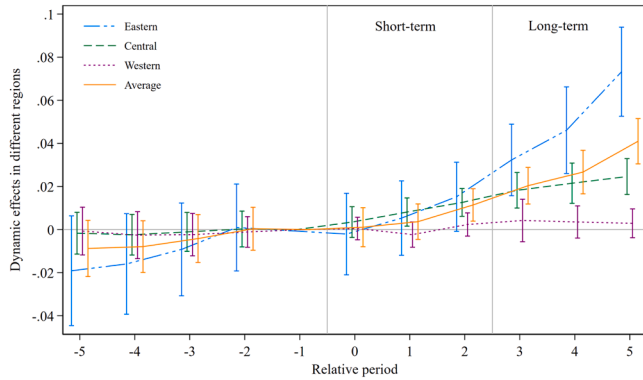


Fig. 7. The dynamic impact in eastern, central, and western cities.

high-agglomeration cities, the BCS exerts a significant positive effect on ICR. While the BCS exerts an influence on low-agglomeration cities, both the statistical significance and effect size are markedly diminished relative to high-agglomeration counterparts. This might be because regions with higher industrial agglomeration tend to share resources more effectively, facilitating optimal utilization of production factors (Li et al., 2021). In addition, industrial agglomeration creates platforms for business communication, facilitating both technological innovation and knowledge spillovers. Moreover, it can engender imperfectly competitive market structures, compelling firms to pursue accelerated technological advancements as a strategic response (Qin et al., 2023).

6. Mechanism analysis

Theoretical analysis suggests that DIC positively influences ICR by bridging the digital divide (DD), enhancing digital human capital (digHC), and improving innovation quality (InnoQ). DD is quantified through the entropy method, incorporating the telecommunications service revenue, the year-end number of mobile phone users, and the number of Internet service users. The DD index ranges from 0 to 1, where higher values indicate narrower digital divides. DigHC is measured by the proportion of employment in information transmission, computer services and software sectors. InnoQ is quantified by the ratio of invention patent filings to the total number of patent applications. Based on the previous theoretical analysis, this study adopts the methodology of Baron and Kenny (1986) and Li et al. (2024) to investigate the underlying pathways linking DIC to ICR:

$$M_{it} = \kappa + \chi did_{it} + \beta_2 control_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (4)$$

$$ICR_{it} = \kappa + \chi did_{it} + \gamma M_{it} + \beta_2 control_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (5)$$

where M_{it} represents the mechanism variable, which is substituted sequentially with DD, digHC and innoQ in that order.

6.1. Digital divide

The regression outcomes regarding the digital divide dimension are detailed in columns (2) and (3) of Table 8. The estimated coefficient of *did* in column (2) is significantly positive, indicating that the BCS has a substantial effect on mitigating DD. The coefficient of DD in column (3) is statistically significant, suggesting that reducing the digital divide effectively enhances ICR. Additionally, the coefficient for DD in column (3) is lower compared to that in column (1), supporting hypothesis 2, which claims that DIC can enhance ICR by bridging the digital divide. Digital infrastructure, as a new institutional arrangement, effectively alleviates the digital divide. Achieving digital equality can significantly lower the risk of social and economic marginalization in various regions (Wu, 2024). Bridging the digital divide is essential for adapting to rapid Internet changes and flexibly utilizing new technologies (Serrecchia, 2024). Adequate digital access and skills enable businesses to accelerate decision-making and enhance supply chain adaptability and flexibility.

6.2. Digital human capital

The results of the test on the digital human capital mechanism are presented in columns (4) and (5) of Table 8. The coefficient of *did* in column (4) is 0.0028, indicating that the BCS significantly promotes the aggregation of digital human capital in cities, as shown by a 1% significance level. The coefficient of *did* in column (5) is significantly positive, and its value is lower than that of column (1), confirming the existence of a pathway for the aggregation of digital human capital. This result suggests that DIC drives ICR by promoting digital human capital aggregation. Thus, Hypothesis 3 is verified. Digital infrastructure serves as a crucial medium for technology diffusion, while digital human capital acts as a driving force for technology adoption and application (Alfaro-Navarro et al., 2024). Digital empowerment theory suggests that digital tools provide individuals with specific capabilities (Mäkinen, 2006), and the collective digital human capital can amplify this effect. Digital human capital enables enterprises to flexibly respond to external shocks, drive digital transformation in both traditional and emerging industries, optimize the economic structure, and enhance overall economic resilience.

6.3. Innovation quality

The specific regression results for innovation quality are shown in columns (6) to (7) of Table 8. The coefficient of *did* in column (6) is 0.0248, demonstrating statistical significance and indicating that the BCS has significantly enhanced urban innovation quality. In column (7), the coefficient of innoQ is significant, and the estimated coefficient of *did* is significantly positive, with a lower absolute value compared to that in column (1). This result supports Hypothesis 4, which posits that DIC can enhance ICR through improving urban innovation quality. As mentioned in Kangmin et al. (2023), the “new infrastructure construction wave” in China, which is based on digital infrastructure, emphasizes the pursuit of key technologies. In accordance with the demand-induced

Table 8
The results of mechanism test.

	(1) ICR	(2) DD	(3) ICR	(4) digHC	(5) ICR	(6) InnoQ	(7) ICR
<i>did</i>	0.0231*** (4.3172)	0.0039*** (4.0467)	0.0220*** (8.9129)	0.0028*** (3.1464)	0.0183*** (4.3625)	0.0248** (2.3381)	0.0225*** (4.1970)
<i>DD</i>			0.2876** (2.0518)				
<i>digHC</i>					1.7231*** (3.9791)		
<i>InnoQ</i>							0.0232** (2.2527)
_cons	0.1077 (0.7814)	0.0035 (0.1136)	0.1067 (1.2786)	0.0707** (2.2722)	-0.0141 (-0.1178)	-0.1620 (-0.7260)	0.1115 (0.8062)
Control	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
obs	3523	3523	3523	3523	3523	3523	3523
R ²	0.8060	0.9387	0.8087	0.6662	0.8287	0.6307	0.8066

innovation theory (Schmookler, 1962), the interactive nature of the Internet enables enterprises to identify market demands, connect with consumers, discern innovation opportunities, enhance innovation quality, gain competitive advantages, and cultivate a virtuous cycle of industrial chain development.

6.4. Further analysis

The preceding theoretical analyses and mechanism tests show that DIC drives urban ICR by bridging the digital divide, developing digital human capital, and improving innovation quality. However, it is important to recognize that these findings represent overall effects and may conceal variations across different urban contexts. The implementation and operation of digital infrastructure depend on the physical environment provided by construction facilities. Regona et al. (2024) emphasize the essential role of the construction industry in promoting sustainable development. Given this, we extend our investigation to test how these three mechanisms are distinctly manifested within the construction sector. We divide the sample into high- and low-development cities, depending on whether their average construction sector employment from 2009 to 2021 exceeds the national mean. Following Yan (2025), we use Model (4) to re-examine the mechanisms in the construction sector.

As shown in Fig. 8, DIC plays a significant role in reducing the digital

divide and fostering digital human capital in high-development cities, whereas its impact on low-development cities is negligible. In comparison, DIC enhances innovation quality across cities with varying construction-sector development levels, particularly in higher-level cities. Possible reasons are as follows. First, the widespread adoption of digital infrastructure primarily addresses hardware-level challenges in communication technology. However, the digital divide also includes disparities in digital technology capabilities (Liao et al., 2022). In lower-level cities, the digital divide may be affected by factors such as low economic development and insufficient technological awareness; therefore, merely enhancing digital infrastructure is insufficient to bridge the deeper gap. Second, higher development cities benefit from a well-established construction industry chain and greater demand for digital technology. As a result, DIC is more effective in fostering the development of digital human capital in these cities. In contrast, lower development cities, with weaker industrial foundations and limited demand, struggle to generate a substantial driving effect. Third, digital infrastructure provides a strong foundation for the construction sector by enhancing information sharing, resource optimization, market responsiveness, and cross-regional collaboration, thereby boosting innovation quality in cities of all development levels. By employing digital technologies, cities can more effectively harness global resources and opportunities, promoting continuous innovation and growth in the construction sector.

7. Extended analysis of high-quality development

As previously noted, resilient governance and high-quality development are mutually reinforcing, simultaneously advancing one another by addressing various challenges. To this end, this paper draws on Liu et al. (2020) to establish a comprehensive index system for measuring the level of urban high-quality development, and employs DDML to further investigate whether DIC can enhance urban high-quality development. Other variables remain consistent with the preceding section. The RF algorithm, lasso algorithm and ridge regression algorithm are

Table 9
The results of extended analysis.

	(1) RF	(2) Lasso	(3) Ridge
<i>did</i>	0.0040** (2.0796)	0.0095*** (5.6595)	0.0054*** (4.7492)
Control	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES
N	3523	3523	3523

Note: z-statistics in parentheses.

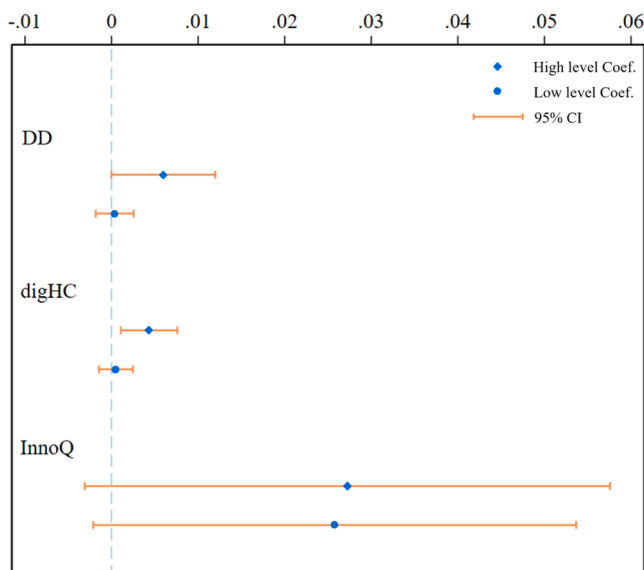


Fig. 8. Mechanism analysis in construction sector.

employed to predict the outcomes. The results, presented in Table 9, demonstrate that all algorithms generate significantly positive outcomes, indicating the successful implementation of DIC in fostering high-quality development across regions.

8. Discussion

This paper explores the link between DIC and ICR, conducting comprehensive heterogeneity analyses and mechanism tests. We use panel data from 271 Chinese cities covering the period from 2009 to 2021 to assess the impact of DIC on ICR. First, we broaden existing research on digital infrastructure by concentrating our study on the perspective of industrial chain resilience. Our findings are partially consistent with the studies by Ma and Zhang (2024) and Yan (2025). Ma and Zhang (2024) confirm that smart city development enhances urban economic resilience from a digital governance perspective; Yan (2025) demonstrates, through the lens of digital platform construction, the critical role of public data accessibility in improving ICR. This study reinforces Aziz et al.'s (2025) proposition that digital transformation facilitates achieving SDG 9, while echoing Patel et al.'s (2024) call to advance SDG 11 through digital construction. Furthermore, our research improves the evaluation framework for China's BCS program, expands the scope of digital infrastructure policy, and moves beyond the path dependence commonly found in existing literature, which mainly focuses on economic progress, low-carbon development, and social well-being. In contrast to Yang and Liu (2024), who apply a provincial-level index system to assess the influence of digital infrastructure on the resilience of China's manufacturing industry, we adopt the BCS to proxy for DIC at the city level, further investigating how DIC affects ICR.

Second, our research highlights the heterogeneity of DIC in terms of geographical location, resource endowment, and the degree of industrial agglomeration. In particular, we provide an in-depth analysis of both the short-term and long-term impacts of DIC across different regions. Specifically, the BCS implementation exhibits a temporally strengthening effect on ICR in the eastern region, whereas its positive influence demonstrates gradual attenuation in central China. This view aligns with the findings of Wang and Zhan (2025) and Wang and Cen (2024), who emphasize that Eastern cities, being among China's most economically developed regions, provide a favorable policy environment and strong incentive mechanisms. Notably, economic disparities create asymmetric impacts on the digital economy, both within national borders and globally. For instance, Mngumi et al. (2024) note that economic disparities among BRICS nations may lead to unpredictable outcomes in the digital economy.

Third, we highlight that DIC boosts the urban ICR by narrowing the digital divide, developing digital human capital, and enhancing innovation quality. Universal and meaningful digital connectivity is essential for achieving the SDGs (Gur & Kulesza, 2024), and the establishment of digital infrastructure provides a solution to the urgent challenge of the digital divide. Within the context of digitalization, our research reaffirms that human capital enhances economic resilience (Ye et al., 2025). Furthermore, the innovation quality pathway reinforces the idea that developing digital infrastructure is fundamental to advancing disruptive emerging technologies (Kangmin et al., 2023), and strengthens the relevance of innovation diffusion theory within the Chinese context (Wang & Zhan, 2025). The construction sector provides the physical space and environmental foundation required for digital infrastructure. In light of this, we further examine how these mechanisms operate in cities with differing levels of construction sector development. The results show that the pathways of the digital divide and digital human capital differ significantly across cities with varying levels of construction sector development. This observation is consistent with Wang et al. (2021), who emphasized that while digital infrastructure resolves access problems, inequalities in urban development and technological capacity can still widen the digital divide. Similarly, the finding of human capital

aligns with He et al. (2025), who demonstrate that the influence of digital infrastructure on human capital is shaped by urban contextual factors.

While this study provides valuable insights into digital infrastructure and industrial chain resilience, it is important to acknowledge certain limitations: First, it focuses on cities at the macro level, leaving room for future research to investigate sectoral and firm-level dynamics at the micro level for more granular insights. In addition, adopting a global perspective—by comparing the resilience of different countries or analyzing the global value chains' resilience of enterprises—could provide deeper insights into optimizing digital infrastructure improvement and enhancing resilience. Second, focusing exclusively on adaptive resistance and transformative adaptability may not fully capture the comprehensive level of ICR in Chinese cities. For instance, recovery time, an essential component of resilience, remains unexplored due to data availability constraints. In addition, future research could consider the internal cooperation networks of cities and their external economic connections.

9. Conclusions and policy recommendations

9.1. Conclusions

Digital infrastructure serves as the cornerstone of modern socio-economic development, enabling nations worldwide to seize digital opportunities and build new advantages. Governments globally face the urgent task of strategically implementing policies to enhance digital infrastructure. Given the "ripple effect" and "chain reaction" of crisis events, ensuring effective management within the industrial chain has become increasingly important. In view of this, this paper aims to investigate the effects of DIC on ICR. By utilizing the strengths of machine learning algorithms in high-dimensional, non-parametric prediction, we apply the DDML model for causal identification. This approach can effectively circumvent the "curse of dimensionality" and model specification bias. In addition, we incorporate sensitivity analysis, PSM, and placebo tests to help mitigate the potential biases in the DID model.

The main conclusions are as follows: (1) DIC can significantly enhance ICR, and this finding is supported by a series of robustness tests. (2) Heterogeneity effects reveal that eastern cities, non-resource-based cities, and cities with high industrial agglomeration have witnessed more substantial improvements in ICR. Notably, in the eastern region, DIC has a long-term effect on ICR, and this positive impact intensifies over time. (3) DIC drives ICR by bridging the digital divide, promoting digital human capital, and enhancing the quality of innovation. (4) Further analysis indicates that DIC simultaneously enhances urban high-quality development.

9.2. Policy recommendations

The findings provide critical insights for promoting the deep integration of digital infrastructure development with the sustainable advancement of industrial chains. The specific policy recommendations are as follows: (1) The government should actively monitor the progress of the BCS and its impacts on the development of Internet infrastructure in pilot cities. Efforts should focus on progressively expanding the scope of digital infrastructure projects to enhance network accessibility. (2) The government should encourage pilot cities to leverage their abundant digital talent to expedite the advancement and iteration of digital technologies and platforms. (3) The government should utilize the empowering role of digital infrastructure to drive high-quality innovation and facilitate the digital transformation of industrial chains to strengthen their resilience against disturbances. (4) The issue of uneven regional development underscores the need for comprehensive long-term planning. Policymakers should implement adaptive strategies that account for the ever-evolving circumstances across different regions. This requires local governments to take a pivotal role in adapting

macro-level policies into targeted actions tailored to local requirements. For example, the eastern regions might require sustained or increased investment to preserve their growth momentum, whereas the central and western regions could benefit from periodic assessments to pinpoint and overcome barriers to long-term development.

CRedit authorship contribution statement

Yi Chen: Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Cailou Jiang:** Supervision, Project administration, Funding acquisition. **Lin Peng:** Writing – review & editing, Validation, Data curation. **Shuang Zhao:** Writing – review & editing, Visualization. **Cheng Chen:** Visualization, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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