ZKG INTERNATIONAL
ISSN / eISSN 2366-1313
Publisher: BAUVERLAG BV GMBH,
AVENWEDDER STR 55, GUTERSLOH, GERMANY, 33311
Volume 25-Issue 1-(2025)

OPEN ACCESS

Collaborative innovation and value creation in the supply chain of engineering general contracting enterprises under the background of digital economy

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Abstract: With the surging wave of the digital economy, the deep penetration of information and intelligent technology in the field of engineering general contracting has triggered a paradigm shift in the traditional supply chain system. The cross-border integration effect brought about by digital empowerment not only provides unprecedented opportunities for enterprise supply chain collaboration, but also poses transformative challenges to existing value creation paths. To address the aforementioned "dual proposition", this article aims to construct a theoretical framework for collaborative innovation and value creation in the supply chain of engineering general contracting enterprises in the context of the digital economy. By systematically sorting out the multi-level internal evolution mechanism, we strive to provide actionable path guidance for practical decision-making. This study relies on literature review and semi-structured expert interviews, integrates integrated innovation theory, collaborative governance perspective, and value co creation model, and constructs a three-dimensional driving architecture of "technology empowerment organizational optimization ecological coordination"; Empirical analysis shows that the deep embedding of digital technology significantly improves the efficiency of supply chain collaboration. Driven by the digital economy, engineering general contracting enterprises should coordinate and promote the three basic aspects of technological empowerment, organizational change, and ecological collaboration. Through multi-level linkage mechanisms, they should catalyze supply chain innovation and achieve a paradigm shift from value co creation to sustained value-added; And based on this, build a dynamic adaptive evaluation system to cope with environmental uncertainty. This article not only enriches the research perspective of supply chain collaborative innovation and value creation theory, but also provides in-depth and operational path suggestions for industry practice, which has important implications for policy-making.

Keywords: Digital economy; Engineering general contracting; Collaborative innovation in supply chain; Value creation

I. Introduction

The booming rise of the digital economy is irreversibly reshaping the global industrial landscape. As a pillar industry of the national economy, the development model and value logic of the engineering construction sector have undergone profound changes (Kankhva et al., 2021; Tkachenko et al., 2019). The core of this transformation lies in the deep penetration of data elements, which triggers the systematic reconstruction of production functions and promotes the transformation of industrial forms from traditional linear chains to digital ecological networks (Raptis et al., 2019). As a new economic form following agricultural and industrial economies, the theoretical core of digital economy is rooted in the reconstruction logic of "mobile space" and "local space" in the theory of "network society" (Van, 2020; Castells, 2004). As shown in Figure 1, the Global Digital Economy Development Index (TIMG) compiled by the Institute of Finance of the Chinese Academy of Social Sciences indicates that the Matthew Effect caused by the development of the digital economy has attracted additional attention from developed countries towards the development of the digital economy.

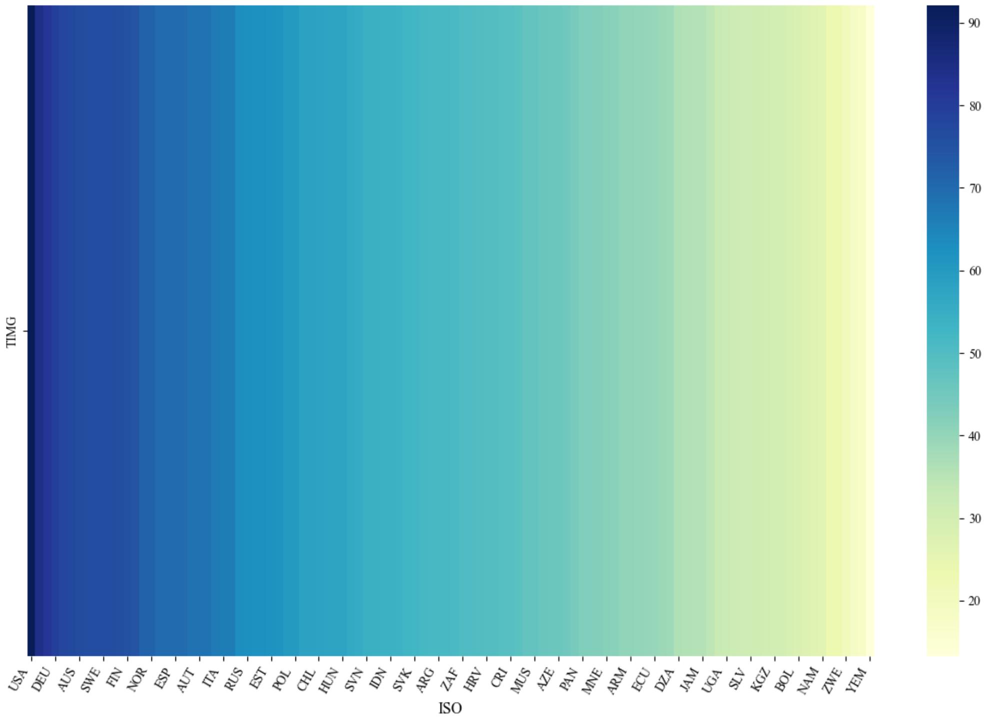

Figure 1 TIMG heatmap

From an economic perspective, the digital economy breaks through the shackles of diminishing marginal returns of traditional factors through the non competitive characteristics of data elements, forming a new growth paradigm of data empowerment, efficiency improvement, and value reconstruction (Goldfarb et al., 2015). The penetration of this paradigm in the field of engineering construction is essentially the systematic reconstruction of capital, labor, technology and other elements in the engineering production function through the "general-purpose technology" attribute of digital technology, promoting the transition of industrial form from linear value chain to networked value ecology (Zhang et al., 2021; Jovanovic & Rousseau, 2005; Baier et al., 2023).

As shown in Figure 2, in the dimension of production factors, data has surpassed traditional factors such as land and capital, becoming the core engine driving the generation of value throughout the entire life cycle of engineering construction (Shahandashti et al., 2011; Kalinichenko, 1990). Through the parameterized iteration of building information models, real-time perception of the Internet of Things, and the trusted authentication technology of blockchain, engineering information can be transformed from fragmented records into structured assets, laying the foundation for full process collaboration (Shahandashti et al., 2011). At the organizational level, as the core organizer of the supply chain, the coordination mode of engineering general contracting enterprises is shifting from hierarchical control to ecological empowerment.

The construction of digital platforms enables real-time interaction between design, construction, supply and other links, significantly improving the response efficiency of the industrial chain (Wagner, 2020). From the perspective of industrial ecology, the emergence of new paradigms such as intelligent construction and green construction has propelled engineering construction from extensive construction to precision intelligent manufacturing. The integrated application of digital technology not only optimizes resource allocation efficiency, but also reconstructs the underlying logic of industrial value creation (Wang et al., 2024). This paradigm reconstruction is not only a technological upgrade, but also a deep adjustment of production relations, requiring engineering general contracting (EPC) enterprises to re-examine the inherent laws of supply chain collaboration to adapt to the new competitive situation in the digital economy (Huang et al., 2024).

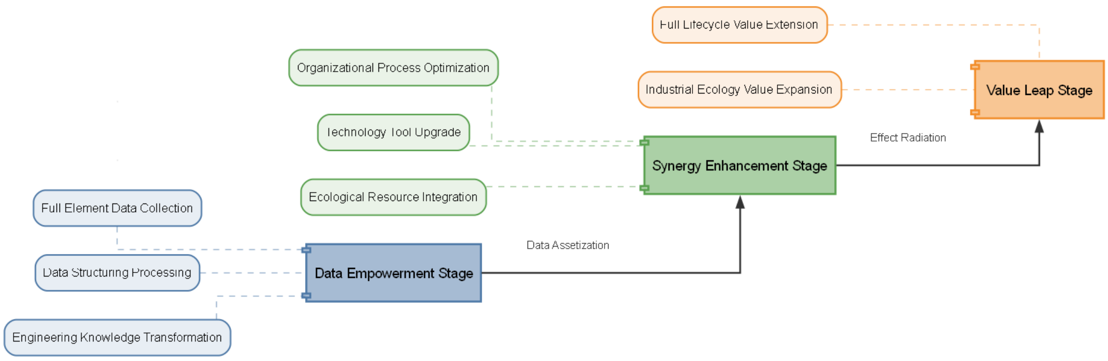

Figure 2 Schematic diagram of the impact of the digital economy

However, as the mainstream paradigm of integrated management in the field of engineering construction, the EPC model has always faced multiple structural challenges in its supply chain collaboration (Yeo & Ning, 2002; Huang et al., 2024). The phenomenon of collaborative obstruction caused by information barriers is particularly prominent, with version differences in design drawings, information lag in construction progress, and parameter deviations in material supply forming "information islands" that constrain the overall efficiency of the supply chain. The collaborative failure caused by the game of interests cannot be ignored. The progress demands of the owners, the cost pressure of the construction party, and the profit pursuit of the suppliers form multiple target conflicts. Short term cooperation under traditional contract constraints is difficult to build a community of interests, resulting in insufficient collaborative innovation momentum. The collaborative gap caused by technological heterogeneity further exacerbates the complexity of the problem, with inconsistent technical standards and incompatible system interfaces adopted by all parties involved, making it difficult to fully unleash the collaborative efficiency of digital technology.

However, it can be said that the development of the digital economy also provides a historic opportunity to solve these problems (Shahandashti et al., 2011; Kalinichenko, 1990; Wang et al., 2024). The integration of 5G and edge computing has realized real-time interaction on the construction site. Digital twin technology supports all factor virtual simulation. The application of smart contracts simplifies the transaction process and provides a technical base for collaborative innovation (Nour et al., 2024). The construction of an engineering big data platform promotes the real-time flow of data such as design parameters, construction progress, and material performance, and drives collaborative decision-making from experience driven to data-driven. The rise of platform based enterprises has broken down traditional industry barriers, enabling engineering general contracting enterprises to integrate full chain resources through digital platforms and build a "symbiotic and win-win" industrial ecosystem (Zhang et al., 2017). In this context, exploring effective paths for collaborative innovation and value creation in the EPC supply chain has become an inevitable choice for EPC enterprises to achieve high-quality development.

Existing research has accumulated certain achievements in the field of engineering supply chain collaboration, but there are still significant theoretical gaps. Firstly, at the level of technological application, most research focuses on the application effects of a single digital technology in the supply chain, lacking a systematic exploration of the collaborative mechanisms of technology clusters and failing to reveal the special relationships between different technologies. Secondly, research on organizational governance is often limited to internal or bilateral cooperation relationships within enterprises, with insufficient attention paid to dynamic governance mechanisms for multilateral entities, particularly overlooking the governance challenges brought about by the blurring of organizational boundaries in the digital economy. Thirdly, research on value creation often stays at the level of short-term benefits such as efficiency improvement, and the analysis of the long-term effects of extending the value of the entire life cycle and ecological value expansion is not in-depth enough, failing to construct a theoretical framework for dynamic transmission. Fourthly, existing research rarely places technology, organization, and ecology within a unified analytical framework, lacking a systematic explanation of their interactive relationship, making it difficult to guide the practice of collaborative innovation in the supply chain of engineering general contracting enterprises.

Based on this, this article focuses on collaborative innovation and value creation in the supply chain of EPC enterprises under the background of the digital economy. Through literature review and expert interviews, integrating multiple perspectives such as integrated innovation theory, a three-dimensional driving architecture of technology empowerment, organizational optimization, and ecological coordination is constructed. The collaborative mechanism of digital technology clusters such as blockchain, Internet of Things, and digital twins is systematically analyzed, and a multi-level linkage mechanism of technology empowerment, organizational change, and ecological governance is designed. The impact of digital collaboration depth on efficiency value, innovation value, and strategic value is empirically tested, and a dynamic adaptive evaluation system is ultimately constructed. In theory, this article enriches the research perspective of supply chain collaborative innovation and value creation, fills the theoretical gap of single technology application, bilateral governance, and short-term benefit analysis, and integrates multidisciplinary theories to form a more systematic analytical framework; In practice, this article provides EPC enterprises with a feasible path for technological empowerment, organizational change, and ecological collaboration, which has important implications for the high-quality development of the industry and the formulation of related policies.

II. Theoretical Analysis

1. Technological development

The development of theoretical technology is shown in Figure 3. The integration of core digital economy technologies with engineering supply chains is essentially a dynamic adaptation process between technological attributes and industrial demands. This integration is reflected not only in the transformation of supply chain processes by technology, but also in the reverse shaping of technology applications in supply chain scenarios (Chupanova et al., 2021; Liu et al., 2023). Blockchain technology, with its distributed accounting, tamper proof, and smart contract features, provides underlying technical support for the trustworthy traceability of engineering supply chains (Huang et al., 2019). In the field of engineering construction, information asymmetry in various links of the supply chain often leads to vague responsibility definition and difficulty in quality traceability. However, blockchain builds a decentralized trust mechanism to store key node information such as material procurement, construction acceptance, and quality inspection on the chain, forming an immutable full process data chain. This technology not only enables traceability from the source to the end, but also reconstructs the trust generation method between supply chain entities, enabling cross organizational collaboration to break free from dependence on a single authoritative entity and shift towards autonomous trust based on technical agreements. In existing research, the application of blockchain in the field of supply chain finance has formed a relatively mature paradigm, such as automatically executing payment conditions through smart contracts, and improving transaction efficiency in scenarios such as engineering advance payment guarantees and performance guarantees; Its exploration in engineering quality traceability focuses on building material traceability and process certification, forming a chain verification system for manufacturers, logistics companies, and construction units.

The Internet of Things technology realizes the dynamic scheduling of engineering supply chain resources through ubiquitous sensing devices and the Internet of Everything (Hada&Mitsugi, 2021). At the project construction site, the IoT terminal can collect equipment operation parameters, personnel operation status, material inventory level and other data in real time, and transmit them to the cloud platform after being processed by the edge computing node to form a globally visible dynamic map of resources. This real-time data feedback mechanism breaks the traditional static mode driven by supply chain planning and shifts towards data-driven dynamic adaptation, enabling resource scheduling to quickly respond to on-site changes. Existing research has explored the integration path of the Internet of Things and BIM technology, by mapping the perception data of physical entities to digital models, and constructing a collaborative scene of "entity virtual" bidirectional interaction (Chen et al., 2023); In the prefabricated component supply chain, the application of IoT technology has achieved full process status monitoring from production, transportation to installation, providing technical support for Just In Time distribution. As an emerging research direction, the application of digital twin technology in engineering supply chain is evolving from single link simulation to full lifecycle collaboration. By constructing real-time mapping between physical engineering and digital images, it supports cross stage collaboration in design optimization, construction simulation, and operation and maintenance prediction.

The applicability of collaborative innovation theory in EPC supply chain can be further explained from two dimensions: supply chain capability construction and system dynamic evolution (Shi et al., 2022). A collaborative capability analysis framework based on the VRIO model decomposes the collaborative capability of EPC supply chain into four dimensions: value, scarcity, non imitability, and organization. At the value level, collaborative innovation in the EPC supply chain can reduce transaction costs, shorten project cycles, and directly create engineering value through resource integration; Scarcity is reflected in the fact that not all enterprises possess the digital infrastructure and organizational coordination capabilities required for high-quality collaboration; Non imitability arises from the implicit knowledge and relational capital formed during the collaborative process, which are difficult for competitors to replicate; Organizing emphasizes the need for EPC general contracting enterprises to establish a suitable process system to activate the value release of collaborative capabilities. The resource dependence theory provides another perspective for analyzing the collaborative motivation among EPC supply chain entities. This theory holds that supply chain entities form a dependency relationship due to resource complementarity, and collaborative innovation is an important path to reduce dependency risks and improve overall efficiency. Existing research has applied this theory to explain the collaborative behavior between design units and construction enterprises in technical disclosure and scheme optimization.

2. Theoretical perspective

From the perspective of Complex Adaptive Systems (CAS) theory, the EPC supply chain is a complex adaptive system composed of multiple heterogeneous entities such as design units, construction companies, suppliers, and supervisory agencies. Each entity achieves overall collaboration through information exchange and behavioral adaptation (Statsenko et al., 2018). The "adaptive learning" characteristic in CAS theory is manifested in the EPC supply chain as the subject adjusts its own strategy according to environmental changes, such as suppliers adjusting production plans based on construction progress, and design units optimizing design schemes based on on-site feedback; And 'emergence' is reflected in the collaborative superposition of individual behaviors to generate new functions at the system level, such as the improvement of project risk management capabilities brought about by multi-agent collaborative decision-making. The social capital theory focuses on the impact of trust, norms, and network structure in supply chain networks on collaborative innovation. Research has shown that social capital formed through long-term cooperation can reduce transaction costs in collaboration and promote the sharing and transformation of tacit knowledge.

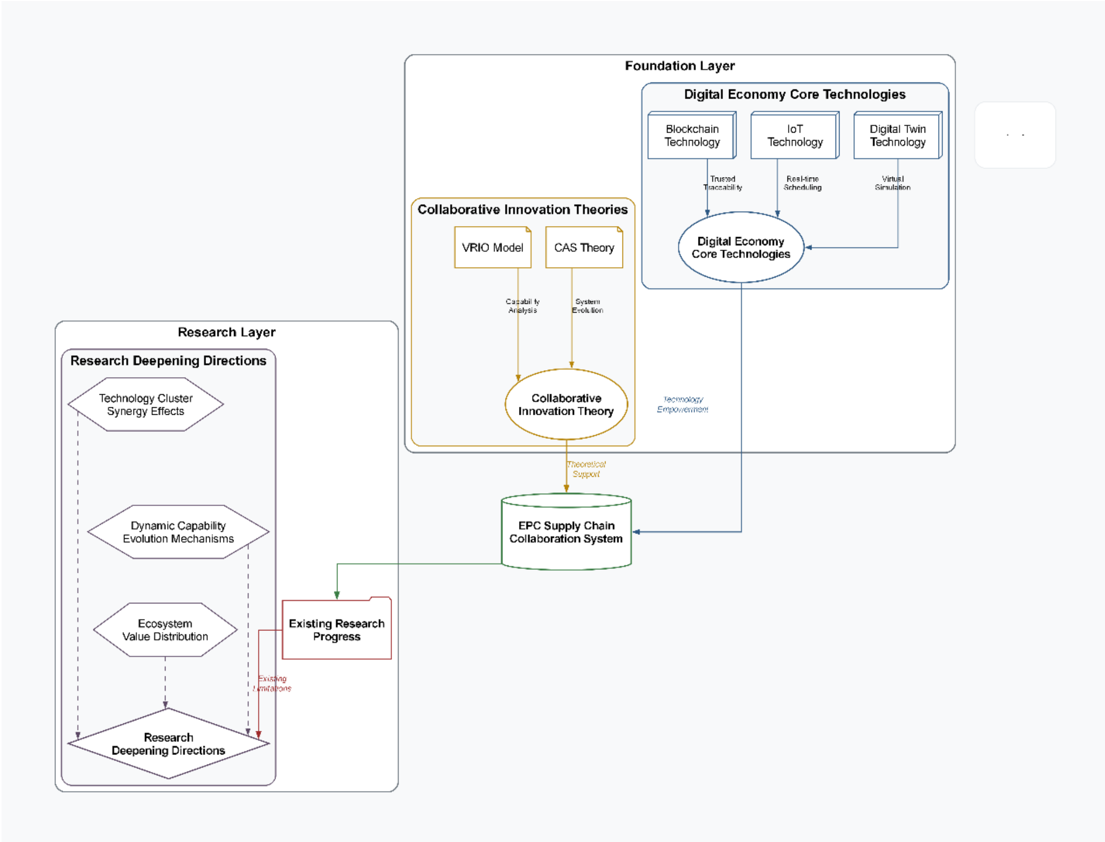

Figure 3 Schematic diagram of theoretical and technological impact

At present, the cross research on collaborative innovation between digital economy and EPC supply chain has accumulated certain achievements, but there is still room for expansion in theoretical depth. In the research of technology integration, most achievements focus on the analysis of application scenarios of a single technology, and there is still insufficient exploration of the adaptability rules of multi technology integration. The dynamic matching mechanism between technology combination and supply chain links still needs to be clarified. At the theoretical application level, existing research lacks integration and application of different theories, such as the insufficient cross analysis between VRIO model and CAS theory, which makes it difficult to fully reveal the dynamic evolution logic of collaborative capabilities. In terms of research perspective, there is still room for improvement in the overall examination of the EPC supply chain ecosystem. As the core production factor of the digital economy, the role mechanism of data elements in the distribution of supply chain value has not yet been systematically explained. The blank spaces in these explorations provide the possibility of constructing a more inclusive theoretical framework and also provide a path for deepening research to connect theory and practice.

III. Mechanism Design

As shown in Figure 4, the driving architecture of the digital economy for the collaborative supply chain of engineering general contracting in this article is designed to form a closed loop through mechanisms at three levels: technological empowerment, organizational change, and ecological governance. This multi-level mechanism reflects not only the reshaping of collaborative foundations by technological architecture, but also the adaptation of organizational forms to collaborative models, and the guarantee of institutional arrangements for collaborative ecology. The three are nested together to form a progressive collaborative momentum.

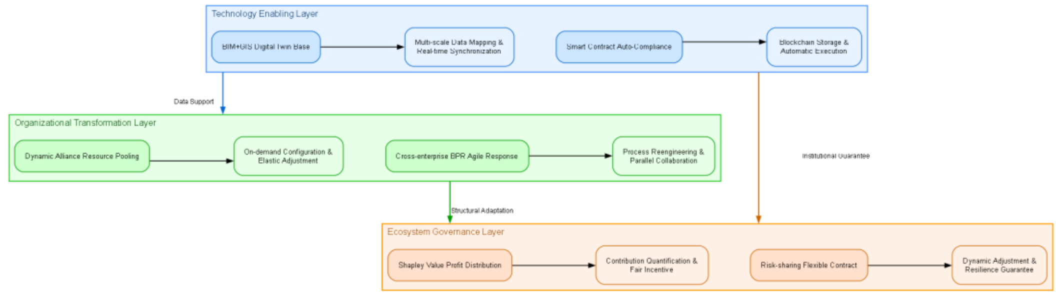

Figure 4 Schematic diagram of supply chain collaboration mechanism driven by digital economy

1. Technical enablement layer

The technology enablement layer serves as the fundamental support for supply chain collaboration, with its core being the penetration flow of data elements in various links of the supply chain through digital technology, breaking down traditional information barriers, and constructing a real-time mapping system between the physical world and digital space to eliminate the bullwhip effect of the supply chain through data penetration.

The integration of BIM and GIS technology provides a key technical path for building a digital twin base for the entire lifecycle of engineering (Deng et al., 2019). BIM technology digitizes the geometric information and physical attributes of building components through parametric modeling, while GIS technology integrates macro information such as the surrounding environment and topography within a geographic spatial framework. The coupling of the two forms a multi-scale digital mapping of "micro components meso architecture macro environment". This digital twin base can not only synchronize dynamic data such as progress, quality, and safety on the construction site in real time, but also provide full chain data support for design optimization, construction organization, and operation and maintenance management through historical data iteration and future scenario simulation. It enables all participants in the supply chain to make collaborative decisions based on a unified digital image and achieve transformation.

Based on the coupling of BIM and GIS, establish a full element digital image of engineering entities. The dynamic mapping relationship can be expressed as:

$$\Phi(P_t) = \sum_{i=1}^{n} \left[\alpha \cdot S_i(\text{GEO}) + \theta \cdot D_i(\text{BIM}) \right] + \varepsilon_{\Delta t} \quad (1)$$

Among them, S_i is the geographic spatial attribute, D_i is the component IoT data, and α and β are the spatiotemporal weight coefficients.

Smart contracts, supported by blockchain technology, have established a new mechanism for automatic performance supervision in the supply chain. By coding and deploying contract terms in a distributed ledger, smart contracts can automatically trigger performance based on preset conditions, such as automatically executing engineering payment instructions when the construction progress collected by IoT devices reaches the node requirements (Chang et al., 2019); When the material testing data meets the quality standards, the acceptance confirmation is automatically completed. This automated performance mechanism not only reduces the manual intervention and communication costs in traditional contract execution, but also ensures the transparency and trustworthiness of the performance process through the immutability of blockchain, reduces the risk of opportunistic behavior, and provides rigid technical constraints for supply chain collaboration.

The execution of smart contracts empowered by blockchain, assuming the supply chain contract term set $C=\{c_1,c_2,...,c_m\}$, is automatically fulfilled through a distributed ledger. The expression is as follows:

$$\forall c_k \in C, \quad \text{Execute}(c_k) = \begin{cases} 1 & \text{if } F(\text{IoT\_data}) \geq \theta_R \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

2. Organizational change layer

The construction of a decentralized collaborative network in the organizational change layer has evolved from a tree like hierarchical structure to a networked dynamic alliance. The resource pooling strategy of its dynamic alliance system integrates the dispersed resources of various supply chain entities guided by project requirements, forming a shared resource pool across enterprises. This type of alliance is not a fixed organizational entity, but dynamically adjusts its member composition based on factors such as project scale, technical requirements, and regional characteristics, achieving precise matching of resources such as design, construction, and manufacturing. For example, in large-scale infrastructure projects, alliances can attract enterprises with special construction qualifications; In green building projects, the focus is on integrating environmental material suppliers and energy-saving technology service providers. Resource pooling achieves real-time integration of supply and demand information through digital platforms, transforming resource allocation from "idle stock" to "incremental sharing" and improving the overall resource utilization efficiency of the supply chain.

The expression for the supplier capability evaluation function established by the dynamic resource pooling model is as follows:

$$C(v_i) = w_1 \cdot Q_{\text{hist}} + w_2 \cdot R_{\text{flex}} + w_3 \cdot I_{\text{tech}} \tag{3}$$

Q_{hist} represents historical performance quality, R_{flex} represents resource elasticity coefficient, and I_{tech} represents technological innovation index.

The agile response mechanism constructed by Cross Enterprise Process Reengineering (BPR) achieves cross organizational process collaboration and rapid response by streamlining the core business processes of the supply chain and eliminating redundant links. With the support of digital technology, the traditional serial design procurement construction process has been restructured into a parallel collaborative mode. The BIM model changes of the design unit can be synchronized in real time to the construction enterprise, triggering the adjustment of the construction plan (Jung & Joo, 2011); Sudden situations on the construction site can also be quickly transmitted to the design party through digital platforms, forming a closed loop of problem feedback to scheme iteration and execution adjustment. This process reengineering is not simply about deleting links, but rather a process reconstruction based on data connectivity. Through standardized data interfaces and modular process design, supply chain entities can quickly adapt to changes in project requirements and enhance collaborative agility. The cross organizational process reengineering mechanism constructs a business process collaboration matrix, expressed as follows:

$$\text{BPR} = \begin{bmatrix} \phi_{11} & \cdots & \phi_{1n} \\ \vdots & \text{API\_Gateway} & \vdots \\ \phi_{m1} & \cdots & \phi_{mn} \end{bmatrix} \tag{4}$$

When monitoring data is abnormal, the system generates optimization instructions to adjust resource allocation.

3. Ecological governance layer

The ecological governance layer is committed to building a symbiotic and win-win value network through institutional design, providing long-term guarantees for supply chain collaboration. The profit distribution model based on Shapley value allocates benefits based on the marginal contribution of each participating entity to the total revenue of the supply chain. Its core logic is to correlate the revenue of each entity with its contribution in different subset alliances, ensuring the fairness of the distribution results (Yue et al., 2025). In the engineering general contracting supply chain, this model not only considers the construction implementation contribution of construction enterprises, but also incorporates multiple contribution elements such as the innovative value of design units and material technology breakthroughs of suppliers. Through quantitative analysis, it avoids the phenomenon of "free riding" and stimulates the collaborative innovation drive of all parties. The improved Shapley value allocation model defines a three-dimensional contribution measurement function, expressed as follows:

$$V_i = \underbrace{0.35\ln(I_i)}_{\text{Input Intensity}} + \underbrace{0.45e^{0.3c_i}}_{\text{Innovation Contribution}} + \underbrace{0.2h_i^{1.5}}_{\text{Risk Bearing}} \quad (5)$$

The total revenue distribution of the alliance satisfies the following expression:

$$\varphi_i(v) = \sum_{S\subseteq N,\ \{i\}} \frac{|S|!(|N|-|S|-1)!}{|N|!}\left(v(S\cup\{i\})-v(S)\right) \quad (6)$$

The flexible contract system of risk sharing addresses uncertainty in the engineering supply chain by designing dynamic adjustment clauses. Unlike traditional fixed contracts, flexible contracts preset risk sharing triggering conditions, such as automatically activating cost sharing mechanisms when raw material prices fluctuate beyond a threshold; When the construction period is delayed due to force majeure, the responsibility ratio of each party shall be adjusted according to the degree of impact. This contract system not only achieves real-time sharing and evaluation of risk information through digital platforms, but also relies on blockchain technology to ensure the rigid execution of contract terms. While safeguarding the legitimate rights and interests of all parties, it enhances the resilience of the supply chain to external disturbances and maintains the long-term stability of the ecological network.

The expression for the risk hedging function established by the elastic risk contract architecture is as follows:

$$\Pi_{\text{hedge}} = \left[\gamma\cdot P_{\text{material}}^{\max} + (1-\gamma)\cdot\mu_{\text{demand}}\right]\cdot V_{\text{reserve}} \quad (7)$$

The dynamic adjustment rules for the risk reserve fund $V_{reserve}$ include:

$$\frac{dV}{dt} = k_p \frac{\partial^2 V}{\partial t^2} - k_d \cdot \text{Claim} \tag{8}$$

IV. Empirical Analysis

As shown in Figure 5, there is an inherent logic of deep coupling between the mechanism design of supply chain collaboration driven by the digital economy and the value creation path. The former constitutes the underlying support of the latter, while the latter is the external manifestation of the former's efficiency release. The technology enablement layer achieves data penetration through BIM+GIS digital twin base and builds an automatic performance system for smart contracts, providing core explanatory variables for empirical analysis of efficiency value dimensions. When design parameters and procurement requirements are linked in real-time through digital mirroring, the DEA model calculates the improvement of procurement efficiency and obtains causal support at the technical level; The inhibitory effect of smart contracts on supply-demand mismatch is precisely the key driving factor for the dynamic improvement of inventory turnover in VAR models. The direct correlation between this technological empowerment and efficiency improvement confirms the reshaping effect of data element integration on the basic operation of the supply chain.

The organizational change layer provides an organizational carrier for the generation of innovative value dimensions. The increase in knowledge sharing density brought about by resource pooling amplifies the knowledge spillover effect through collaborative networks, providing a foundation for the implementation of chain innovation triggered by modular design. This is also the organizational root of innovation cycle improvement in the empirical value of innovation. The ecological governance layer provides institutional guarantees for the ecological niche transition and ESG premium in the strategic value dimension. The fair interest coordination mechanism promotes the transformation of supply chain entities from simple transactional relationships to symbiotic partnerships. The accumulation of such relationship capital not only broadens the breadth of the enterprise's ecological niche, but also lays a trust foundation for the continuous promotion of green collaborative practices.

The three levels of mechanism design and the three dimensions of value creation form a corresponding transmission chain. The precision of technological enablement supports the quantitative improvement of efficiency value, the flexibility of organizational change catalyzes the quality and efficiency improvement of innovation value, and the stability of ecological governance ensures the long-term accumulation of strategic value. The subsequent empirical analysis follows this logical chain and verifies the actual impact of different mechanisms on value creation through quantitative methods.

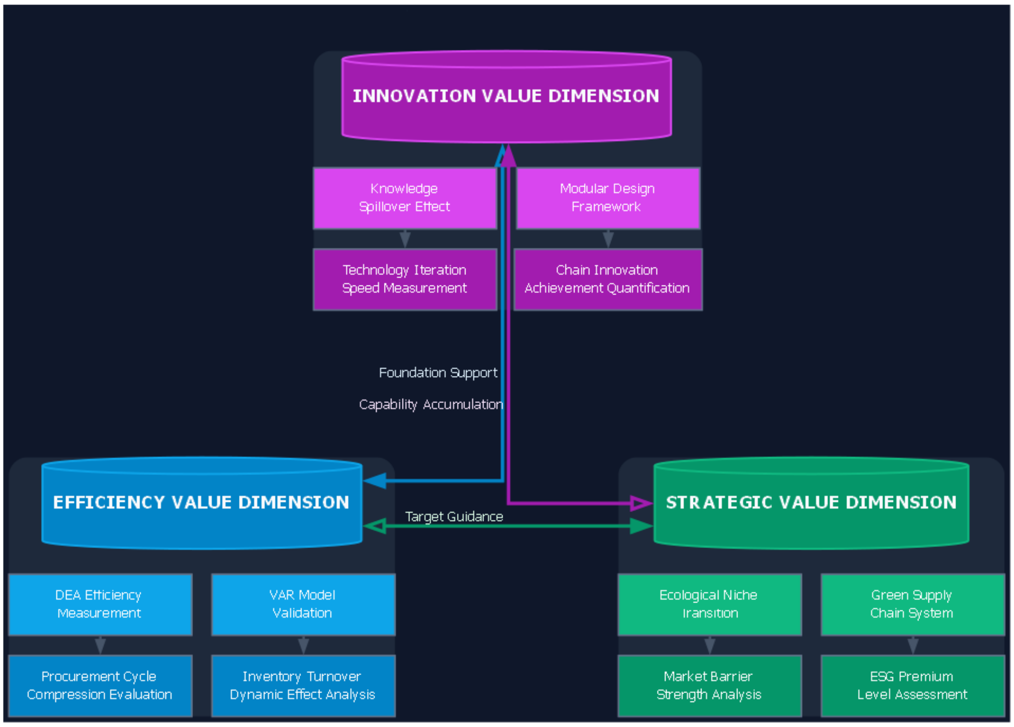

Figure 5 Schematic diagram of value creation path

1. Data collection

This study constructs a three-dimensional research sample library for multi-source heterogeneous data fusion. Data collection strictly follows the three-level stratified sampling framework, and based on the "Smart Construction Demonstration Project Library" of the Ministry of Housing and Urban Rural Development, 126 EPC projects that apply core digital technologies such as blockchain and the Internet of Things from 2019 to 2023 are selected to form the basic sample pool, ensuring a high degree of fit between the research object and the digital economy application scenarios; The middle layer integrates the "Engineering Construction Enterprise Annual Report Database" of the National Bureau of Statistics, systematically extracts financial and operational indicators of sample project related enterprises in supply chain management during the same period, and forms the basic dimension for quantitative analysis; At the bottom level, based on the targeted enterprise research initiated by the author's research group, in-depth interviews were conducted with the supply chain management departments of 48 special qualification general contracting enterprises to collect unstructured collaborative practice details and fill the information gap of public data at the micro operational level.

To ensure the representativeness of the sample, the study covers three major infrastructure fields including municipal, transportation, and energy in terms of project types, and covers seven major national strategic regions including the Yangtze River Delta, Guangdong Hong Kong Macao, and Chengdu Chongqing Economic Circle in terms of regional distribution. Ultimately, a non-equilibrium panel data consisting of 1742 annual observations of enterprises was formed. The data cleaning stage uses Bayesian network correction algorithm to identify and eliminate outlier interference. Firstly, with regard to the threshold setting for the application of digital technology, 18 projects that have not substantially deployed blockchain trustworthy traceability systems or IoT real-time sensing devices will be excluded. This is because such samples lack the basic carrier of the core variable "digital collaborative technology application" and do not meet the definition of "digital economy driven" in this study. Secondly, based on the principle of data integrity, samples with a missing rate of more than 15% for key indicators were excluded, including annual observations of enterprises with three or more quarters of missing indicators such as supply chain collaboration efficiency, as well as project samples with incomplete records of micro operation data such as BIM model collaboration frequency and smart contract execution frequency. Finally, 63 observations with structural data gaps were excluded.

At the level of logical consistency verification, samples with conflicting information are excluded. Firstly, there are 12 samples where the deviation between the supply chain management costs disclosed in the annual report and the collaborative expenses recorded at the project level exceeds 30% and cannot be verified through original vouchers; Secondly, there are 7 cases where there is a substantial conflict between the collaborative practice description in the targeted interview records and the system log data, which may pose a risk of data forgery or recording errors. In addition, considering the interference of extreme values on model estimation, the modified Z-score method was used to identify and eliminate 14 abnormal observations with Z-score absolute values greater than 3.29 in financial indicators. After multiple rounds of screening, 1640 valid annual observations of enterprises were ultimately retained.

2. Variable definition

The independent variable is Digital Collaboration Depth (DCD), which characterizes the penetration intensity and collaborative complexity of digital technology throughout the entire supply chain. The expression is as follows:

$$DCD = \underset{\text{Weight}}{0.25} \times \frac{D_T}{D_{\max}} + \underset{\text{Weight}}{0.35} \times \ln\left(1 + API_d\right) + \underset{\text{Weight}}{0.40} \times \left(1 - e^{-0.2K_p}\right) \qquad (9)$$

D_T is the digital twin coverage index, D_T=BIM+GIS fusion rate x IoT device density, API_d is the number of cross organizational API interfaces, and K_p is the proportion of daily active users on the knowledge collaboration platform.

The dependent variable system is divided into three dimensions, namely efficiency value dimension, innovation value dimension, and strategic value dimension. The specific definitions of dependent and control variables are shown in Table 1.

Table 1 Variable Definition

Variable Category	Variable Name	Symbol
Dependent Variables	Procurement Cycle Reduction	PCR
	Inventory Turnover Acceleration	ITA
	Knowledge Spillover Intensity	KSE
	Chain Innovation Diffusion Index	CDI
	Ecological Niche Barrier	ENB
	ESG Premium Factor	ESGpf
Control Variables	Firm Size	Size
	Financial Leverage	Lev
	Project Complexity	PComp
	Contract Type	ContTyp
	Regional Digital Infrastructure	RegInf
	Material Price Volatility	MatVol

The PCR expression is as follows:

$$PCR = \frac{\text{Threshold} - T_{\text{actual}}}{T_{\text{benchmark}}} \times 100\% \qquad (10)$$

The ITA expression is as follows:

$$ITA = \left(\frac{\text{Current Period Turnover}}{\text{Industry Base Period Turnover}} - 1\right) \times \frac{365}{\Delta t} \qquad (11)$$

The KSE expression is as follows:

$$KSE=\frac{\text{Avg. Patent Citations}}{\text{Avg. Path Length in Knowledge Network}}\times e^{-0.05\cdot\text{Technology Gap}} \quad (12)$$

The CDI expression is as follows:

$$CDI=\frac{N_{\text{Innovation}}}{N_{\text{Source}}}\times\left(1-e^{-0.01t_{i/j}}\right) \quad (13)$$

The ENB expression is as follows:

$$ENB=\frac{\text{Market Share}\times\ln\left(1+\text{Proprietary Technology Ratio}\right)}{\text{HHI}} \quad (14)$$

The ESGpf expression is as follows:

$$ESGpf=\frac{(P/E)_{\text{firm}}-(P/E)_{\text{Industry}}}{\sigma_{\text{Industry}}}+0.1\cdot\Delta\text{MSCI Rating} \quad (15)$$

Size=ln(Total Assets) (Log-transformed), Lev=Interest-bearing Liabilities/Equity, PComp=0.6×BIM Components+0.4×Special Equipment Ratio, ContTyp is dummy, EPC=1, DB=2, DBB=3, RegInf=Provincial Digital Economy Index, the MatVol expression is as follows:

$$MatVol=\frac{1}{52}\sum_{k=1}^{52}\text{AbsReturn}_k\times 100 \quad (16)$$

3. Model setting

To empirically test the impact of supply chain collaboration mechanisms driven by the digital economy on value creation, this study constructs the following econometric model system to reveal the quantitative relationships between core variables:

$$Y_{it}=\alpha_0+\alpha_1X_{it}+\sum\alpha_x\text{control}_{it}+\mu_i+\lambda_t+\varepsilon_{it} \quad (17)$$

Among them, $Y_{i,t}$ represent dependent variables; $X_{i,t}$ is the core independent variable; $control_{i,t}$ is a series of control variables, including enterprise size, project complexity, industry competition level, etc; μ_i is an individual fixed effect that controls for individual characteristics that do not change over time; λ_t is a time fixed effect that captures temporal fluctuations in the macro environment; $\varepsilon_{i,t}$ is a random perturbation term; α_0 is a constant term, α_1 is the coefficient of the core explanatory variable, and α_k is the coefficient of the control variable.

4. Descriptive analysis

The variables of value creation in various dimensions show a trend of differentiation. The PCR mean is 23.7% and the median is 22.1%, indicating that the overall distribution is relatively symmetrical. The 8.2% standard deviation shows that there are certain differences in the improvement of procurement efficiency among different projects. The difference between the minimum value of 5.3% and the maximum value of 47.6% reflects the uneven level of digital collaborative application. The ITA mean is 1.82, median is 1.79, skewness is 0.68, showing a slight right skewed distribution, indicating that the inventory turnover efficiency of most projects is at a moderate level, while a few projects achieve high-speed improvement through digital collaboration. In the dimension of innovation value, the mean KSE is 3.17 and the standard deviation is 1.23, with a relatively flat distribution, indicating that the overall strength of supply chain knowledge flow is moderate. The minimum value of 0.85 suggests that some traditional projects still have knowledge barriers. CDI exhibits significant right skewed features and a spike distribution, with a mean of 2.56 higher than the median of 2.38, and a maximum value of 8.03 much higher than the mean, indicating that the innovation chain reaction caused by modular design is prominent in a few benchmark projects, while most projects are still in the progressive innovation stage.

The ENB of the strategic value dimension has a mean of 0.68 and a median of 0.63, showing a right skewed distribution. The maximum value of 1.92 indicates that top companies have established strong market barriers through digital collaboration. The mean value of ESGpf is 1.05, with a standard deviation of 0.47, and the distribution is close to symmetrical. The minimum value of -0.38 reflects that some companies have not yet achieved ESG value conversion, while the maximum value of 3.27 verifies the value differentiation effect of green supply chain practices.

The mean value of DCD is 0.59, with a median of 0.61. The distribution shows a slight left bias, indicating that more than half of the sample enterprises have reached a moderate or above level of collaboration. The range of 0.21-0.93 covers the entire spectrum from basic digitization to deep collaboration. The kurtosis of 2.86 is close to a normal distribution, providing a data basis for robust estimation of the core explanatory variables.

The distribution patterns of various variables reveal significant heterogeneity in the engineering general contracting supply chain under the digital economy, and the value creation indicators generally exhibit a rightward bias, indicating that a few leading enterprises have achieved value leaps through deep collaborative innovation, while most enterprises are still in the catching up stage. The contrast between the concentrated distribution of DCD and the high dispersion of value creation indicators suggests a difference in the efficiency of digital collaboration to value transformation, which provides a starting point for further research on the boundary conditions of digital collaboration.

The analysis of skewness and kurtosis shows that variables such as CDI and MatVol exhibit significant non normal characteristics, indicating the need to consider heteroscedasticity in empirical models, and the use of robust standard errors has been corrected for this. The left skewed distribution of the region number basis in the control variables and the uniform distribution of engineering complexity ensure the applicability of empirical results in different scenarios.

Table 2 Descriptive Analysis

Variables	Mean	Std. Dev.	Min	Median	Max	Kurtosis	Skewness
PCR	23.7%	8.2%	5.3%	22.1%	47.6%	4.31	1.37
ITA	1.82	0.76	-0.24	1.79	4.37	3.02	0.68
KSE	3.17	1.23	0.85	3.02	7.14	2.78	0.94
CDI	2.56	1.41	0.32	2.38	8.03	5.17	1.83
ENB	0.68	0.31	0.11	0.63	1.92	3.45	1.25
ESGpf	1.05	0.47	-0.38	1.03	3.27	2.13	0.51
DCD	0.59	0.18	0.21	0.61	0.93	2.86	-0.32
Size	23.75	1.84	19.11	23.68	28.92	1.95	0.27
Lev	1.83	0.67	0.41	1.79	4.26	3.78	1.32
PComp	6.52	2.31	2.17	6.48	12.75	2.04	0.63
RegInf	73.4	12.6	41.8	75.2	95.3	1.68	-0.45
MatVol	18.3%	6.7%	4.2%	17.5%	42.1%	4.87	1.94

5. Correlation analysis

As shown in Figure 6, the correlation analysis between variables provides preliminary statistical support for the theoretical logic of the value creation path. The Pearson correlation coefficient matrix can intuitively identify the strength of the correlation between digital synergy depth and various value dimensions, providing a basis for subsequent regression model settings. Overall, the correlation direction between core variables is consistent with theoretical expectations, and there is no high risk of collinearity, which verifies the rationality of the research framework.

DCD is significantly positively correlated with various value creation variables, and there are dimensional differences in the strength of the correlation. In terms of efficiency value dimension, the correlation coefficient between DCD and PCR is 0.62, and the correlation coefficient with ITA is 0.58, indicating that digital collaboration has a stable driving effect on improving operational efficiency, and its optimization effect on the procurement process is slightly stronger than that on inventory management. This is consistent with the high sensitivity of the procurement cycle to data sharing in DEA efficiency measurement. The innovation value dimension shows a stronger correlation strength, with a correlation coefficient of 0.71 between DCD and KSE, which is the highest among all dimensions, confirming the promoting effect of digital platforms on knowledge encoding, transmission, and absorption. The correlation coefficient between CDI and DCD is 0.63, while the correlation coefficient between CDI and KSE is as high as 0.76, indicating that knowledge spillover is an important antecedent variable for chain innovation, and digital collaboration provides a transmission carrier for innovation diffusion by accelerating knowledge flow.

In the dimension of strategic value, the correlation coefficient between DCD and ENB is 0.68, indicating the substantial impact of digital synergy depth on the construction of market barriers, which is consistent with the core role of technological empowerment in the theory of ecological niche transition. The correlation coefficient between ESGpf and DCD is 0.53, which is lower than other dimensions, but still maintains a significant positive correlation. The correlation coefficient between ESGpf and KSE is 0.65, suggesting that the spillover of green innovation knowledge may be an important path for ESG value transformation. The correlation coefficient between ENB and ESGpf is only 0.35, indicating that the two sub dimensions of strategic value are relatively independent. Ecological niche barriers rely more on market power construction, while ESG premiums focus on market recognition of sustainable development capabilities.

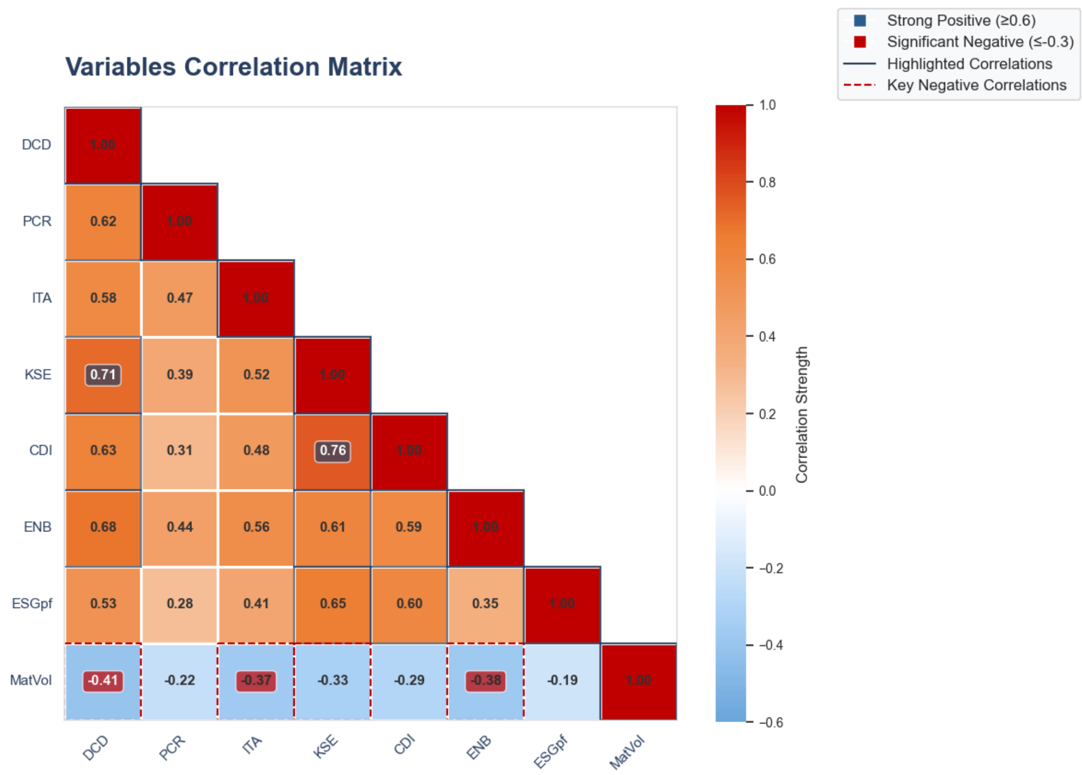

Figure 6 Correlation heatmap

6. Empirical results

The empirical results, as shown in Table 3, indicate that DCD has a significant positive impact on all dimensions of supply chain value creation, verifying the fundamental role of digital empowerment in the theoretical framework. From the coefficient magnitude perspective, CDI has the highest sensitivity to DCD, indicating that digital collaboration has the strongest driving effect on the innovation value dimension, which is consistent with the theoretical expectation of data interface standardization in modular design to accelerate innovation transmission. Next are ITA and KSE, reflecting the dual role of digital technology in improving operational efficiency and knowledge flow. In contrast, the absolute value of the coefficient of ESGpf is the smallest, possibly due to the longer transmission chain of green value conversion, which needs to be gradually released through niche construction and market awareness accumulation.

From a significance level perspective, DCD passed the 5% level test in all models, with PCR, ITA, CDI, and ENB reaching the 1% significance level, indicating that digital collaboration has a highly statistically robust impact on procurement cycle compression, inventory efficiency improvement, chain innovation, and niche barriers. The t-value distribution shows that CDI has the highest t-value and ESGpf has the lowest t-value, further confirming the differences in response strength of different value dimensions to digital collaboration.

Table 3 Empirical Results

Variables	PCR	ITA	KSE	CDI	ENB	ESGpf
DCD	0.407***	2.183***	1.791**	4.326***	0.926***	0.348**
	(3.92)	(4.27)	(2.56)	(5.14)	(3.78)	(2.14)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-0.226**	-1.847***	-3.592***	-8.739***	-1.073***	0.427
	(-2.31)	(-3.88)	(-4.15)	(-6.33)	(-3.42)	(1.27)
N	1640	1640	1640	1640	1640	1640
R^2	0.413	0.387	0.351	0.427	0.298	0.265
Ad_R^2	0.402	0.374	0.338	0.412	0.282	0.248
F	38.17***	32.45***	27.83***	49.62***	19.62***	15.94***

Note: The values in parentheses represent the robust standard error t-values for clustering; * p<0.01, p<0.05, * p<0.1； Fixed effects of controlling year and segmented industries in the construction industry

V. Conclusion

This article systematically explores the path of collaborative innovation and value creation in the supply chain of EPC enterprises under the background of digital economy through theoretical construction, mechanism design, and empirical testing. The conclusion is drawn that firstly, the digital economy reshapes the collaborative mode of EPC supply chain through the three-dimensional driving framework of "technology enablement organizational change ecological governance", where the technology enablement layer achieves data penetration flow and breaks down information barriers; Organizational change layer enhances collaborative agility; The ecological governance layer ensures collaborative ecological stability, and the three form a closed-loop linkage mechanism. Secondly, empirical results indicate a significant positive correlation between DCD and various dimensions of value creation, with the strongest driving effect on innovation value. The impact on efficiency value and strategic value is statistically robust, verifying the transmission logic of digital technology to value transformation. Thirdly, there are gaps in existing research on technology cluster collaboration, multilateral dynamic governance, and full lifecycle value extension. This study fills the relevant theoretical gaps by integrating multidisciplinary theories and quantitative analysis, and constructs an EPC supply chain collaborative innovation framework adapted to the digital economy.

Based on the research findings, this article suggests that EPC companies should prioritize the application of digital technology clusters, focus on deploying digital twin bases that integrate BIM and GIS, simplify transaction processes through smart contracts, and dissolve "information silos" through data penetration; Simultaneously restructuring the organizational model, establishing a dynamic resource pool based on supplier capability assessment, promoting the parallel process reengineering of design construction supply, and improving collaborative response speed; In addition, it is necessary to establish a fair benefit distribution mechanism and risk sharing contract with supply chain entities, shift from short-term transactions to long-term symbiosis, and strengthen ecological synergy resilience.

At the industry level, it is necessary to accelerate the development of digital technology application standards, unify technical specifications such as BIM models and IoT interfaces, and solve the problem of technological heterogeneity; Promote the construction of industry level engineering big data platforms, facilitate cross enterprise data sharing and knowledge spillover, and amplify the chain innovation effect; Encourage leading enterprises to take the lead in building a "symbiotic and win-win" industrial ecosystem, integrate full chain resources through platformization, cultivate new paradigms such as intelligent construction and green construction, and promote the transformation of the industry from extensive construction to precision intelligent manufacturing.

The government needs to increase investment in digital infrastructure, focus on supporting the deployment of 5G, edge computing and other technologies on the project site, and reduce the cost of enterprise digital transformation; Improve the institutional guarantee for market-oriented allocation of data elements, clarify the rules for supply chain data ownership and circulation, and provide legal basis for data assetization; Introduce incentive policies to guide EPC enterprises to carry out green collaborative practices, incorporate ESG indicators into the supply chain evaluation system, and promote the deep integration of strategic value and sustainable development goals.

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