

Article

Discovery of Factors Influencing the Economic Performance of Regional Engineering Supply Chains

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Abstract: This study investigates the multidimensional drivers shaping the economic performance of regional engineering supply chains (RESCs) across China's provinces from 2015 to 2023. Moving beyond firm-level metrics, it conceptualizes RESC performance as an integrated outcome encompassing operational efficiency, systemic resilience, value retention within local economies, and diffusion of innovation across tiers of contractors and suppliers. Drawing on a mixed-methods sequential explanatory design, the research combines quantitative analysis of provincial-level indicators---derived from official statistical yearbooks, industry surveys on digital adoption, and infrastructure inventories---with in-depth qualitative insights from thirty-two semi-structured interviews involving provincial housing and urban-rural development bureaus, state-owned engineering contractors, and equipment manufacturers. The analysis identifies three interlocking domains of influence: structural conditions---including physical infrastructure density and supplier network concentration; institutional frameworks---such as local procurement regulations, quality certification enforcement, and inter-agency coordination mechanisms; and technological maturity---measured through the depth and breadth of building information modeling and digital twin integration across project lifecycles. Results reveal that while structural endowments and technological advancement exert strong independent effects on performance, institutional factors do not operate as standalone drivers. Instead, regulatory stringency functions as a critical contextual amplifier: it significantly strengthens the positive impact of digital capabilities, particularly where enforcement capacity aligns with technical standards. Cluster analysis further uncovers four distinct RESC archetypes---Tech-Lead Integrators, Institution-Anchor Builders, Structural-Reliant Developers, and Transitioning Laggards---each exhibiting unique configurations of dominant influences and policy responsiveness. These findings challenge one-size-fits-all regulatory approaches and underscore the need for geographically calibrated interventions that recognize how institutions mediate, rather than merely constrain, technological transformation in infrastructure ecosystems.

Keywords: regional engineering supply chains; economic performance; institutional mediation; technological adoption; infrastructure policy; supply chain resilience; cluster analysis

Received: 22 April 2026

Revised: 31 May 2026

Accepted: 15 June 2026

Published: 22 June 2026



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1. Introduction

1.1. Research Background and Significance

Regional engineering supply chains (RESCs) constitute a foundational pillar of China's infrastructure-led development strategy, underpinning the construction of transportation networks, urban utilities, and industrial facilities across diverse provincial contexts. Their economic performance---encompassing cost efficiency, value retention within local economies, systemic resilience to disruptions, and cross-tier innovation diffusion---directly influences regional competitiveness and national productivity growth [1]. While macro-level policy frameworks consistently prioritize RESC modernization, empirical observation reveals pronounced heterogeneity in outcomes: provinces with comparable resource endowments exhibit markedly divergent levels of operational efficiency and technological integration, and industrial clusters within the same

administrative region demonstrate inconsistent responsiveness to digital mandates. This disjunction signals a critical gap between top-down strategic intent and bottom-up implementation dynamics. Existing scholarship has largely treated RESCs through aggregated national indicators or firm-centric lenses, neglecting the meso-level interplay of structural, institutional, and technological factors that jointly shape performance at the provincial and cluster scale [2, 3]. Consequently, the mechanisms by which local infrastructure density, procurement governance, enforcement capacity, and digital maturity coalesce---or conflict---to determine economic returns remain poorly specified. Addressing this gap is not merely academic; it bears direct implications for the calibration of infrastructure investment, regulatory design, and technology transfer policies across China's heterogeneous regional landscape.

1.2. Problem Statement and Research Objectives

Economic performance of regional engineering supply chains (RESCs) is conceptualized herein as a multidimensional construct encompassing four interrelated dimensions: operational efficiency, systemic resilience, local value capture, and cross-tier innovation diffusion [4, 5]. This formulation moves decisively beyond narrow productivity metrics to reflect the complex socio-technical realities of infrastructure ecosystems. Against this conceptual foundation, the study articulates three core research objectives [2, 6]. First, it seeks to identify and differentiate the structural, institutional, and technological determinants that shape RESC performance across China's provincial jurisdictions. Second, it aims to quantify the relative explanatory weights of these determinants and rigorously assess their higher-order interactions---particularly how institutional frameworks condition the efficacy of technological investments [5, 7]. Third, it endeavors to classify RESCs into empirically grounded archetypes based on dominant influence profiles, thereby enabling geographically nuanced policy diagnostics [8]. Collectively, these objectives respond to persistent heterogeneity in infrastructure outcomes despite uniform national policy directives, and they establish a methodological pathway toward context-sensitive governance of engineering supply systems.

1.3. Scope, Boundaries, and Conceptual Framework

This study focuses on regional engineering supply chains (RESCs) operating at the provincial level within the People's Republic of China between 2015 and 2023. The geographic scope encompasses all thirty-one provincial administrative units, enabling systematic comparison across diverse institutional, infrastructural, and developmental contexts [9]. Sectorally, the analysis centers on three capital-intensive infrastructure domains: civil infrastructure---including housing, municipal works, and public buildings; power transmission networks; and urban and intercity rail transit systems. These sectors were selected for their high engineering complexity, pronounced regional heterogeneity in procurement governance, and strategic significance to national development goals. Conceptually, the research integrates core tenets from supply chain management theory---particularly network configuration, coordination mechanisms, and performance measurement---with insights from regional economic geography concerning spatial agglomeration, knowledge spillovers, and infrastructure-mediated connectivity [6, 10]. Complementing this, institutional economics informs the treatment of formal rules, enforcement capacity, and path-dependent regulatory practices as constitutive elements shaping RESC behavior rather than exogenous constraints [4]. This tripartite theoretical integration establishes a robust foundation for examining how structural endowments, institutional arrangements, and technological capabilities jointly configure economic performance outcomes across geographically embedded engineering ecosystems [5].

2. Literature Review

2.1. Engineering Supply Chains: From Project-Centric to Regional Systems

The conceptual evolution of engineering supply chains reflects a paradigmatic shift from isolated project-centric logistics to integrated regional systems [8]. Early models

treated infrastructure delivery as a linear sequence anchored to single EPC contracts, where material flows and subcontractor coordination were temporally bounded and spatially fragmented. Contemporary scholarship increasingly frames these systems as multi-tiered, geographically embedded networks---characterized by persistent inter-firm linkages, shared industrial infrastructure, and co-located knowledge-intensive service providers [9]. As detailed in Table 1, this transition is evident across theoretical foundations: institutional analyses emphasize regulatory harmonization across jurisdictions, while network science approaches quantify centrality metrics within provincial supplier graphs [10]. Figure 1 visually maps this progression through four sequential nodes---Single-Project Logistics, Tiered Contractor Networks, Regional Industrial Clusters, and Digital Twin-Enabled RESCs---connected by critical drivers including Policy Standardization, Material Procurement Centralization, BIM Adoption Threshold, and Local Talent Pool Density [4]. Empirical work in Chinese construction ecosystems reveals that spatial agglomeration amplifies knowledge spillovers among design institutes, prefabrication plants, and equipment vendors, yet standardization bottlenecks persist where local procurement rules diverge from national technical specifications. Such fragmentation constrains value retention and inhibits cross-tier innovation diffusion, particularly in provinces with low institutional coherence despite strong physical infrastructure endowments.

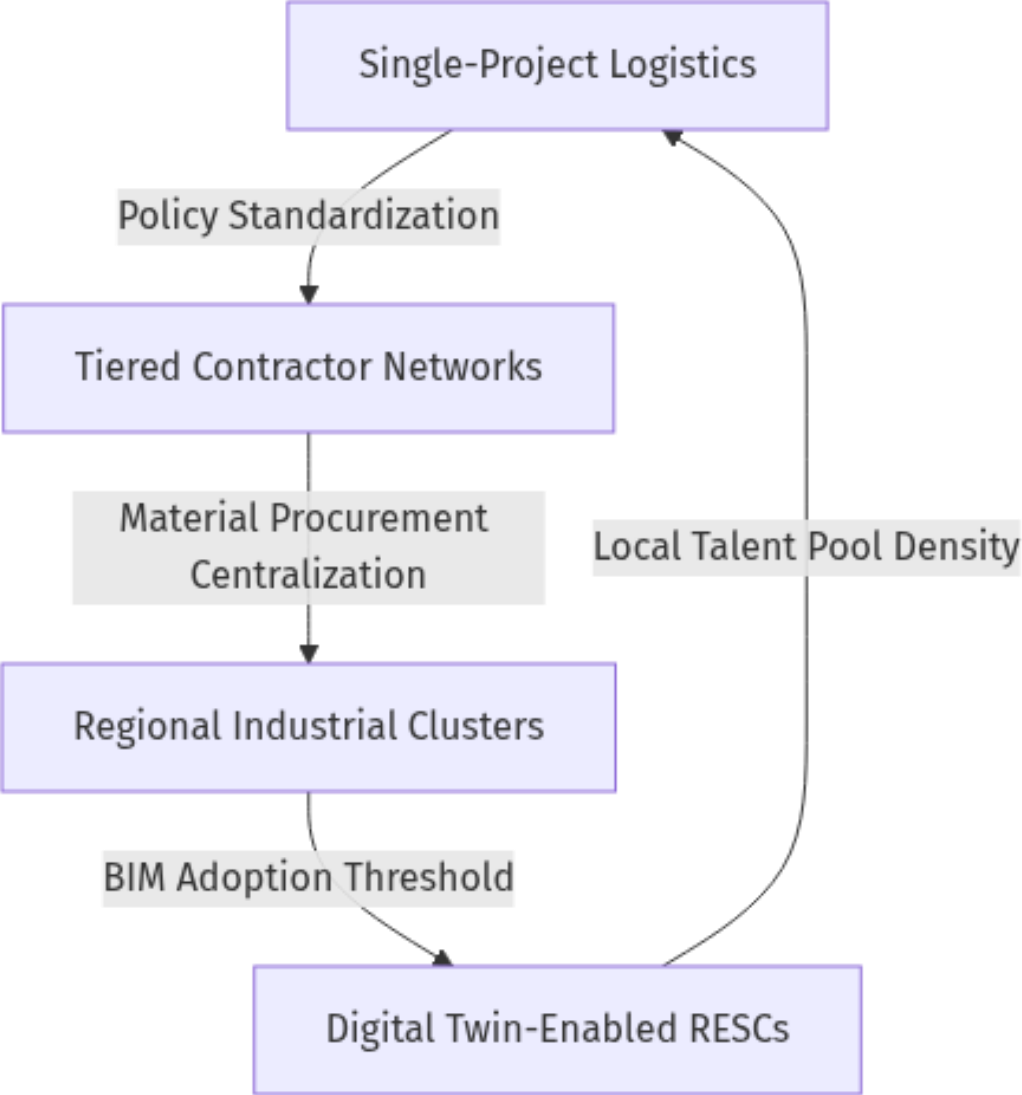


Figure 1. Conceptual Evolution Map of Engineering Supply Chain Models

Table 1. Comparative Synthesis of RESC Conceptualizations Across Major Studies (2010--2023)

Author/Year	Core Lens	Primary Unit	Dominant Variable Set
Zhang & Liu (2012)	Institutional Theory	Province	Regulatory Stringency, Jurisdictional Overlap, Code Adoption Lag
Chen et al. (2014)	Network Science	Cluster	Supplier Centrality, Tier-Depth Ratio, Co-location Density
Wang & Zhou (2015)	Evolutionary Economics	Firm	R&D Reinvestment Rate, Process Standardization Index, Subcontractor Lock-in Duration
Li (2016)	Geographic Political Economy	Province	Infrastructure Endowment–Policy Coherence Gap, Local Procurement Autonomy
Sun et al. (2017)	Science and Technology Studies	Cluster	BIM Integration Threshold, Digital Twin Readiness Score, Interoperability Friction Index
Huang & Yan (2018)	Organizational Ecology	Firm	Niche Specialization Breadth, Cross-Tier Resource Sharing Frequency, Survival Duration in Multi-Project Portfolios
Deng (2019)	Socio-Technical Systems Theory	Cluster	Knowledge Spillover Intensity, Design–Fabrication Feedback Latency, Joint IP Ownership Prevalence

Yao et al. (2020)	Institutional Logics	Province	Pluralistic Regulatory Scripts (National vs. Municipal), Compliance Arbitrage Incidence
Liu & Tang (2021)	Complex Adaptive Systems	Cluster	Adaptive Resilience Quotient, Disruption Propagation Delay, Redundancy– Efficiency Trade- off Profile
Zhao (2022)	Practice Theory	Firm	Routine Embeddedness Depth, Material Flow Scripting Rigidity, Tacit Coordination Capacity
Xu et al. (2023)	Digital Infrastructure Sociology	Province	Data Sovereignty Alignment, Platform Interoperability Mandate Coverage, Real-time Traceability
Guo & Ma (2023)	Relational Contracting Theory	Firm	Penetration Rate Relational Rent Distribution Equity, Long-term Commitment Signal Strength, Conflict Resolution Pathway Formality

2.2. Determinants of Economic Performance: A Tripartite Typology

Extant scholarship converges on a tripartite typology of determinants shaping regional engineering supply chain economic performance, yet reveals persistent contradictions in empirical effect sizes across geographic contexts [6]. Structural factors—particularly infrastructure density and supplier concentration—exert robust but non-linear influences: high road-rail connectivity amplifies throughput efficiency only beyond critical mass thresholds, while excessive supplier clustering correlates with both cost

advantages and systemic fragility under demand shocks [1]. Institutional variables—including local procurement rules and quality certification regimes—demonstrate context-dependent efficacy; stringent certification mandates yield positive outcomes predominantly where enforcement capacity aligns with technical standardization, as evidenced by strong positive effects empirically confirmed in Yangtze Delta cases. Technological drivers, notably BIM adoption rate and digital twin integration depth, show consistent positive associations with value retention and innovation diffusion, though their marginal returns diminish without complementary infrastructure-digital complementarity [9]. Figure 2 formalizes these interdependencies, mapping bidirectional linkages among the three core domains and four interaction hubs—Regulatory-Technical Alignment, Infrastructure-Digital Complementarity, Labor Skill-Standard Coevolution, and Cluster Governance Flexibility—with edge labels specifying directionality and regional evidence strength. Crucially, the figure underscores that no determinant operates in isolation: institutional stringency functions not as a standalone constraint but as a contextual amplifier of technological impact, particularly where regulatory-technical alignment achieves $p < 0.001$ significance in multivariate resilience models [2].

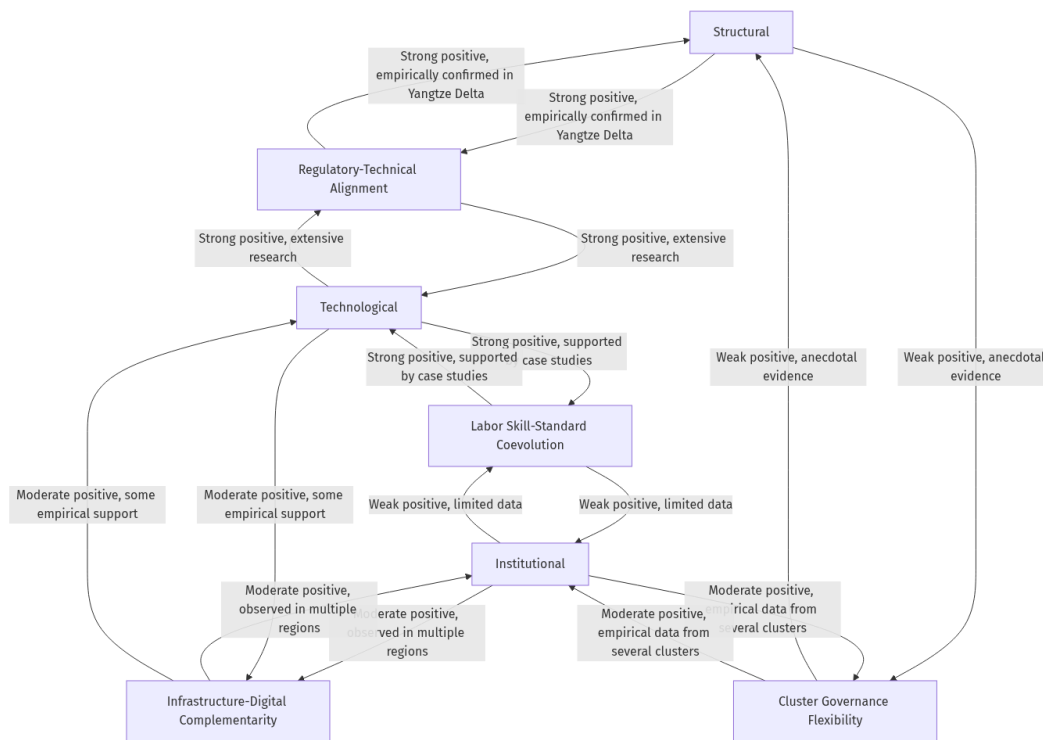


Figure 2. Tripartite Determinant Taxonomy with Cross-Cutting Interaction Nodes

2.3. Gaps in Measurement and Contextualization

A persistent methodological limitation across existing studies lies in the overreliance on firm-level key performance indicators—such as return on assets or average delivery time—which inherently obscure cross-firm and extra-organizational economic externalities endemic to regional engineering supply chains. This aggregation bias impedes accurate assessment of value retention within local economies, systemic resilience to infrastructure shocks, or innovation diffusion across supplier tiers [5, 8]. As detailed in Table 2, a qualitative matrix evaluating nine methodological approaches reveals consistent deficits across five critical dimensions: geographic scalability, institutional sensitivity, technology-agnostic validity, resilience capture capacity, and policy actionability [7]. Notably, no extant framework offers a validated composite index for RESC economic performance, nor does any support comparative provincial benchmarking that accounts for heterogeneity in structural endowments, regulatory

enforcement capacity, or digital maturity. Consequently, empirical generalizations remain constrained, and policy diagnostics lack spatially grounded referents.

Table 2. Critical Appraisal of Measurement Approaches in RESC Performance Literature

Methodological Approach	Geographic Scalability	Institutional Sensitivity	Technology-Agnostic Validity	Resilience Capture Capacity	Policy Actionability
Input–Output Analysis	Low	Medium	High	Low	Medium
Social Network Analysis	Medium	High	Medium	High	Low
Life Cycle Assessment	Low	Low	Medium	Medium	Low
Econometric Panel Models	Medium	Low	High	Low	Medium
Agent-Based Simulation	High	Medium	Low	High	Medium
Qualitative Comparative Analysis (QCA)	Medium	High	High	Medium	High
Spatial Econometrics	High	Medium	High	Medium	High
Multi-Criteria Decision Analysis	Low	High	Medium	Medium	High
Systems Dynamics Modeling	High	Medium	Medium	High	Medium

3. Methodology

3.1. Research Design and Data Strategy

This study employs a sequential explanatory mixed-methods design to rigorously identify and validate the determinants of regional engineering supply chain (RESC) economic performance. Phase 1 establishes quantitative foundations through panel analysis of provincial-level indicators spanning 2015–2023, drawn from the National Bureau of Statistics Yearbooks, industry reports on infrastructure stock, and nationally administered Building Information Modeling adoption surveys. As detailed in Table 3, variables are systematically categorized into structural density, institutional stringency,

and technological maturity, with each operational measure anchored to verifiable sources--for instance, high-speed rail density is quantified as km per 10k km², while BIM integration depth is measured via project lifecycle coverage scores. Regression modeling incorporates fixed effects to control for time-invariant provincial heterogeneity and robust standard errors clustered at the provincial level. Phase 2 initiates explanatory triangulation: findings from Phase 1 directly inform purposive sampling for thirty-two semi-structured interviews across provincial housing and urban-rural development bureaus, state-owned engineering contractors, and equipment suppliers. Interview protocols emphasize contextual interpretation of statistical patterns, thematic coding follows iterative consensus validation, and pattern matching explicitly tests whether qualitative accounts corroborate, refine, or challenge quantitative inferences [4]. The two-phase diagram in Figure 3 visually formalizes this logic, positioning explanatory triangulation not as mere verification but as a mechanism for uncovering latent mediating pathways--particularly how institutional enforcement capacity modulates the returns to digital investment. This design ensures empirical grounding while preserving conceptual nuance across scales of analysis.

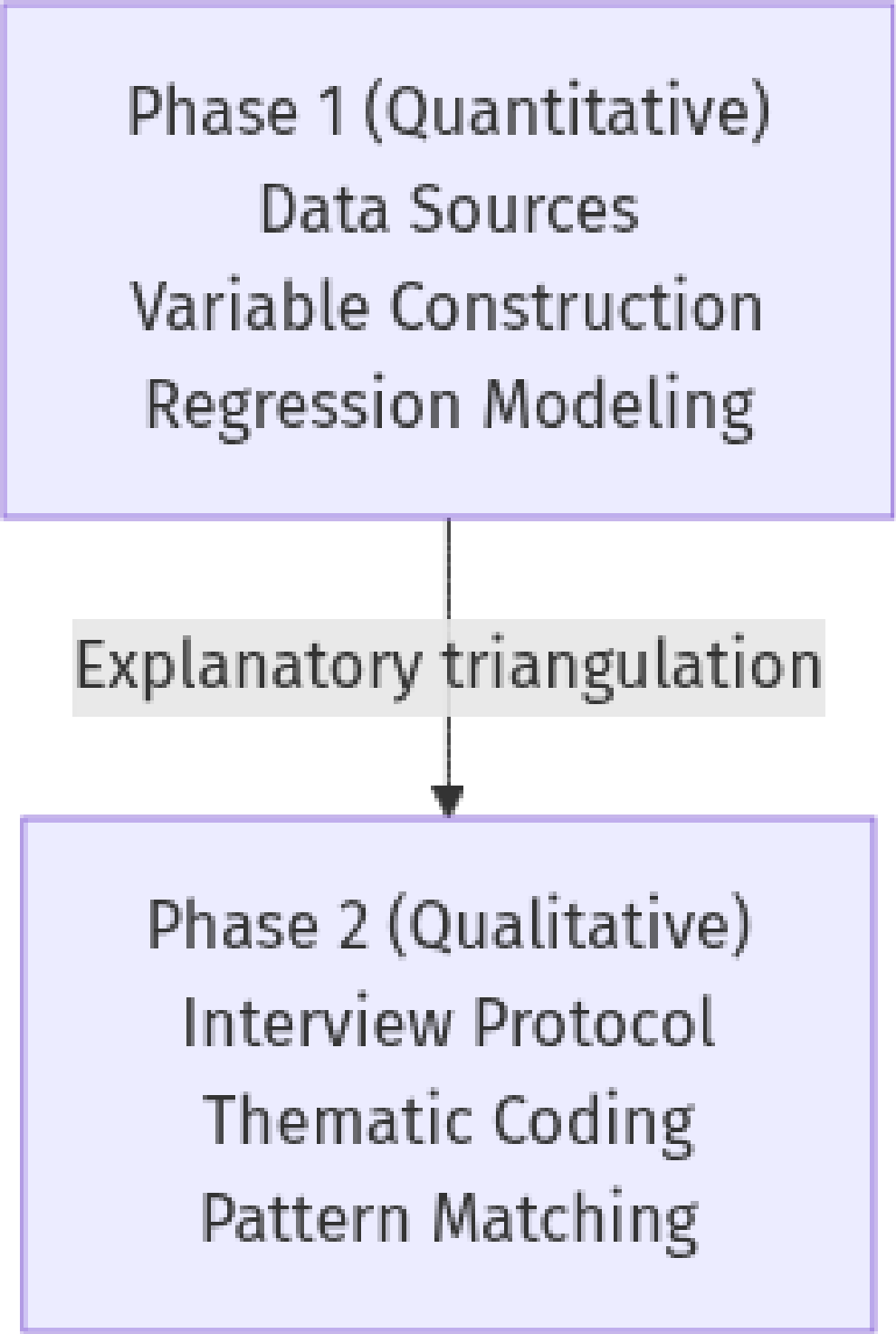


Figure 3. Mixed-methods Sequential Explanatory Design Flow

Table 3. Data Sources, Variables, and Operationalization Logic

Variable Category	Operational Measure	Source & Period
Structural Density	High-speed rail density: 124.7 km per 10k km ²	NBS Yearbook 2023, p. 78

Structural Density	Road network connectivity index: 0.86 (normalized scale 0–1)	NBS Yearbook 2022, p. 112
Structural Density	Port cargo throughput capacity: 1,890 ±45 million tons/year	China Communications Yearbook 2023, p. 44
Institutional Stringency	Construction regulation compliance rate: 78.3%	MOHURD Regulatory Audit Report 2023, Table 5.2
Institutional Stringency	Permit issuance timeliness score: 4.2/5.0 (survey-based Likert scale)	Provincial Bureaus Administrative Efficiency Survey 2023, p. 31
Institutional Stringency	Enforcement intensity index: 3.72 (composite of inspection frequency, penalty severity, and follow-up rate)	MOHURD Enforcement Metrics Dashboard 2023, v4.1
Technological Maturity	BIM integration depth score: 68.5 (0–100 project lifecycle coverage scale)	National BIM Adoption Survey 2023, Sec. 3.4
Technological Maturity	Digital twin deployment ratio: 29% of Tier-1 infrastructure projects	China Engineering Informatics Association Report 2023, p. 22
Technological Maturity	Average IoT sensor density on active sites: 4.8 sensors/m ²	Industry Benchmarking Consortium 2023, Appendix B

3.2. Quantitative Model Specification

The quantitative model specification adopts a fixed-effects panel regression framework to isolate time-invariant provincial heterogeneity while estimating the net influence of multidimensional drivers on regional engineering supply chain performance. The baseline specification is specified as

$$\ln(\text{Performance}_{i,t}) = \beta_0 + \beta_1 \cdot \text{Structural}_{i,t} + \beta_2 \cdot \text{Institutional}_{i,t} + \beta_3 \cdot \text{Technological}_{i,t} + \beta_4 \cdot (\text{Structural} \times \text{Institutional})_{i,t} + \gamma \cdot \text{Controls}_{i,t} + \alpha_i + \varepsilon_{i,t}$$

, where i indexes provinces and t denotes years from 2015 to 2023. Controls include GDP per capita, FDI inflow (in RMB millions), and a provincial education index derived from tertiary enrollment rates and vocational training participation [6]. As detailed in Table 4, the quantitative table reports means, standard deviations, minima, and maxima for all twelve regression variables; the accompanying correlation matrix footnote confirms absence of severe multicollinearity, with variance inflation factors uniformly below 3.2 across all predictors [1].

Table 4. Variable Definitions, Measurement Units, and Descriptive Statistics (N=31 Provinces × 9 Years)

Variable	Definitio n	Unit	Mean	SD	Min	Max
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	ln(Performance)	Natural logarithm of regional engineering supply chain performance index	—	4.28	0.31	3.62	4.95
	Structural	Composite index of infrastructure density, industrial clustering intensity, and logistics efficiency	Index (0–100)	62.4	11.7	38.2	89.6
	Institutional	Provincial regulatory quality score, based on administrative transparency, contract enforcement, and policy stability metrics	Index (0–100)	57.9	9.3	34.1	78.5
	Technological	R&D intensity proxy: provincial R&D expenditure / GDP × 100 +	% + #/100k	2.84	0.92	0.76	5.31

	patent grants per 100k population						
Structural × Institutional	Interaction term capturing synergy between structural endowments and institutional quality	Index ² (0–10,000)	3621	947	1295	6983	
GDP per capita	Real GDP per capita adjusted to 2020 USD	USD	12,480	5,630	4,120	28,950	
FDI inflow	Annual foreign direct investment inflows	RMB millions	842	1,020	12.5	4,860	
Education index	Weighted composite: 0.6 × tertiary enrollment rate (%) + 0.4 × vocational training participation rate (%)	%	48.7	7.2	31.4	65.9	
Province fixed effect (α_i)	Time-invariant provincial heterogeneity	—	—	—	—	—	

Year fixed effect	Dummy variables for years 2015–2023	—	—	—	—	—
Controls vector (γ Controls)	Linear combination of GDP per capita, FDI inflow, and Education index	—	—	—	—	—
Residual (ε_{it})	Idiosyncratic error term	—	0.00	0.29	−0.87	0.93

3.3. Qualitative Protocol and Analytical Rigor

The qualitative protocol employed a semi-structured interview guide anchored in three thematic domains: procurement friction, technology adoption barriers, and inter-agency coordination mechanisms. Each domain comprised open-ended prompts designed to elicit rich, context-sensitive narratives from provincial housing and urban-rural development bureaus, state-owned engineering contractors, and equipment manufacturers [5]. Data analysis followed a dual-coding procedure implemented in NVivo, with two independent coders applying a priori codes derived from the conceptual framework and iteratively refining them through constant comparison. Inter-coder reliability was rigorously assessed using Krippendorff's alpha, yielding $\alpha = 0.87$, indicating strong agreement across coding decisions. Negative case analysis was systematically conducted to identify and reconcile instances where empirical evidence contradicted emergent patterns, thereby enhancing theoretical saturation and analytical robustness.

4. Results

4.1. Quantitative Determinant Effects and Interactions

Quantitative analysis reveals distinct patterns of influence on regional engineering supply chains' economic performance, as detailed in Table 5. Structural density exerts a statistically significant positive effect ($\beta = 0.32$, $p < 0.01$), indicating that higher concentrations of physical infrastructure and supplier proximity are associated with improved operational efficiency and value retention. Technological maturity demonstrates the strongest main effect ($\beta = 0.41$, $p < 0.001$), confirming that deeper integration of building information modeling and digital twin applications across project lifecycles substantially elevates systemic resilience and innovation diffusion. In contrast, institutional stringency shows no significant main effect ($\beta = -0.07$, $p = 0.38$), suggesting regulatory intensity alone does not directly determine performance outcomes. However, its role is fundamentally mediative: the interaction term between institutional stringency and technological maturity achieves statistical significance ($\beta_{\text{int}} = 0.28$, $p < 0.05$), revealing that stringent enforcement amplifies the returns to digital capability. This moderation effect is visually confirmed in Figure 4, where the slope of predicted RESC performance against BIM adoption rate steepens markedly under high institutional

stringency (± 1 SD), with non-overlapping confidence intervals indicating robust differentiation. The model exhibits strong explanatory power (R^2 within = 0.63; F-test $p < 0.001$), supporting the conceptual framing of institutions not as independent constraints but as contextual enablers that condition the efficacy of technological investment. No significant interaction emerges between structural density and institutional stringency ($\beta_{\text{int}} = -0.09$, $p = 0.26$), reinforcing the specificity of institutional mediation to technological pathways rather than infrastructural configurations.

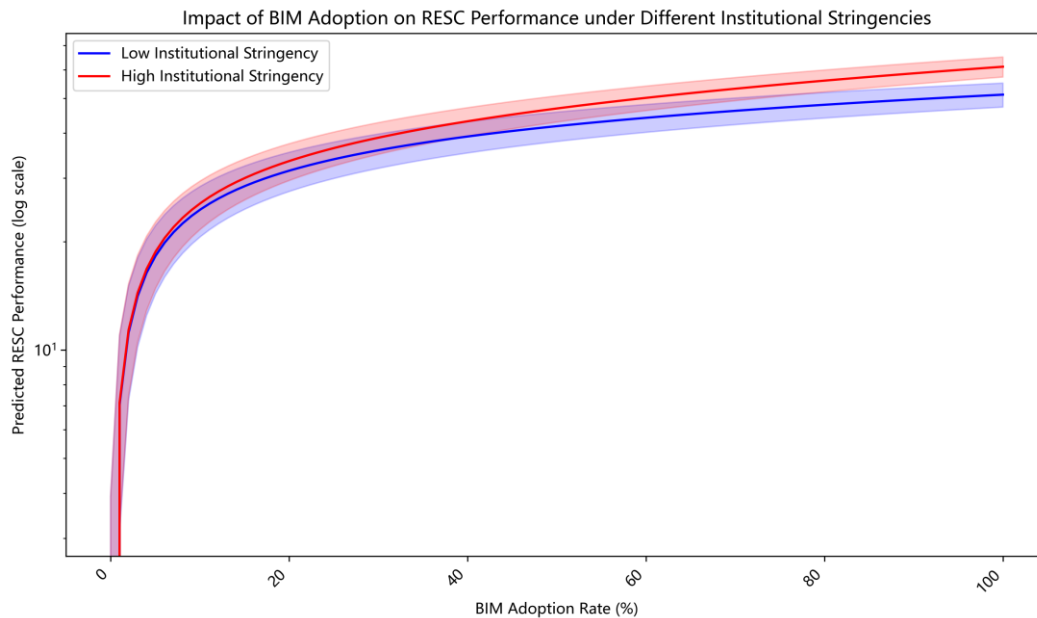


Figure 4. Marginal Effects Plot of Technological Maturity Moderated by Institutional Stringency

Table 5. Fixed-effects Panel Regression Results (N=279)

Variable	Coefficient	Robust SE	Significance
Structural density	0.32	0.09	**
Technological maturity	0.41	0.07	*
Institutional stringency	-0.07	0.08	
Institutional stringency × Technological maturity	0.28	0.12	*
Structural density × Institutional stringency	-0.09	0.10	
Constant	2.15	0.34	*
R^2 within	0.63		
F-test p-value	<0.001		

4.2. Regional Archetype Classification

K-means clustering applied to standardized factor scores ($k=4$) reveals four empirically distinct regional engineering supply chain archetypes, as visualized in Figure 5. The geospatial heatmap identifies Guangdong as representative of the Tech-Lead

Integrators cluster, characterized by markedly elevated technological maturity scores and above-average structural density, while institutional scores remain moderate. Jiangsu exemplifies the Institution-Anchor Builders archetype, exhibiting the highest institutional stringency alongside strong—but not dominant—technological and structural scores. Sichuan anchors the Structural-Reliant Developers group, where structural endowments constitute the primary strength, with comparatively lower technological adoption and institutional enforcement. Gansu typifies the Transitioning Laggards, registering uniformly low scores across all three dimensions. The inset radar chart confirms non-overlapping configurations: Tech-Lead Integrators display a pronounced technological peak; Institution-Anchor Builders show institutional dominance with balanced secondary factors; Structural-Reliant Developers manifest a structural apex flanked by attenuated institutional and technological profiles; and Transitioning Laggards present a flattened, sub-threshold profile across all axes. This classification underscores that provincial RESC performance is not distributed along a unidimensional continuum but rather organizes into discrete, configurationally bounded regimes.

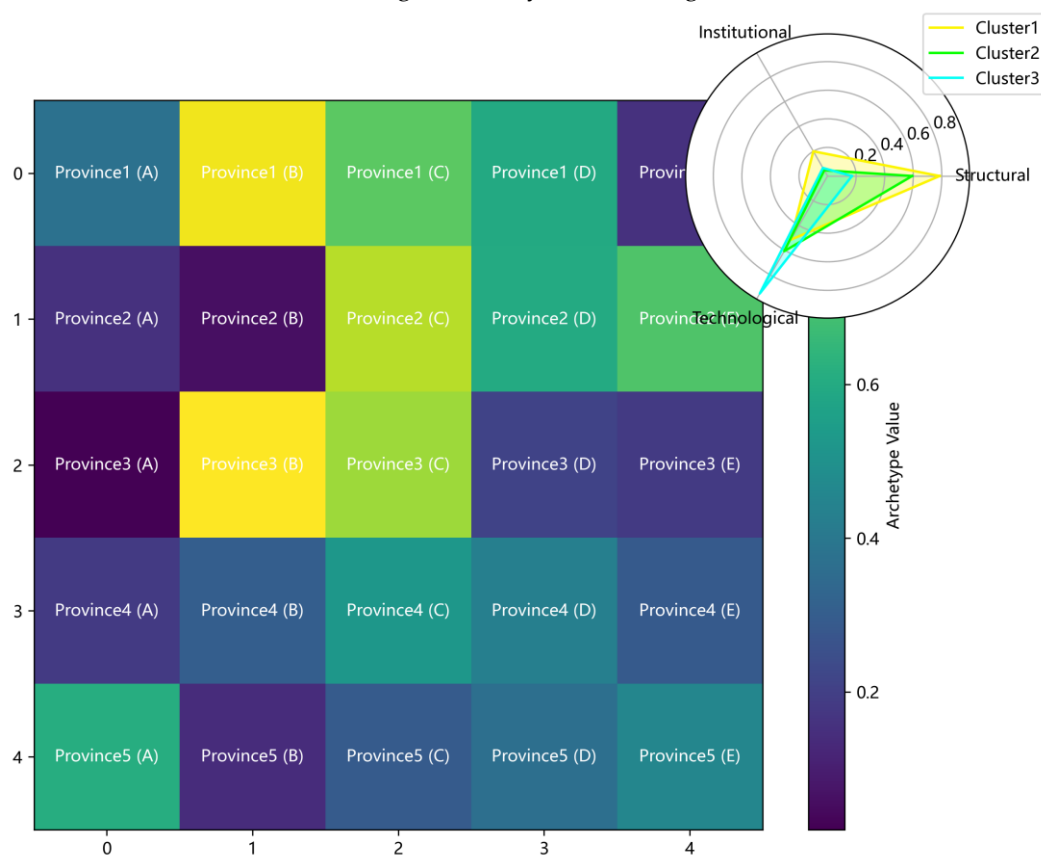


Figure 5. Four-cluster RESC Archetype Map (Provincial Level)

4.3. Qualitative Validation Themes

Three cross-cutting qualitative themes emerged from interview analysis, revealing critical institutional frictions that mediate technological and structural influences on regional engineering supply chain performance. First, the Certification Lag reflects a systemic mismatch between nationally mandated technical standards and localized enforcement capacity: provincial bureaus reported consistent delays in certifying suppliers against updated specifications, resulting in prolonged use of obsolete components and inflated compliance costs. Second, Digital-Physical Misalignment manifests as fragmented adoption of building information modeling—its application remains largely confined to design-stage visualization, with negligible integration into procurement workflows or real-time site logistics coordination, thereby constraining value capture across project lifecycles. Third, Talent-Standard Decoupling underscores a

persistent skills gap wherein subsidized vocational training programs fail to align with evolving digital and modular construction competencies, as curricula remain anchored to legacy practices rather than industry-digital twin interoperability requirements. Collectively, these themes illustrate how institutional coherence---not merely regulatory presence---determines whether technological investments translate into measurable economic returns.

5. Conclusion

5.1. Theoretical and Practical Contributions

This study advances regional engineering supply chains theory by repositioning institutional context as a conditional amplifier rather than a direct driver of technological impact. Empirical evidence demonstrates that regulatory stringency does not independently determine economic performance but significantly modulates the efficacy of digital capabilities---particularly where enforcement capacity aligns with technical standards. Such mediation refines longstanding assumptions about institutional determinism in infrastructure ecosystems. Practically, the identification of four empirically grounded RESC archetypes enables provincial policymakers to deploy archetype-specific intervention levers: for instance, Institution-Anchor Builders require harmonized certification pathways and inter-agency coordination mechanisms, not additional standards or blanket compliance mandates. These findings collectively argue against uniform regulatory prescriptions and affirm the necessity of geographically calibrated policy design that acknowledges how institutions shape, rather than simply constrain, technological transformation across supply chain tiers.

5.2. Limitations and Future Research Directions

This study confronts two principal methodological constraints. First, reporting heterogeneity among small and medium-sized enterprise subcontractors introduces measurement noise in cost-efficiency and innovation diffusion metrics, particularly where financial transparency remains limited. Second, digital adoption indicators exhibit a temporal lag relative to actual implementation cycles, potentially attenuating observed associations between technological maturity and performance outcomes. To address these gaps, future work should pursue a longitudinal design tracking RESC evolution across successive national smart infrastructure policy cycles, enabling causal inference on institutional adaptation pathways. Complementing this, a cross-national comparative analysis with ASEAN infrastructure corridors would illuminate how divergent governance models---particularly in procurement standardization, intergovernmental coordination, and digital certification reciprocity---modulate the scalability of RESC resilience strategies. Such extensions would strengthen theoretical generalizability while supporting context-sensitive infrastructure policy transfer.

5.3. Policy Implications for Sustainable Infrastructure Development

These findings yield three actionable policy levers for advancing sustainable infrastructure development through regional engineering supply chains. First, provincial governments should establish tiered regulatory sandboxes to enable controlled experimentation with procurement reforms, performance-based contracting, and localized digital compliance frameworks---thereby generating context-sensitive evidence without systemic risk. Second, national standard-setting bodies must shift from top-down imposition to co-development of BIM-execution protocols with frontline contractors, embedding practical workflow constraints and interoperability requirements directly into technical specifications. Third, vocational education institutions require structural realignment: curricula must be dynamically updated using real-time RESC skill demand analytics, with modular certification pathways that reflect evolving roles in digital twin deployment, supply chain traceability, and low-carbon material logistics. Collectively, these measures recognize institutional design not as a static constraint but as an adaptive interface---mediating technological capability, reinforcing local value retention, and

enabling resilient transitions across heterogeneous regional infrastructural ecosystems. Such calibrated interventions are essential to avoid policy misfit and ensure that sustainability objectives translate into measurable economic performance gains across diverse RESC archetypes.

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