

Evaluation of Capital Efficiency of Public-Infrastructure Projects Based on Project Financial-Cost Governance Theory

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Abstract

Traditional efficiency evaluation for public-infrastructure projects focuses on physical performance while ignoring soft factors of financial governance, suffering from imperfect systems and imprecise causal identification. Based on the Engineering-Financial Governance Nexus (EFGN) theory, this paper uses panel data of 117 U.S. public-infrastructure projects from 2011 to 2022. Super-SBM-DEA, Malmquist-Luenberger (ML) index, Tobit regression and PSM-DID models are adopted to explore the causal impact of financial-cost governance on infrastructure capital efficiency. The results show that the average capital efficiency of sampled infrastructure projects is merely 0.723, and governance deficiency acts as the primary cause of capital inefficiency (Tone, K., 2001). The annual average growth rate of infrastructure total-factor productivity reaches 4.1 %, driven almost exclusively by technological progress with marginal contributions from governance optimization. Audit supervision and joint engineering-financial collaborative review significantly improve capital efficiency, whereas project scale and high-debt financing produce notable inhibitory effects. This study remedies defects of traditional evaluation frameworks and provides references for optimal capital allocation and governance upgrading of public-infrastructure projects.

Keywords: public-infrastructure project, capital efficiency, financial-cost governance, EFGN theory, Super-SBM-DEA, Malmquist-Luenberger index, Tobit model, PSM-DID, heterogeneity analysis

1. Introduction

1.1 Practical Research Background

After the enactment of the U.S. Bipartisan Infrastructure Law, large-scale federal infrastructure investments have been continuously implemented, effectively remedying shortages of public facilities and empowering regional economic development. Nevertheless, traditional

infrastructure-performance-evaluation systems have obvious shortcomings, generally ignoring heterogeneity in project-governance quality and risk-related undesirable outputs. According to 2023 public statistics from the U.S. Office of Management and Budget (OMB), the average budget overrun rate of U.S. federal public-infrastructure projects reaches 18.7 %, and more than one-quarter of projects suffer implicit-liability problems, resulting in

prominent waste of public capital. Under such circumstances, it is urgent to construct a multi-dimensional quantitative evaluation system that balances engineering performance, financial-risk control and governance quality so as to precisely optimize the allocation efficiency of public capital.

1.2 Literature Review and Research Gaps

Existing studies on capital efficiency of public-infrastructure projects have three core shortcomings, creating distinct academic research gaps.

- **Imperfect factor system for efficiency evaluation:** Traditional DEA-based efficiency measurement models only incorporate physical production factors such as capital, manpower and construction cycles, and commonly omit governance quality as a core soft factor. They fail to explain substantial efficiency heterogeneity among infrastructure projects with identical physical inputs, leading to systematic bias in efficiency-measurement outcomes.
- **Prominent disciplinary barriers:** Engineering-management research concentrates on project construction-delivery and physical-quality control; CPA financial auditing focuses on cash-flow compliance and static valuation. The two fields have long been isolated, lacking integrated evaluation paradigms that combine engineering-construction logics and full-cycle financial-auditing logics.
- **Defective empirical-research paradigms:** Most studies merely conduct static efficiency calculation without time-series dynamic productivity decomposition. Endogeneity bias is widespread: high-efficiency infrastructure projects tend to be allocated superior governance resources. Conventional Tobit regression can only test variable correlations instead of distinguishing causal relationships, and robust identification tools such as PSM-DID are rarely adopted, undermining the credibility of empirical conclusions.

1.3 Core Research Questions

This paper puts forward four core research questions and constructs a complete research-logic system:

- **RQ1:** How to formalize the Project

Financial-Cost Governance theory with the Engineering-Financial Governance Nexus (EFGN) as its core? How to build a multi-dimensional capital-efficiency evaluation indicator system incorporating governance-quality inputs and undesirable outputs?

- **RQ2:** What are the characteristics of static capital super-efficiency distribution and time-series decomposition of dynamic total-factor productivity for sampled projects?
- **RQ3:** What are the impacts of each dimension of project financial-cost governance on capital efficiency? Adopt PSM-DID for endogeneity robustness tests to confirm whether improved governance quality causally enhances capital efficiency.
- **RQ4:** How can this evaluation framework be adapted for ex-ante screening and capital allocation of U.S. federal infrastructure projects?

1.4 Research Innovations and Contributions

This paper delivers three dimensions of SCI-level academic contributions:

- **Theoretical contribution:** Formally establish the Project Financial-Cost Governance theory; define governance quality as a special production input for public-infrastructure projects; take the Engineering-Financial Governance Nexus (EFGN) as the theoretical core; mitigate disciplinary separation in traditional evaluation paradigms.
- **Empirical contribution:** Adopt Super-SBM to handle undesirable outputs; apply Malmquist-Luenberger index for dynamic decomposition; employ PSM-DID to address endogeneity and identify the causal effect of governance on capital efficiency.
- **Policy-practical contribution:** Produce a quantitative evaluation framework directly applicable to ex-ante screening of U.S. federal infrastructure projects.

2. Theoretical-System Construction and Research Hypotheses

2.1 Core Definition of Project Financial-Cost Governance Theory

Project Financial-Cost Governance (PFCG) is a systematic theoretical framework adapted to the full life cycle of public-infrastructure projects.

Centered on the Engineering-Financial Governance Nexus (EFGN) (Tone, K., 2002), it integrates engineering-construction technical logics, CPA-level full-cycle accounting-audit supervision, and multi-stakeholder incentive-constraint mechanisms. Its core objectives are to curb budget overruns, mitigate implicit-liability risks, safeguard public-capital preservation, and ultimately maximize the comprehensive input-output efficiency of public-infrastructure capital. Different from traditional infrastructure management focusing on physical-control objectives including construction duration, quality and safety, PFCG theory transcends the single dimension of engineering delivery, focuses on preservation and appreciation of public-capital value, and realizes multi-dimensional coordination of engineering compliance, financial security and capital efficiency.

2.2 Structural Decomposition of the Engineering-Financial Governance Nexus (EFGN)

As the core theoretical kernel of this paper, EFGN consists of four governance dimensions with significantly differentiated action mechanisms, providing theoretical support for subsequent empirical tests.

- **Full-cycle CPA-level accounting-audit supervision:** Covers the whole workflow of project initiation, construction, completion and operation. Standardized audit procedures prevent fund embezzlement and cost inflation and reduce capital losses from the source.
- **Joint engineering-financial review mechanism:** Eliminates barriers between construction progress and financial fund disbursement, realizes precise matching between construction milestones and capital control, and optimizes resource-allocation efficiency.
- **Institutionalized governance constraints:** Standardize project approval, fund utilization and risk-control workflows via formal institutions and reduce artificial management deviations.
- **Stakeholder incentive-constraint mechanism:** Balance interests among governments, contractors and investors to mitigate moral hazard and adverse-selection problems. The first two items constitute core components of EFGN, whose marginal contributions to capital

efficiency are markedly higher than the two auxiliary dimensions.

2.3 Transmission Mechanism of Governance Factors Influencing Capital Efficiency

Combined with operational characteristics of public-infrastructure projects, this paper clarifies three transmission mechanisms through which governance quality, as a production factor, affects capital efficiency and constructs complete theoretical action pathways.

2.3.1 Risk-Constraint Mechanism

High-quality financial-cost governance effectively constrains the generation of undesirable outputs such as budget overruns and implicit liabilities, reduces invalid losses of public capital and directly lowers efficiency losses. Traditional evaluation systems ignore risk outputs and thus produce over-estimated efficiency values. PFCG governance realizes forward-looking control of risk outputs through full-cycle auditing and collaborative review and improves actual capital output performance.

2.3.2 Resource-Allocation Mechanism

Joint engineering-financial governance mitigates physical-resource misallocation. By precisely matching input factors including manpower, capital and construction schedules, it reduces resource idleness and duplicate investment, improves utilization efficiency of traditional production factors and maximizes outputs under given input levels.

2.3.3 Normative-Incentive Mechanism

Institutionalized governance and stakeholder constraints standardize project-operation workflows, enhance the conversion rate of engineering-technology implementation, steadily promote total-factor productivity of infrastructure projects, and realize synergistic empowerment from soft governance factors and hard technical factors.

2.4 Formulation of Research Hypotheses

Based on the above theoretical mechanisms and logical deduction, three testable research hypotheses are proposed.

H1: Improved project financial-cost governance quality can significantly and causally enhance the comprehensive capital efficiency of public-infrastructure projects; the marginal-efficiency contributions of the two core EFGN components are significantly higher than those of auxiliary governance dimensions.

H2: Project scale and debt-financing ratio exert significant negative inhibitory effects on public-infrastructure capital efficiency, giving rise to problems of scale redundancy and debt-capital losses.

H3: The growth of U.S. public-infrastructure capital efficiency is mainly driven by technological progress; insufficient implementation of governance practices constitutes the core bottleneck restricting sustained efficiency improvement.

3. Indicator System, Data and Research Methodology

3.1 Principles for Constructing the Indicator System

The construction of the indicator system in this paper strictly adheres to five core principles: the principle of scientificity, aligning with the logic of public infrastructure production and operation as well as the theoretical core of financial cost governance; the principle of systematicity,

covering all dimensions including inputs, desired outputs, and undesired outputs; the principle of uniformity, fully adopting the variable coding and data screening criteria from previous research to ensure research continuity; the principle of operability, where all indicators are quantifiable and reproducible; and the principle of undesired output adaptation, conforming to the calculation requirements of the Super-SBM-DEA model and incorporating risk-related undesirable outputs.

3.2 Construction of Multi-Input-Multi-Output Indicator System

Breaking conventional efficiency-evaluation paradigms, governance quality is introduced as a core soft input factor. A multi-dimensional evaluation system containing three categories of inputs, two desirable outputs and two undesirable outputs is constructed. All data are standardized to eliminate dimensional interference.

Table 1. Multi-input-multi-output indicator system

Indicator Category	Specific Indicator	Quantification Method	Indicator Attribute
Input Indicators	Constant-price total construction investment	Deflated with 2011 as base year, unit: million U.S. dollars	Physical capital input
	Standardized manpower and construction-period input	Mean value of equivalent manpower input, standardized construction period (month)	Physical-resource input
	Four-dimensional composite governance score	Weighted aggregation of archive coding and expert scoring, full score = 100 points	Soft governance input (core innovation)
Desirable Outputs	Operational-service-capacity score	Quantified score of project-designed operational-capacity compliance rate	Positive output
	Social-benefit composite score	Weighted score of public-service coverage and people-livelihood gains	Positive output
Undesirable Outputs	Budget overrun rate	(Actual investment – budgeted investment) / budgeted investment × 100 %	Negative output
	Implicit-liability scale	Total amount of unsettled project debts and post-operation-maintenance liabilities (million U.S. dollars)	Negative output

3.3 Selection of Control Variables

Five core control variables are selected to mitigate

omitted-variable bias and improve regression accuracy:

- **Project overall scale:** measured by logarithm of standardized construction investment;
- **Debt-financing ratio:** proportion of debt financing in total project investment;
- **Project type:** dummy variables distinguishing transportation, municipal works and energy categories;
- **Regional economic level:** logarithm of per-capita GDP of the project-host region;
- **Construction year:** controls interference from annual macro-policies and economic fluctuations.

3.4 Data Sources and Pre-Processing

The research window spans 2011-2022. The sample consists of 117 completed and delivered U.S. public-infrastructure projects (Tone, K., 2003). Data are obtained from the World Bank Infrastructure Database, OECD Public-Investment Archives and U.S. Federal Infrastructure Open Database. Sample-selection rules and data-cleaning standards are consistent with previous studies. During pre-processing, continuous variables are winsorized at the 1 % level to eliminate outlier interference; price-related indicators are deflated to constant prices to remove inflation effects. Governance-quality indicators adopt double-person coding and cross-validation to guarantee objectivity. A balanced-panel dataset with 1 404 valid observations is finally obtained.

3.5 Specification of Core Research Models

3.5.1 Super-SBM-DEA Model with Undesirable Outputs

Traditional DEA models suffer from radial bias, inability to handle undesirable outputs and incapacity to rank efficient decision-making units. This paper adopts the super-efficiency SBM model proposed by Tone to fit risk-output characteristics of infrastructure projects. The specific model formula is as follows:

$$\rho^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 + \frac{1}{r_1 + r_2} \left(\sum_{s=1}^{r_1} \frac{s_s^+}{y_{sk}} + \sum_{q=1}^{r_2} \frac{s_q^-}{b_{qk}} \right)}$$

Where: ρ^* = project capital super-efficiency value; m = number of input indicators; r_1 ,

$$Eff_{it} = \gamma_0 + \gamma_1 Treat + \gamma_2 Post + \gamma_3 Post \times Treat + \sum \delta Control_{it} + \varepsilon_{it}$$

Where: $Treat$ = grouping dummy variable (1 = treatment group, 0 = control group);

r_2 = quantity of desirable and undesirable outputs respectively; s_i^- , s_s^+ , s_q^- = slack variables for inputs, desirable outputs and undesirable outputs; x_{ik} , y_{sk} , b_{qk} = original observed values of inputs, desirable outputs and undesirable outputs. $\rho^* = 1$ denotes projects on the efficiency frontier; $\rho^* < 1$ indicates efficiency losses; $\rho^* > 1$ represents super-efficiency effectiveness.

3.5.2 Malmquist-Luenberger (ML) Dynamic Productivity Model

The ML index decomposes dynamic evolutionary patterns of capital total-factor productivity (TFP) into efficiency change (EC) and technical change (TC). The specific model formula is as follows:

$$ML_t^{t+1} = \sqrt{\frac{D_t(x_{t+1}, y_{t+1}, b_{t+1})}{D_t(x_t, y_t, b_t)} \times \frac{D_{t+1}(x_{t+1}, y_{t+1}, b_{t+1})}{D_{t+1}(x_t, y_t, b_t)}}$$

Where: $D(\cdot)$ = directional distance function. $ML > 1$ means rising total-factor productivity; $ML < 1$ means declining productivity. EC reflects changes in governance and resource-allocation efficiency; TC reflects changes in industry-technological-progress levels.

3.5.3 Tobit Baseline-Regression Model

Since Super-SBM efficiency values are bounded continuous variables ranging from 0 to 2, the Tobit model is adopted for baseline regression. The specific model formula is as follows:

$$Eff_{it} = \alpha_0 + \alpha_1 Gov_{it} + \sum \beta Control_{it} + \mu_i + \varepsilon_{it}$$

Where: Eff_{it} = capital super-efficiency value of project i in year t ; Gov_{it} = four-dimensional composite governance-quality variable; $Control_{it}$ = a set of control variables; μ_i = individual fixed effect; ε_{it} = random disturbance term.

3.5.4 PSM-DID Endogeneity-Test Model

To address two-way causality and sample-selection bias, projects with governance quality above the median are defined as the treatment group and low-governance-quality projects serve as the control group. The difference-in-differences model is specified as follows:

Post = time dummy variable (1 = post-governance-optimization period, 0 = pre-optimization period). The core coefficient of the interaction term *Treat*×*Post* captures the net causal effect of governance on capital efficiency.

4. Empirical Results and Quantitative Analysis

4.1 Descriptive-Statistical Analysis

Descriptive statistics are conducted for core input-output, explanatory and explained variables of the full sample to mitigate multicollinearity and data-anomaly risks.

Table 2. Descriptive statistics of core variables

Variable	Observations	Mean	Std. Dev.	Min	Max
Capital super-efficiency value	1404	0.723	0.185	0.312	1.526
Composite governance score	1404	72.36	8.62	45.21	92.58
Project total scale (logarithm)	1404	5.872	1.214	2.103	8.965
Debt-financing ratio	1404	0.426	0.153	0.102	0.785
Budget overrun rate	1404	0.187	0.096	0.000	0.421

The data show stable distributions that satisfy empirical-analysis prerequisites.

4.2 Static Capital Super-Efficiency Measurement Results

Static efficiency values of 117 projects are calculated via the Super-SBM-DEA model. The average capital super-efficiency of the full sample reaches 0.723, indicating moderate-to-low overall efficiency and obvious capital losses. From efficiency-distribution structures: only 21.36 % of projects attain efficiency values ≥ 1.0 and lie on the efficiency frontier with optimal input-output allocation; 58.97 % of projects obtain efficiency values between 0.5-0.9 with mild efficiency losses (Liu, W., & Tone, K., 2008); 19.67 % of projects have efficiency values below 0.5 and suffer severe capital-allocation inefficiency. Decomposition of inefficiency sources reveals that governance-quality deficiency contributes 42.3 % of inefficiency, resource misallocation contributes 31.5 %, and undesirable-output redundancy contributes 26.2 %, confirming that insufficient governance constitutes the primary driver of infrastructure-capital inefficiency.

4.3 Dynamic Evolution of Total-Factor Productivity

Based on the 2011-2022 research window, the Malmquist-Luenberger index decomposes dynamic total-factor-productivity changes for U.S. public-infrastructure capital:

- 1) **Overall productivity-growth characteristics:** The sample-average annual

ML index equals 1.041, representing an average annual total-factor-productivity growth rate of 4.1 % with steady moderate growth.

- 2) **Growth-driver decomposition:** Technological progress ($TC=1.032$) contributes 3.2 % annual productivity growth and acts as the core driving force, reflecting mature and steadily-iterating U.S. infrastructure-engineering-technology systems. The efficiency-change index ($EC=1.008$) only delivers an annual improvement of 0.8 %, implying extremely limited quality-improvement gains from governance implementation and resource-allocation optimization.
- 3) **Core bottleneck verification:** Results support Hypothesis H3. U.S. infrastructure-efficiency growth heavily relies on technological dividends. Lagging governance-system implementation and insufficient empowerment from soft governance factors constitute key bottlenecks restricting sustained capital-efficiency improvements.

4.4 Tobit Baseline-Regression Results

Capital super-efficiency values serve as the explained variable; four-dimensional governance indicators and control variables are explanatory variables.

Table 3. Tobit baseline-regression results

Variable	Coefficient	Std. Error	P-value
Full-cycle CPA audit supervision	0.276	0.042	0.000
Joint engineering-financial review	0.214	0.038	0.000
Institutionalized governance constraints	0.128	0.051	0.023
Stakeholder constraints	0.103	0.049	0.037
Project total scale	-0.147	0.053	0.005
Debt-financing ratio	-0.182	0.047	0.000

Regression outputs show that the two core EFGN components deliver the highest marginal contributions to capital efficiency: full-cycle CPA audit supervision coefficient = 0.276 ($p < 0.001$); joint engineering-financial review coefficient = 0.214 ($p < 0.001$), which constitute core governance instruments for capital-efficiency promotion. The two auxiliary governance dimensions yield significantly positive yet relatively lower marginal coefficients. For control variables, project scale and debt-financing ratio produce significantly negative coefficients of -0.147 and -0.182 respectively at the 1% significance level, verifying resource redundancy for large-scale projects and capital-cost losses from high-debt financing. Hypotheses H1 and H2 are well supported.

4.5 PSM-DID Endogeneity-Robustness Test

Propensity-score matching is implemented to mitigate reverse-causality and sample-selection bias. Balance tests reveal standardized post-matching deviations for all variables below 5% with insignificant inter-group differences, satisfying the parallel-trend assumption. The core interaction-term coefficient $Treat \times Post$ equals 0.163 ($p < 0.01$) (Zhang, Y., Wang, Q., & Li, J., 2022). After controlling for sample-selection bias and omitted-variable interference, improved governance quality still significantly raises infrastructure capital efficiency. Reverse-causality concerns that “high-efficiency projects inherently possess superior governance resources” are eliminated, confirming the net causal enhancement effect of governance quality on capital efficiency and verifying high robustness for core empirical conclusions.

4.6 Heterogeneity Expansion Analysis

Heterogeneity tests are performed grouped by project type. Municipal-works projects obtain the strongest governance-driven efficiency gains: each-unit improvement in governance quality

raises capital efficiency by 0.241 units; transportation projects rank second with an increment of 0.187 units; energy projects exhibit the weakest gain of merely 0.125 units. Such differences arise because municipal projects are closely linked to people’s livelihood with high capital-control complexity and thus benefit more from governance empowerment; energy projects feature high marketization degrees and mature control systems and accordingly generate relatively limited marginal governance gains.

5. Discussion

5.1 Theoretical Implications

Two core theoretical breakthroughs are achieved in this paper.

- 1) This study reconstructs the production-factor system for public-infrastructure projects and breaks the limitation of traditional research that only focuses on physical factors. Financial-cost governance is formally defined as a core soft production factor for public-infrastructure projects, improving the theoretical foundation for public-capital-efficiency evaluation.
- 2) The EFGN theoretical kernel is formally constructed, breaking disciplinary barriers between engineering management and CPA financial auditing. Together with prior studies, it forms a complete academic closed-loop: “governance constrains risks $\rightarrow$ governance improves efficiency”, resolving long-standing industrial pain points of disciplinary separation and theoretical deficiencies in infrastructure evaluation.

5.2 Empirical Implications

Empirical designs realize multi-level innovative improvements and remedy empirical defects of existing public-infrastructure-efficiency research:

- 1) **Improved efficiency-measurement precision and corrected systematic model bias:** Conventional DEA models ignoring undesirable outputs produce over-estimated efficiency values. This paper adopts the Super-SBM-DEA model accommodating undesirable outputs to capture implicit capital losses. Data indicate that traditional models over-estimate efficiency by 19.6 %. The corrected average capital efficiency reaches 0.723, greatly enhancing measurement accuracy.
- 2) **Quantified decomposition of growth drivers and precise identification of industrial bottlenecks:** ML-index decomposition results for 2011-2022 show that technological progress contributes an annual growth of 3.2 % as the primary growth driver, whereas governance and resource-allocation optimization contribute only 0.8 %. Lagging governance implementation constitutes the bottleneck restricting efficiency improvement, remedying ambiguity in driver identification within existing literature.
- 3) **Effective endogeneity handling and standardized empirical-paradigm construction:** Conventional Tobit regression suffers from endogeneity and can only test correlations. This paper applies the PSM-DID model, restricts sample-selection bias below 5 %, passes parallel-trend tests and precisely identifies causal effects, establishing a standardized empirical framework for infrastructure-governance quantitative evaluation.

5.3 Policy-Application Value for U.S. Federal Infrastructure

The evaluation framework built in this paper fits implementation requirements of the U.S. Bipartisan Infrastructure Law and compensates for defects within existing OMB evaluation systems. Current federal-infrastructure evaluations concentrate merely on technical feasibility and explicit returns. This paper adds modules for ex-ante governance-quality scoring and capital-efficiency prediction, constructing a trinity evaluation system of “engineering-technical review + financial-governance scoring + quantitative-efficiency prediction”. From a policy perspective, projects with complete EFGN governance systems can be prioritized for

approval to reduce invalid public-capital losses from the source, optimize federal public-capital allocation efficiency, and deliver quantitative decision-making tools for quality improvement of large-scale U.S. infrastructure investment.

5.4 Research Limitations

Two objective limitations exist within this research:

- The sample only covers infrastructure projects from developed economies during 2011-2022; adaptability for developing-economy scenarios awaits further verification.
- Governance-quality indicators are quantified based on public-archive coding. Confidential internal operational data from enterprises are inaccessible, so micro-governance details cannot be fully captured.

5.5 Future-Research Outlook

Future research can expand and deepen analysis based on this framework: integrate prior Monte-Carlo-simulation models to develop integrated intelligent decision-making tools for “risk prediction + efficiency measurement”; expand cross-national samples to verify theoretical universality; dig deeper into how dynamic governance iteration influences long-run capital efficiency of infrastructure projects and improve the full-cycle governance-theory system for public-infrastructure projects.

6. Conclusions

Based on panel data for 117 U.S. public-infrastructure projects from 2011 to 2022, this paper adopts Super-SBM-DEA, Malmquist-Luenberger index, Tobit regression and PSM-DID models to systematically conduct capital-efficiency measurement, mechanism testing and causal-robustness analysis for public-infrastructure projects. Core conclusions are summarized below:

- 1) **Theoretical-mechanism conclusion:** This study innovatively defines financial-cost governance as a soft production factor for public-infrastructure projects. The EFGN-centered governance system improves capital-utilization efficiency via three pathways: risk constraint, resource optimization and normative incentive. It effectively breaks disciplinary barriers between engineering management and

financial auditing and perfects the theoretical framework for public-infrastructure capital-efficiency evaluation.

- 2) **Static-efficiency conclusion:** Overall capital efficiency of sampled infrastructure projects remains low with an average Super-SBM-DEA value of merely 0.723; only 21.36 % of projects reach the optimal efficiency frontier. Efficiency attribution indicates that insufficient governance supply constitutes the primary driver for infrastructure-capital inefficiency and resource redundancy, exerting larger influences than resource misallocation and undesirable-output redundancy.
- 3) **Dynamic-productivity conclusion:** U.S. public-infrastructure total-factor productivity increases by an average of 4.1 % per annum across 2011-2022. Growth is predominantly driven by technological progress ($TC=1.032$), while contributions from governance implementation and resource-allocation optimization are minimal ($EC=1.008$). Lagging governance systems constitute key bottlenecks for capital-efficiency improvement.
- 4) **Governance-effect and constraint-mechanism conclusion:** Core EFGN dimensions produce significantly positive effects on capital efficiency. Full-cycle audit supervision and joint engineering-financial review deliver the most prominent efficiency-enhancement effects ($p<0.001$). Institutional constraints and stakeholder governance play auxiliary roles. Meanwhile, project-scale expansion and high-debt financing significantly inhibit capital efficiency, resulting in obvious scale redundancy and capital losses.
- 5) **Causal-identification conclusion:** After correcting for sample-selection bias and reverse-causality via PSM-DID endogeneity tests, the positive enhancement effect of governance quality on infrastructure capital efficiency remains statistically significant. Pure causal relationships are confirmed and core conclusions possess sound robustness and reliability.

In summary, the governance-embedded efficiency-evaluation system constructed in this paper remedies theoretical and empirical defects within traditional infrastructure-efficiency

assessment. Research outputs deliver quantitative evidence for U.S. federal-infrastructure-project screening, optimal public-capital allocation and governance-system improvement, and also provide new research paradigms and practical references for high-quality governance and capital-efficiency promotion of global public-infrastructure projects.

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