Frontiers in Economics and Management Volume 7 Issue 8, 2026
ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

Mechanism and Realization Path of Digital-Physical Integration Empowering Digital Transformation of Specialized, Refined, Distinctive and Innovative Enterprises

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Abstract

Digital-physical integration is a critical driving force for fostering new productive forces and optimizing the modern industrial system. As vanguards among small and medium-sized enterprises (SMEs), Specialized, Refined, Distinctive and Innovative (SRDI) enterprises play a pivotal role in segmented industrial chains, and their digital transformation serves as a core foothold to deliver tangible outcomes of digital-physical integration. Nevertheless, SRDI enterprises are still plagued by multiple dilemmas in digital upgrading. Based on the Resource-Based Theory, Technology Empowerment Theory and Collaborative Governance Theory, this paper dissects the functional mechanism through which digital-physical integration fuels the digital transformation of SRDI enterprises. Through two-way internal and external empowerment channels, digital-physical integration can effectively mitigate five prevailing transformation predicaments of enterprises: being unwilling to transform, fearing transformation, lacking capacity to transform, suffering defective transformation results, and advancing transformation at a sluggish pace. Accordingly, this paper proposes targeted realization paths, including constructing tiered empowerment platforms, developing integrated digital industrial chain ecosystems, upgrading regional digital infrastructure and policy frameworks, and perfecting talent cultivation and cybersecurity safeguards. The research outcomes can offer references for local governments to formulate differentiated supportive policies and accelerate the digital transformation of SRDI enterprises.

Keywords

Digital-Physical Integration; Specialized, Refined, Distinctive and Innovative Enterprises; Digital Transformation; Functional Mechanism.

1. Introduction

1.1. Research Background and Problem Formulation

Digital-physical integration constitutes the core strategic direction for China to cultivate new productive forces and upgrade industrial systems. In December 2021, the State Council issued the 14th Five-Year Plan for Digital Economy Development, which identified the in-depth integration of digital technologies and the real economy as the core thread to consolidate the foundation of Digital China. The report to the 20th National Congress of the Communist Party of China further elevated this strategic deployment, proposing to accelerate the development of the digital economy and advance the deep integration between the digital economy and the real economy. Now that the digital economy has become a new growth engine for the national economy, promoting digital-physical integration has turned into a vital lever for realizing the modernization of industrial chains. However, industrial practices reveal that the development of digital-physical integration in China is still restrained by multiple practical obstacles. A

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

digital divide persists across industries and enterprises; meanwhile, incomplete market-oriented circulation systems for data factors, severe shortages of digital professionals, and imperfect intellectual property protection regimes continuously hinder the deep integration of digital and real economies[1].

Against this policy and industrial backdrop, SRDI enterprises act as core carriers to guarantee stable industrial and supply chains by deeply cultivating segmented market niches, so their digital transformation becomes a key implementation anchor for digital-physical integration to yield tangible results. The Special Action Plan for Digital Empowerment of Small and Medium-Sized Enterprises (2025–2027), jointly released by the Ministry of Industry and Information Technology and three other central departments, clearly mandates tiered digital transformation for SRDI enterprises. It targets full coverage of national-level "Little Giant" enterprises with digital maturity above Level II, and a substantial increase in the transformation penetration rate of provincial-level SRDI enterprises. Data from the 2024 Research Report on Digital Transformation of SRDI Small and Medium-Sized Enterprises, published by the China Academy of Information and Communications Technology, shows that more than 62% of domestic SRDI enterprises remain stuck at the basic informatization stage, while merely 11% have achieved full digital integration of core business workflows. Their transformation progress lags significantly behind the pace of industrial upgrading. Therefore, advancing the digital transformation of SRDI enterprises carries immense practical value for accelerating the deep integration of digital technologies and the real economy[2].

In light of the above context, this paper focuses on three core research questions: First, can digital-physical integration effectively resolve the transformation dilemmas confronting SRDI enterprises? Second, what is the functional mechanism through which digital-physical integration empowers corporate transformation? Third, how can tailored, adaptable realization paths for transformation be constructed?

1.2. Research Significance

Centering on the core attributes of SRDI enterprises (specialization, refinement, differentiation, innovation) and their five major transformation dilemmas, this paper constructs a dual-dimensional empowerment framework (internal empowerment + external empowerment) to interpret how digital-physical integration drives SRDI enterprises' digital upgrading, enriching theoretical research on SMEs' digital transformation. At present, most SRDI enterprises are constrained by capital, technology, talent and cognitive limitations, which create prominent practical barriers to digital transformation. The realization paths proposed in this study can provide operable lightweight, phased digital transformation solutions for SRDI operators, helping them cut renovation costs and avoid blind capital investment. Meanwhile, the research delivers policy references for local authorities to design tiered, categorized digital support policies and build cross-industry collaborative platforms.

2. Literature Review

2.1. Research on Digital-Physical Integration

With the continuous iteration and upgrading of the digital economy, digital technologies have evolved into a new growth engine empowering the development of real industries, and deep integration between digital and real economies has emerged as the core driving force for high-quality economic development worldwide (Guo et al., 2023)[3]. As an innovative development paradigm formed by embedding digital technologies and data factors deep into real economic operations, digital-physical integration has fostered a layered research agenda examining its conceptual evolution and practical effects. Early studies simplified digital-physical integration as superficial informatization renovations such as enterprises purchasing digital software and

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

intelligent equipment. As industrial digitalization practices were widely rolled out, the scope of research expanded, gradually extending to the perspective of full industrial chain and full-production-cycle integration. Ding et al. (2024) clarified that digital-physical integration is not merely one-dimensional technological empowerment; it covers the complete circulation of production, distribution, circulation and consumption, representing a systematic transformation reform across all industrial links[1].

Studies on the economic effects of digital-physical integration fall into two strands: macro-industrial research and micro-firm research. At the macro-industrial level, scholars mainly explore the enabling value of digital-physical integration for regional industrial upgrading and economic growth. Cui et al. (2026) adopted big data comprehensive pilot zone policies as a quasi-natural experiment to conduct empirical research, verifying that big data-related digital policies can elevate regional digital-physical integration levels through two transmission channels: digital technological innovation and digital industrial agglomeration, and the empowering effects of such policies display obvious regional heterogeneity[4]. At the micro-firm level, existing research focuses on the operational impacts of digital-physical integration on enterprises, and thoroughly unpacks the empowerment logic of digital elements and technologies. Ren et al. (2023) proposed that driven by digital technological innovation and data factor deployment, digital-physical integration can fundamentally reshape traditional corporate factor allocation models and break the development shackles of the traditional real economy[5]. Wang et al. (2025) further confirmed that digital-physical integration can optimize the allocation structure of regional industrial factors and activate indigenous industrial innovation momentum[6]. It can not only boost the high-quality development of local enterprises, but also effectively strengthen regional attractiveness to foreign investment. Overall, existing literature has fully verified the diverse economic spillover effects of digital-physical integration, laying a solid theoretical foundation for this paper to explore its empowerment mechanism for SRDI enterprises' digital transformation.

2.2. Research on Digital Transformation of SRDI Enterprises

Digital transformation derives its theoretical roots from Schumpeter's Innovation Theory and Teece's Dynamic Capabilities Theory, whose core logic lies in reconstructing organizational capabilities via digital technologies to realize fundamental reform of value creation models. Research on SRDI enterprises' digital transformation has gradually become a core research theme in the field of SMEs. In terms of transformation characteristics, SRDI enterprises' deep cultivation of segmented market niches generates differentiated transformation logics that distinguish them from large conglomerates and traditional SMEs. Yang (2024) constructed a development quality evaluation system based on samples of listed SRDI enterprises, and pointed out that SRDI enterprises carry out digital transformation mainly to iterate niche technological breakthroughs, which differs drastically from the full-process intelligent retrofits adopted by large manufacturing factories[7]. Tian et al. (2024) supplemented and refined relevant research, stating that the digital transformation of SRDI enterprises bears distinct innovation orientation. Their digital resource input mainly serves the iteration of innovative technologies in segmented fields, unlike traditional SMEs whose digital transformation centers on cost reduction and efficiency improvement. This conclusion clarifies the unique traits of SRDI enterprises' digital upgrading[8].

In terms of transformation dilemmas, Yu et al. (2023) classified transformation constraints into four dimensions (internal resources, external services, industrial chain collaboration) based on survey data of SRDI enterprises, identifying internal capital shortages, digital talent deficits and cross-firm data silos as core barriers hindering transformation implementation[9]. Combined with an analysis of national "Little Giant" enterprises, Yu (2025) supplemented external development constraints including uneven geographic distribution of digital resources and

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

insufficient supply of high-end digital talents[10]. Wang (2024) systematically summarized five practical contradictions restricting SRDI enterprises' transformation: On the capital side, high digital renovation costs and long return cycles make enterprises unwilling to transform; risks of core process data leakage generate fear of transformation; the absence of standardized industrial solutions tailored to segmented sectors leaves enterprises unable to transform; generic digital service providers fail to match niche business demands, resulting in defective transformation outcomes; fragmented industrial chain data and insufficient coverage of public digital services slow down transformation progress. This framework fully depicts the practical constraints on corporate digital upgrading[11].

2.3. Cross-Disciplinary Research on Digital-Physical Integration and Corporate Digital Transformation

In recent years, scholars have gradually integrated digital-physical integration ecosystems with corporate digital transformation, forming an emerging cross-disciplinary research stream. From a macro-regional perspective, Xiao (2026) pointed out that major infrastructure projects including the East Data-West Computing Initiative and big data comprehensive pilot zones upgrade computing power and network foundations, build shared public digital resource pools, and lower the baseline digitalization threshold for regional SMEs[12]. Cui et al. (2026) verified that big data comprehensive pilot zones construct full-domain digital-physical integration ecosystems, which improve regional digital infrastructure and digital service supply, reduce digital renovation expenditures for local SMEs, and deliver inclusive digital tools for enterprises[4].

From a meso-industrial chain perspective, Ji (2025) put forward the dual-space coexistence theory of physical industrial agglomeration and virtual digital agglomeration. Relying on digital-physical integration, industrial clusters build shared online production platforms, allowing SMEs to complete supporting digital manufacturing workflows by leveraging cluster-shared computing resources[13]. Xu (2023) supplemented that digital-physical integration constructs full-chain data sharing circles, alleviates the pressure of independent digital investment for SRDI enterprises, distributes technological trial-and-error costs across industrial chains, and improves the feasibility of transformation[14]. Pei et al. (2025) proposed a dual-track development path of digital industrialization and industrial digitalization. Integrated industrial chain convergence can unblock R&D and sales data pipelines to ease the standalone digitalization pressure of SMEs[15]. Sun (2024) emphasized that digital-physical integration ecosystems converge computing power, technological assets and talent pools to offset internal digital resource deficiencies within SRDI enterprises[16].

At the micro-firm level, Chen (2026) conducted research from the perspective of corporate investment, financing and resource allocation, proposing that digital-physical integration aggregates fiscal subsidies, digital talents and other factor inputs to effectively fill the resource gaps of SRDI enterprises and resolve resource constraints during their digital transformation[17]. Taking SRDI enterprises across five major urban agglomerations in China as research samples, Wang (2025) verified that digital inclusive finance, empowered by integrated digital-real ecosystems, expands innovative financing channels for SRDI firms and supports the implementation of digital R&D projects[18]. In summary, extant literature has separately explored the economic effects of digital-physical integration and the digital transformation of SMEs, forming a certain research foundation. On this basis, this paper analyzes the mechanism through which digital-physical integration drives SRDI enterprises' digital transformation, filling the research gap in existing studies.

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

3. Functional Mechanism of Digital-Physical Integration Empowering SRDI Enterprises' Digital Transformation

The 2026 China Internet Development Report, released by the China Internet Association, indicates that China's digital intelligence development has reached a new stage, and the construction of Digital China presents an overall stable, sound and coordinated development pattern. The country's digital infrastructure continues to iterate and upgrade, with solid foundations built for 5G, Industrial Internet, Internet of Things and other digital infrastructure. Various AI intelligent terminals and lightweight digital tools have been mass-produced and widely deployed, and digital technologies are penetrating and integrating into all segmented sectors of the real economy at an accelerated pace, providing mature technological foundations and industrial ecological support for the transformation and upgrading of manufacturing and small and medium-sized real enterprises[19]. Centered on digital technologies and data factors, in-depth digital-physical integration embeds digital capabilities into all business workflows of SRDI enterprises in an all-round manner, forming digital productive forces to drive SRDI enterprises' digital transformation and upgrading. It can specifically resolve five major transformation bottlenecks prevalent in the industry, serving as a core path to break various practical dilemmas restricting SRDI enterprises' digital upgrading[11]. Combined with the core traits of SRDI enterprises (specialization, refinement, differentiation, innovation), the empowerment mechanism can be divided into two dimensions: internal empowerment mechanism and external empowerment mechanism. The two mechanisms interact and coordinate synergistically to push enterprises to complete digital transformation.

3.1. Internal Empowerment Mechanism

The internal empowerment of digital-physical integration for SRDI enterprises focuses on core links of corporate production, operation and organizational management. It leverages digital intelligent technologies to address enterprises' internal development pain points, and activates internal development momentum through full-process digital transformation of enterprises. According to data from the 2024 Research Report on Digital Transformation of SRDI Small and Medium-Sized Enterprises, although most enterprises possess technological advantages in segmented fields, they launched digital transformation late with weak accumulation and insufficient digital investment. Over 40.1% of enterprises spend less than 1 million RMB on digitalization each year. Most manufacturing enterprises prioritize digital transformation in two core links: production & manufacturing, and operation & management. Digital-physical integration can consolidate the foundation of corporate digital transformation by accurately matching enterprises' transformation characteristics[9].

3.1.1. Digital Empowerment of Production and Operation

From the internal production perspective of enterprises, most SRDI enterprises take root in traditional real industries with weak digital transformation foundations, plagued by outdated equipment and lagging digital renovation. Industrial equipment owned by SMEs accounts for more than 60% of the national total stock, and a large quantity of industrial equipment lacks networking and data collection functions, leaving a massive gap in equipment digital renovation. Meanwhile, most SRDI enterprises adopt small-batch, multi-variety production modes, and the adaptation renovation cost of production lines is far higher than that of standardized production enterprises. Digitalization requires large upfront investment, long construction cycles and slow returns. SRDI enterprises have narrow external financing channels for digital transformation funds, and exorbitant renovation costs have become the primary barrier restricting digital upgrading in production links. As a result, most enterprises can only carry out shallow informatization transformation and fail to realize full-process intelligent production.

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

Through digital renovation, digital-physical integration accurately addresses enterprises' production-side pain points including outdated equipment, high renovation costs and low production efficiency, achieving quality improvement and efficiency growth via digital production and operation. On the one hand, Internet of Things and other digital technologies are adopted to carry out low-cost digital retrofits on the stock of traditional industrial equipment. Enterprises do not need to fully replace old equipment to realize intelligent control of production procedures, revitalize idle stock equipment resources, and resolve problems of low equipment utilization and large production capacity loss. On the other hand, full-process collection and analysis of production data optimize non-standard customized production workflows, reduce inventory backlogs and material losses, effectively cut corporate digital renovation costs, and shorten the investment return cycle[20].

3.1.2. Digital Empowerment of Organization and Management

Most SRDI enterprises deeply engage in segmented technological sectors, with teams dominated by R&D and manufacturing talents, resulting in a severe shortage of internal digital professionals. Meanwhile, digital training services for SMEs are generally homogeneous, failing to meet personalized transformation demands of enterprises in segmented market niches. In addition, corporate management teams hold vague perceptions of digital transformation, simply equating digitalization with online office work or software procurement, lacking systematic transformation thinking. Blind investment in digital transformation severely restricts the depth of transformation advancement.

Digital-physical integration comprehensively resolves corporate management and talent constraints through three layers of empowerment: organizational structure reconstruction, management system upgrading and cognitive capacity improvement. First, integrated platforms such as ERP and OA break data barriers among internal modules including human resources, finance, production, supply chain and sales, shorten information transmission chains, shift corporate management from experience-driven to data-driven, and reverse extensive management modes[8]. Second, the exclusive industry training system and industrial talent sharing mechanism under the digital-physical integration ecosystem provide customized digital training tailored to segmented industries for enterprises, alleviating the shortage of compound digital talents. Normalized application of digital management systems can continuously update management teams' digital cognition, help enterprises formulate systematic transformation plans, comprehensively improve corporate internal governance and the precision of digital transformation, and activate enterprises' willingness to carry out transformation[14].

3.2. External Empowerment Mechanism

At present, China's industrial digital penetration rate only reaches 24%, less than half of that of developed European and American countries. Most enterprises are in the transition stage from Industry 2.0 to Industry 3.0, facing prominent problems of weak industrial chain digital foundations and imperfect ecosystems. Meanwhile, multiple external constraints overlap, including inconsistent industrial interconnection standards, data security worries, mismatched service adaptability and insufficient precision of policy implementation, making SRDI enterprises afraid to transform, unable to transform well, and slow to advance transformation. Digital-physical integration eliminates external transformation constraints by improving public service systems and perfecting institutional safeguards, providing external support for corporate digital transformation.

3.2.1. Digital Empowerment of Industrial Collaboration

At the current stage, inconsistent industrial digital standards and fragmented interface protocols remain prominent problems in China. Most enterprises adopt independent standards for equipment networking and system construction, and there is no unified data migration

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

standard across various Industrial Internet and cloud service platforms. When SRDI enterprises access industrial chain systems, they face difficulties in system docking and high data migration costs, making it hard to achieve interconnection between upstream and downstream players. Meanwhile, there exists a striking digital hierarchy gap between leading industrial chain enterprises and small and medium-sized supporting SRDI enterprises. Most SRDI enterprises cannot integrate into the digital collaborative systems of chain leaders, remaining outside closed industrial chain data loops for a long time. Independent transformation fails to generate industrial collaborative effects, accompanied by high transformation input costs and weak industrial empowerment outcomes[13].

Relying on the top-level architecture of Industrial Internet and industrial standardization construction, digital-physical integration removes interconnection constraints of industrial chains and builds a full-domain collaborative industrial digital ecosystem. Unified industry data interfaces and standardized digital construction norms for segmented industries drastically lower the access threshold for SRDI enterprises to join industrial chain digital systems, enabling efficient linkage between corporate equipment, systems, businesses and industrial chain platforms. Furthermore, the industrial digital collaborative system led by chain leaders unblocks data barriers across industrial chains and supply chains. SRDI enterprises can share digital resources and distribute transformation costs by relying on industrial cluster ecosystems, breaking the limitations of standalone corporate transformation. This realizes the leap from independent digital renovation of single enterprises to collaborative digital upgrading of the entire industrial chain, and fully releases the empowering effects of industrial collaboration.

3.2.2. Empowerment of Public Service Platforms

Mismatched supply of digital transformation services is a vital external factor restricting the implementation of SRDI enterprises' digital transformation. Existing market-oriented digital solutions are mostly universal designs, unable to satisfy the personalized demands of SRDI enterprises in segmented sectors. In addition, the number of third-party service institutions is limited, and their service capabilities vary greatly[21]. Against the backdrop of digital-physical integration, public digital empowerment platforms jointly built by leading enterprises, research institutes, industry associations and cloud service providers effectively make up for service deficiencies. Focusing on SRDI enterprises' transformation demands, the platforms develop lightweight, targeted digital products and customized solutions, while providing one-stop integrated services including technical diagnosis, talent cultivation, scheme implementation and resource matching. This effectively resolves enterprises' dilemmas of being unable to transform and suffering defective transformation outcomes, drastically lowering the technical threshold and implementation difficulty of digital transformation.

3.2.3. Policy and Resource Empowerment

Digital transformation requires large investment, long return cycles and entails high risks. Restricted by capital and talent resources, most SRDI enterprises hold a wait-and-see attitude, being afraid to transform and advancing transformation slowly. Targeted policy support and industry-university-research collaborative resources have become critical external support for corporate digital transformation. In terms of policies, differentiated supportive measures such as special technical renovation subsidies, financial interest discounts and innovation vouchers effectively alleviate enterprises' capital pressure for digital renovation, and guide social capital to flow into corporate digitalization sectors. In terms of resources, the government-industry-university-research collaborative model cultivates digital professionals in a targeted manner to resolve enterprises' talent shortages[10]. By establishing industrial digital standard systems and regulating the third-party service market, the industrial ecosystem for digital transformation is optimized, providing institutional and resource safeguards for SRDI

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

enterprises to continuously deepen digital-physical integration and advance comprehensive digital transformation.

Digital-physical integration's internal empowerment and external empowerment are not isolated from each other, but form a complete transmission closed loop. Optimization of the external ecosystem lowers enterprises' transformation thresholds and dispels transformation concerns, creating favorable conditions for enterprises' internal digital renovation. The improvement of internal corporate capabilities further promotes enterprises to integrate into industrial digital ecosystems, access public services and policy dividends, and reversely drives the iterative upgrading of industrial ecosystems. Ultimately, a synergistic, virtuous circular empowerment system centered on digital-physical integration is formed, which systematically addresses the multiple transformation dilemmas of SRDI enterprises in an all-round, systematic manner, and pushes enterprises to achieve deeper digital transformation and high-quality development.

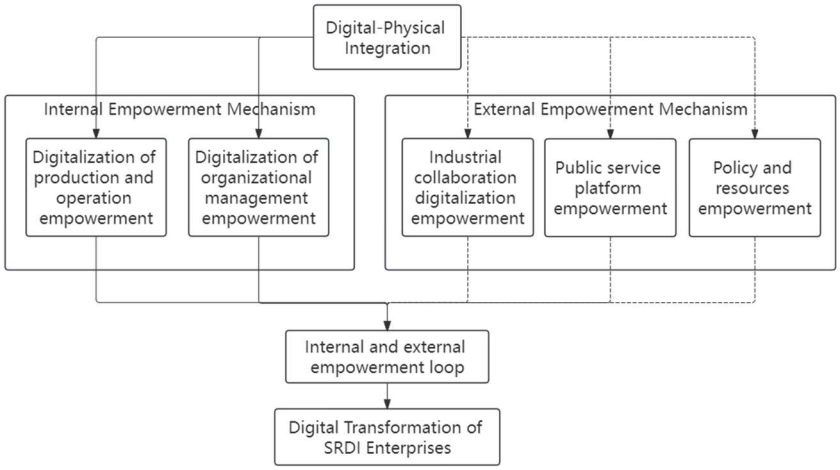

Figure 1. Functional Mechanism Framework of Digital-Physical Integration Empowering SRDI Enterprises' Digital Transformation

4. Realization Paths of Digital-Physical Integration Empowering SRDI Enterprises' Digital Transformation

4.1. Construct Tiered Empowerment Platforms

Relying on the national SRDI cultivation system, a targeted empowerment mechanism should be established to abandon the one-size-fits-all universal support model. For national-level SRDI "Little Giant" enterprises, high-end digital platforms should be prioritized for construction, integrated internal digital management systems should be built, full business data links should be unblocked, and data-driven refined operational decision-making should be leveraged to help enterprises deepen segmented market niches and overcome core "bottleneck" technologies. For provincial-level SRDI enterprises, focus should be placed on lightweight, low-cost transformation demands. The government should take the lead in building public digital service platforms to address enterprises' basic digital demands including production control, inventory management and customer operation maintenance[11].

Take Zhejiang Siling Intelligent Drive Technology Co., Ltd., an SRDI enterprise engaged in auto parts and robot components, as an example. Confronted with pain points such as operation management relying heavily on manual experience and difficult traceability of technological processes under the traditional manufacturing model, the enterprise built an intelligent manufacturing Industrial Internet platform, introduced high-end equipment and digital

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

technologies including 5G, MES and ERP, and unblocked information barriers between upstream and downstream industrial chains and production equipment. The enterprise realized traceable management of full-process production data, and acquired capabilities for precise positioning & backtracking of quality defects and intelligent prediction of production trends. Its per capita production efficiency rose by 20.9%, production costs per ten thousand yuan output value dropped by 16.7%, and product development cycles were shortened by 27.8%. The enterprise successfully transcended the traditional manufacturing stage and shifted toward lean and intelligent operation[2]. This case demonstrates that SRDI enterprises can realize the leap from single-point renovation to full-chain intelligent upgrading through high-end digital platform construction, offering a replicable transformation template for enterprises of the same tier.

4.2. Integrate Digital Industrial Chain Ecosystems

Based on Collaborative Governance Theory, leading industrial chain enterprises should play a driving role to unblock industrial chain data barriers and resolve the low efficiency of standalone transformation. First, leading enterprises in various industries should construct secondary Industrial Internet nodes and exclusive industrial digital platforms, unify data interfaces, transmission standards and security specifications for segmented sectors, drive upstream and downstream SRDI enterprises to access platforms in a lightweight manner, realize real-time interconnection of production data, and form a full-domain collaborative digital ecosystem[13]. Second, a digital collaborative assessment mechanism for industrial chains should be established to encourage leading enterprises to open mature technical systems, share supply chain resources, and distribute technological trial-and-error costs for SMEs.

According to pilot data from the Ministry of Industry and Information Technology, in industrial clusters with built industrial chain collaborative platforms, the digital transformation success rate of SRDI enterprises rose from 45% to 78%, and the average supply chain response speed improved by 25.6%. Meanwhile, focusing on technology-intensive key industries such as high-end equipment and new materials, vertical digital scenarios should be deeply cultivated to develop customized solutions matching segmented market niches, and strengthen the empowering effects of digital-physical integration on core production and R&D links.

4.3. Optimize Regional Digital Infrastructure and Policies

Based on regional development disparities and institutional constraints, differentiated regional empowerment strategies should be implemented to balance the transformation development gap between eastern, central and western regions. Relying on complete computing power and Industrial Internet infrastructure advantages, eastern regions should prioritize cultivating digital service providers for segmented sectors, expand digital service industrial clusters, launch specialized renovation schemes matching SRDI enterprises' niche customized demands, and build benchmark clusters for digital-physical integration transformation. Central and western regions should focus on making up for digital infrastructure weaknesses, deploy public computing power centers relying on the East Data-West Computing Initiative, roll out inclusive digital transformation subsidies and low-interest digital financial products, and lower enterprises' capital threshold for accessing digital ecosystems[4]. Meanwhile, drawing on special policies from Hubei, Hunan and other provinces, a dynamic digital transformation assessment mechanism for regional SRDI enterprises should be established, and special subsidies should be provided for enterprises carrying out transformation in equipment renovation, software procurement and talent training, alleviating empowerment constraints brought by regional institutional deficiencies and gradually narrowing regional transformation gaps.

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

4.4. Perfect Talent Cultivation and Cybersecurity Safeguards

Targeting core pain points including enterprises' shortage of digital talents and worries over data security, a dual safeguard system covering talent cultivation and cybersecurity protection should be constructed. In terms of talent development, deep industry-university-research integration should be promoted; universities, research institutes and industrial clusters should jointly build digital training bases to cultivate compound digital talents tailored to segmented manufacturing sectors. Digital talent sharing pools should be built relying on digital-physical integration platforms to resolve SMEs' difficulties in recruiting full-time digital talents at high costs[20].

In terms of security, regional data property rights protection and data security supervision systems should be improved, the ownership and security boundaries of enterprises' core process data and R&D data should be clarified, and industrial chain data security protection systems should be built to eliminate enterprises' worries over data leakage. Meanwhile, data compliance and other risks should be incorporated into enterprises' risk control systems to realize synchronous iteration of digital transformation and risk management, resolving enterprises' core pain point of fearing transformation.

5. Conclusion and Implications

5.1. Research Conclusion

Centering on digital-physical integration empowering SRDI enterprises' digital transformation, this paper conducts theoretical analysis. Grounded in relevant theories and combined with survey data from the China Academy of Information and Communications Technology and existing literature, it sorts out multiple constraints restricting SRDI enterprises' digital transformation, and constructs a closed-loop empowerment framework with dual internal and external channels. The analysis shows that digital-physical integration can eliminate enterprises' internal deficiencies in capital, equipment, talent and cognition from the dimensions of production & operation and organizational management; it can also resolve external dilemmas including poor industrial chain interconnection, data security risks and mismatched service supply through industrial collaboration, public services and policy resources, systematically addressing the five major transformation predicaments of SRDI enterprises: being unwilling to transform, fearing transformation, lacking capacity to transform, suffering defective transformation results, and advancing transformation slowly. Internal and external empowerment interact and generate cyclic synergies, jointly driving SRDI enterprises to complete digital transformation.

5.2. Implications

From the perspective of enterprise operation, SRDI enterprises should abandon radical transformation ideas of one-time full-production-line renovation. Combined with their own revenue scale and segmented production characteristics, they should prioritize deploying low-cost production management digital tools such as MES and ERP, and adopt a phased, lightweight renovation route. Meanwhile, enterprises should take the initiative to connect with regional public digital service platforms, leverage platform diagnosis and talent resources to fill internal digital talent gaps, and rely on industrial chain collaborative platforms to access upstream and downstream data resources, reducing standalone digital investment costs. Data-driven optimization of production scheduling and control workflows can fundamentally activate enterprises' willingness to transform.

From the perspective of government and industrial governance, local authorities should abandon one-size-fits-all universal supportive policies, and match technical renovation subsidies, innovation vouchers and other supportive tools in tiers for national-level Little Giant

ISSN: 2692-7608 DOI: 10.6981/FEM.202608_7(8).0009

enterprises and provincial-level SRDI enterprises. Leading industrial chain enterprises should be promoted to build Industrial Internet collaborative platforms, unify data interface standards for segmented industries, and break cross-firm data silos. Central and western regions should prioritize deploying computing power and digital infrastructure to narrow regional digital divides, while eastern industrial clusters should focus on cultivating vertical digital service providers. Meanwhile, industrial data security norms should be perfected to dispel enterprises' worries over core process data leakage, and build a comprehensive digital-physical integration industrial ecosystem matching the development demands of SRDI enterprises.

Acknowledgments

This project is the outcome of the provincial-level college student entrepreneurship practice project of Chengdu University. The project name is "Research on the Impact of Digital-Physical Integration on the Investment and Financing Behaviors of Specialized, Refined, Distinctive and Innovative Enterprises", and the project number is S202511079014S.

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