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Impact of Digital Transformation on Green Production Efficiency of Construction Enterprises and Its Mechanism

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Abstract: *Taking digital transformation as a quasi-natural experiment, this paper constructs a multi-period difference-in-differences (DID) model using the data of China's A-share listed construction enterprises from 2013 to 2022 to investigate the impact of digital transformation on the green production efficiency of construction enterprises. The study reveals that digital transformation significantly improves the green production efficiency of construction enterprises, and this conclusion remains valid after multiple robustness tests. Mechanism analysis demonstrates that digital transformation elevates green production efficiency by boosting corporate green technological innovation and alleviating financing constraints. Heterogeneity analysis shows that the positive effect of digital transformation on green production efficiency is more pronounced for construction enterprises located in eastern China and state-owned enterprises (SOEs). Theoretically, this research offers a new perspective for enhancing construction enterprises' green production efficiency via digital transformation. Practically, it provides empirical evidence and policy implications for governments and enterprises to collaboratively advance green production efficiency and standardize the development of digital transformation in the construction sector.*

Keywords: *Digital Transformation; Green Production Efficiency; Mediating Effect; Multi-period Difference-in-Differences*

1. Introduction

As core participants in urban development, construction enterprises' green production efficiency is the foundation for practicing green development and advancing comprehensive green transformation of economic and social development. Digital transformation serves as an effective pathway for enterprises to raise production efficiency and facilitate low-carbon green development. Driven by national policies, the construction industry is entering a critical phase of digital upgrading.

Existing literature mainly focuses on the economic growth effects and corporate performance outcomes of digital transformation [1–3], while few studies examine its impacts on post-transformation green production efficiency. In recent years, a growing body of research has explored how digital transformation affects high-quality corporate development [4,5] and technological innovation in the digitalization process [6,7]. Research on green production efficiency of construction enterprises falls into two strands: first, scholars adopt Data Envelopment Analysis (DEA), directional distance function and super-efficiency SBM models to measure green production efficiency and analyze its spatial-temporal characteristics [8]; second, studies explore driving factors of construction enterprises' green production efficiency from external policy shocks and internal resource endowments [9]. External policy factors mainly cover pilot policies, green finance, smart city construction, environmental regulation, regional integration and new urbanization [10–12]; internal resource factors include economic development level, firm size, industrial structure upgrading, scientific and technological innovation, opening-up and digital infrastructure [13–15].

In summary, extant research primarily investigates the direct economic consequences and technological innovation effects of digital transformation, while studies on construction enterprises' green production efficiency concentrate on measurement, evaluation and driving factors. Limited literature addresses whether digital transformation improves corporate ecological performance and further facilitates green production. Therefore, this paper crawls digital transformation-related information from annual reports of A-share listed construction enterprises (2013–2022) via web scraping

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and textual analysis, constructs a panel multi-period DID model, and empirically evaluates whether digital transformation improves construction enterprises' green production efficiency as well as its underlying mechanisms.

This paper makes three main contributions to the literature: First, it measures construction enterprises' green production efficiency using the super-efficiency SBM model. Second, it incorporates digital transformation into the analytical framework of drivers of construction enterprises' green production efficiency, revealing the causal effect and internal mechanisms of digital transformation, which enriches theoretical frameworks and empirical evidence on green production efficiency, and provides references for objectively evaluating the policy effects and standardized development of digital transformation. Third, it explores heterogeneous effects of digital transformation from geographic location and corporate ownership perspectives, expanding relevant research dimensions.

2. Policy Background and Theoretical Mechanisms

2.1. Direct Impacts of Digital Transformation on Construction Enterprises' Green Production Efficiency

As a product of green development philosophy, green production efficiency of construction enterprises aims to maximize economic, social and environmental benefits with minimal resource input and optimal resource allocation. By embedding digital technologies and intelligent management into the whole production chain of construction enterprises, digital transformation optimizes resource utilization and boosts green production efficiency [16].

First, digital transformation lifts corporate economic output. Featuring economies of scope and scale, digital transformation delivers higher output per unit resource compared with traditional production modes. Large-scale investment in digital transformation directly stimulates economic growth, and digital technologies oriented to intelligent manufacturing and green construction streamline production workflows and raise economic output.

Second, digital transformation drives full employment. Digital transformation generates massive new jobs and fuels upstream and downstream industrial chains, creating employment opportunities in software development, intelligent equipment manufacturing, data analytics and other sectors. Post-transformation intelligent operation and management also demand a large workforce of technical specialists, raising employee income and improving people's livelihoods.

Third, digital transformation improves corporate ecological conditions. As a form of technological upgrading, digital transformation enables enterprises to proactively advance green production and enhance ecological performance, which significantly lifts green production efficiency [17]. For instance, intelligent management systems cut resource waste and boost utilization efficiency; green construction technologies support energy conservation and emission reduction to mitigate climate change. Additionally, digital transformation outsources waste disposal to specialized third-party firms, which improves waste treatment quality and ecological governance efficiency while reducing decentralized treatment costs for individual enterprises. This allows firms to concentrate resources on core competitive businesses and raise output per unit investment.

Accordingly, Hypothesis H1 is proposed: Digital transformation directly improves the green production efficiency of construction enterprises.

2.2. Indirect Impacts of Digital Transformation on Construction Enterprises' Green Production Efficiency

Beyond the direct effects outlined above, digital transformation indirectly elevates green production efficiency through two channels: promoting corporate green technological innovation and alleviating financing constraints.

Promoting Corporate Green Technological Innovation： Enterprises pursue digital transformation to expand revenue, optimize government-enterprise relations and enhance brand value, which further stimulates green technological innovation via corporate strategic orientation and knowledge spillovers. First, digital transformation streamlines operational efficiency, expands the share of green business, consolidates corporate green development strategies and increases investment in green technological innovation [18]. Second, digital transformation features risk-sharing and win-win cooperation, uniting

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participants into a community of shared interests and accelerating cross-party knowledge flow and exchange. This reduces innovation risks and generates knowledge spillovers that benefit other innovation projects, thereby advancing green technological innovation [19].

Alleviating Corporate Financing Constraints: Digital transformation mitigates financing constraints through multiple channels to indirectly boost green production efficiency. First, digital transformation projects require substantial capital investment and grant enterprises wider access to financing. Financial institutions strongly support digital transformation initiatives, while governments incentivize green credit issuance, supplying enterprises with abundant capital[20]. Second, enterprises must regularly disclose ESG information of digital transformation projects for financial institution review, improving corporate transparency and creditworthiness and easing financing frictions[21]. Third, successful digital transformation significantly strengthens corporate market competitiveness and brand value, attracting more investors and diversified financing channels to optimize financing conditions.

Accordingly, Hypothesis H2 is proposed: Green technological innovation and alleviated financing constraints exert mediating effects in the relationship between digital transformation and construction enterprises' green production efficiency.

3. Empirical Research Design

3.1. Model Specification

This paper treats digital transformation as a policy shock to improve corporate green production efficiency. Given the wide distribution of transformation start years across firms, the staggered rollout of digital transformation can be regarded as quasi-random. Since different enterprises implement digital transformation in different years, a multi-period DID model is adopted to assess the average treatment effect of digital transformation on green production efficiency. A two-way fixed-effects model is constructed as follows:

$$\mathrm{GR}_{it} = \alpha_0 + \beta Did_{it} + \lambda X_{it} + \mu_i + \sigma_t + \epsilon_{it} \tag{1}$$

In the formula:

GR_{it} denotes the green production efficiency of firm i in year t; Did is the difference-in-differences dummy variable, with β as its estimated coefficient; X_{it} represents a set of control variables; α_0 is the constant term; μ_i and σ_t stand for firm fixed effects and year fixed effects respectively; ϵ_{it} is the random error term.

3.2. Variable Selection

Dependent Variable: Green Production Efficiency (GPE) of Construction Enterprises. Following existing literature [8], this paper adopts the super-efficiency SBM model to measure green production efficiency, specified as:

$$\rho = \min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^+}{y_{r0}^+}+\sum_{r=1}^{s_2}\frac{s_r^-}{y_{r0}^-}\right)} \tag{2}$$

subject to:

$$x_0 = X\lambda + s^-$$
$$y^+ = Y^+\lambda - s^+$$
$$y^- = Y^-\lambda + s^-$$
$$s^- \geq 0, s^+ \geq 0, s^- \geq 0, \lambda \geq 0$$

Where: ρ is efficiency score; m is number of input categories; s_1、s_2 represent number of desirable output categories and undesirable output categories; s_i^-, s_r^+, s_r^- indicate slack variables of inputs, desirable outputs and undesirable outputs respectively; x_{i0}, y_{r0}^+, y_{r0}^- indicate inputs, desirable outputs and undesirable outputs of decision-making units.

Input indicators include labor input, R&D input and capital input, measured by total number of employees, total R&D expenditure and net fixed assets respectively. Desirable output indicators reflect

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economic benefits, measured by total profit and operating revenue. Undesirable output indicator covers depreciation of fixed assets, oil and gas assets and productive biological assets. The complete evaluation index system is shown in Table 1.

Table 1: Input-Output Indicator System for Green Production Efficiency.

Indicator Type	Consideration Dimension	Selected Indicator
Input Indicators	Employee skill level & training investment	Total number of employees
	R&D project volume & R&D personnel qualification	Total R&D expenditure
	Fixed asset service life & maintenance cost	Net fixed assets
Desirable Output Indicators	Profit sources & profit growth rate	Total profit
	Revenue composition & revenue growth rate	Operating revenue
Undesirable Output Indicators	Resource consumption rate & resource market price	Depreciation of fixed assets, oil & gas assets and productive biological assets

Core Independent Variable: DID Term for Digital Transformation Implementation. Digital transformation is treated as a quasi-natural experiment, captured by the interaction term of firm treatment dummy and time dummy per multi-period DID rules. For firms that implement digital transformation, Did equals 1 from the first transformation year onwards and 0 pre-transformation; firms that never implement digital transformation take a value of 0 throughout the sample period.

Mediating Variables: Drawing on prior research, green technological innovation is measured by the number of authorized green patents; financing constraints are proxied by the SA financing constraint index.

Control Variables: The following control variables are selected based on existing studies: Herfindahl-Hirschman Index (HHI): Measures market concentration, calculated as the sum of squared market shares of all industry participants to reflect competition intensity. Tobin's Q: Ratio of corporate market value to asset replacement cost, reflecting market valuation relative to tangible asset value. Return on Assets (ROA): Ratio of net profit to total assets, measuring asset utilization efficiency. Firm Size (Size): Natural logarithm of total corporate assets to capture overall firm scale. Cash Flow (Cflow): Net cash flow generated from operating activities, reflecting daily operational liquidity. Total Liability Ratio (TL): Ratio of total liabilities to total assets, representing corporate leverage level. These control variables improve the accuracy of regression analysis and result interpretation.

3.3. Data Description

Digital economy expansion and digital technology penetration accelerated post-2012, hence this paper selects A-share listed construction enterprises from 2013 to 2022 as the initial sample. Sample screening criteria: Retain only construction industry firms; Exclude ST, PT and insolvent listed firms; Eliminate observations with missing core variables. The final sample contains 64 listed construction firms with 640 firm-year observations. Corporate financial data are sourced from the China Stock Market & Accounting Research (CSMAR) Database; regional-level data are collected from annual <China City Statistical Yearbooks>. All continuous variables are winsorized at the 1st and 99th percentiles, and standard errors are clustered at the firm level in regressions, as shown in table 2.

Table 2: Variable Definition and Descriptive Statistics

Variable Name	Variable Definition	Observations	Mean	Standard Deviation	Min	Max
GPE	Green production efficiency	640	0.789	0.830	0.248	1.063
HHI	Herfindahl-Hirschman Index	640	0.274	0.211	0.153	1
tobin	Tobin's Q	640	1.407	1.186	0.826	15.55
roa	Return on total assets	640	0.0170	0.0210	-0.588	0.231
size	Firm size (ln total assets)	640	23.29	22.95	18.16	28.61
cflow	Operating cash flow ratio	640	0.0110	0.0130	-0.198	0.304
tl	Total liability ratio	640	0.665	0.683	0.164	1.465

4. Empirical Results and Analysis

4.1. Baseline Regression

Table 3 reports regression results of digital transformation's impact on construction enterprises' green production efficiency. Column (1) excludes all control variables; Columns (2) to (4) sequentially add control variables while controlling for year and firm fixed effects. The core explanatory variable

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Did carries a significantly positive coefficient across all specifications, confirming that digital transformation improves construction enterprises' green production efficiency and validating Hypothesis H1.

Table 3: Baseline Regression Results.

Variables	(1)	(2)	(3)	(4)
Did	0.027***	0.027***	0.017*	0.017*
	(0.009)	(0.009)	(0.009)	(0.009)
HHI		-0.094***	-0.070**	-0.071**
		(0.033)	(0.032)	(0.032)
tobin		0.002	0.002	0.002
		(0.004)	(0.004)	(0.004)
roa			0.229***	0.199***
			(0.041)	(0.051)
size			0.002	0.004
			(0.007)	(0.007)
cflow				0.008
				(0.042)
tl				-0.034
				(0.034)
_cons	0.808***	0.832***	0.772***	0.748***
	(0.007)	(0.013)	(0.164)	(0.166)
Fixed Effects	YES	YES	YES	YES
N	640.000	640.000	640.000	640.000
R ²	0.101	0.114	0.162	0.163

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

4.2. Robustness Tests

Parallel Trend Test: The prerequisite for valid multi-period DID estimation is the parallel trend assumption: before digital transformation, the green production efficiency trends of treatment and control group firms should remain statistically identical. This paper adopts the event study method to conduct parallel trend testing and plot corresponding results. As shown in Figure 1, the vertical axis represents the green production efficiency gap between treatment and control groups; the horizontal axis denotes relative years around digital transformation implementation.

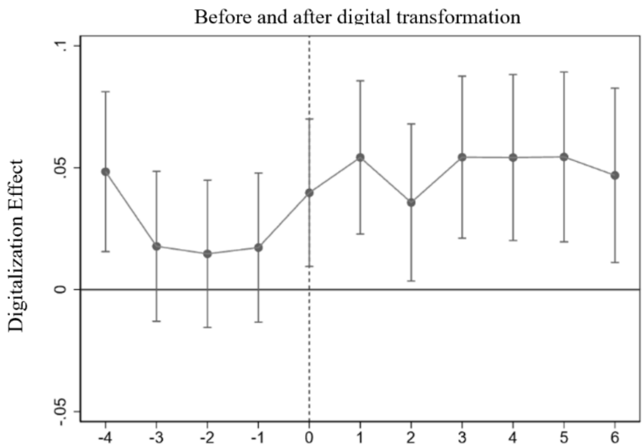

Figure 1: Parallel Trend Test

Observations four years before transformation are grouped into period -4 due to limited sample size; observations six years after transformation are grouped into period 6. Pre-transformation coefficients are all statistically insignificant, indicating no systematic difference between the two groups and satisfying the parallel trend assumption. The graph also shows that the positive effect of digital transformation on green production efficiency emerges immediately upon implementation.

Placebo Test: Firm-level Placebo Test. To exclude the possibility that the baseline results are driven by random confounding factors, a counterfactual placebo test is conducted by randomly assigning false treatment firms and false implementation years. As shown in Figure 2, we randomly generate treatment groups for 500 sampling iterations and plot the kernel density distribution of estimated coefficients and corresponding p-values. The mean regression coefficient approaches zero, and most p-values exceed 0.1,

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passing the firm-level placebo test.

Time Placebo Test. To verify the time-specificity of digital transformation's effect, we artificially advance transformation implementation by one, two and three years to construct false time dummy variables and interact them with the core explanatory variable. Table 4 Columns (1)–(3) show that coefficients for all false pre-transformation time variables are insignificant. This confirms that digital transformation exerts a causal impact on green production efficiency only after actual implementation, further validating the robustness of baseline findings.

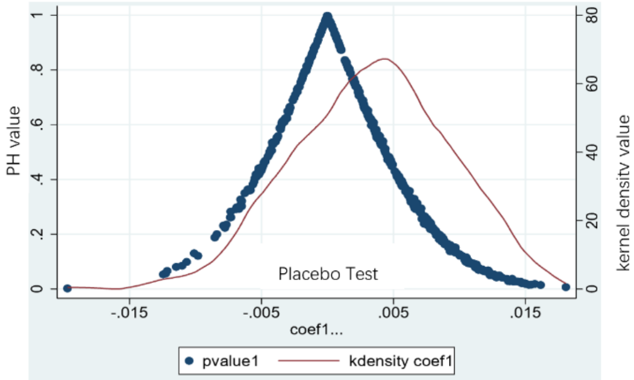

Figure 2: Individual Placebo Test (coef1: coefficients1…)

Table 4: Time Placebo Test

Variables	(1) One Year in Advance	(2) Two Years in Advance	(3) Three Years in Advance
year1	0.008		
	(0.010)		
year2		-0.003	
		(0.011)	
year3			-0.014
			(0.015)
Constant	0.711***	0.704***	0.724***
	(0.165)	(0.165)	(0.166)
Fixed Effects	YES	YES	YES
N	640.000	640.000	640.000
R^2	0.159	0.158	0.159

Standard errors in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

PSM-DID Robustness Test: Propensity Score Matching (PSM) mitigates bias from observable confounding variables. This paper applies nearest neighbor matching, radius matching and kernel matching, followed by multi-period DID regression. Table 5 presents PSM-DID results: the Did coefficient remains significantly positive under all three matching methods, consistent with baseline regression and reinforcing result reliability.

Table 5: PSM-DID Test Results

Matching Method Variable name	Nearest Neighbor Matching	Radius Matching	Kernel Matching
Did	0.030	0.017	0.020
	(0.012)	(0.009)	(0.009)
Control Variables	YES	YES	YES
Fixed Effects	YES	YES	YES
N	524.000	640.000	609.000
R^2	0.148	0.163	0.158

Standard errors in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

Mechanism Test (Mediating Effect Model): A mediating effect model is adopted to unpack the transmission channels: financing constraints and green technological innovation. Regressions take SA financing constraint index (SA) and total green patent applications (GPA) as dependent variables respectively, with digital transformation as the core independent variable. Table 6 reports mediating effect results. Columns (1) and (2) show that digital transformation significantly alleviates financing constraints, which in turn lifts green production efficiency. Columns (3) and (4) indicate that although digital transformation's coefficient on green technological innovation is insignificant, green patent quantity correlates positively with green production efficiency in magnitude after inclusion. Overall, financing constraints and green technological innovation exert partial mediating effects between digital

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transformation and construction enterprises' green production efficiency, supporting Hypothesis H2.

Table 6: Mediating Effect Test Results

Variables	(1) SA	(2) GPE	(3) GPA	(4) GPE
Did	0.033***	0.025***	-3.545	0.026***
	(0.012)	(0.009)	(2.292)	(0.009)
SA		0.063*		
		(0.032)		
GPA				-0.001*
				(0.013)
Constant	-3.637***	1.036***	1.940	0.809***
	(0.009)	(0.118)	(1.832)	(0.007)
Control Variables	YES	YES	YES	YES
Fixed Effects	YES	YES	YES	YES
N	640.000	640.000	640.000	640.000
R^2	0.553	0.107	0.037	0.106

Standard errors in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

5. Heterogeneity Analysis

5.1. Regional Heterogeneity

Existing studies confirm that digital transformation outcomes depend on regional macroeconomic conditions. This paper divides the full sample into eastern, central and western subgroups for grouped regression to explore regional heterogeneous effects. Results show that the Did coefficient is only statistically significant for eastern firms, meaning digital transformation significantly boosts green production efficiency for construction enterprises in eastern China but exerts no significant impact on central and western counterparts.

The underlying logic is that eastern regions feature higher industrial sophistication, with abundant talent, capital and factor support for low-carbon green industrial development. As such, digital transformation delivers stronger efficiency gains for eastern construction firms. Central and western regions face shortages of high-end factors, limiting the marginal benefits of digitalization on green production.

5.2. Ownership Heterogeneity

Table 7 reports grouped regression results split by corporate ownership. The positive impact of digital transformation on green production efficiency is significantly stronger for state-owned enterprises (SOEs) than private enterprises. Two explanations apply:

First, SOEs enjoy greater policy support and resource endowments, enabling large-scale investment in digital transformation projects to generate substantial green efficiency improvements. Second, SOEs bear heavier environmental protection and social responsibility mandates, driving higher investment in green production upgrades.

While private firms feature more flexible and innovative digital transformation models, they lack comparable policy and resource backing. Private enterprises prioritize cost control and short-term market returns under competitive pressure, leading to insufficient long-term investment in green production, hence weaker efficiency gains from digitalization.

Table 7: Heterogeneity Regression Results

Variables	(1) Eastern China	(2) Central China	(3) Western China	(4) SOEs	(5) Private Firms
Did	0.022	0.005	-0.013	0.042	-0.010
	(0.011)	(0.015)	(0.017)	(0.017)	(0.005)
_cons	1.182	1.922	-0.320	0.703	0.787
	(0.259)	(0.228)	(0.228)	(0.314)	(0.117)
Control Variables	YES	YES	YES	YES	YES
Fixed Effects	YES	YES	YES	YES	YES
N	504.000	66.000	70.000	303.000	295.000
R^2	0.177	0.739	0.619	0.102	0.558

Standard errors in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

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6. Conclusions

Based on panel data of A-share listed construction enterprises from 2013 to 2022, this paper employs a staggered multi-period DID model to systematically examine the impact of digital transformation on construction enterprises' green production efficiency. Key findings are summarized as follows:

(1) Digital transformation significantly improves the green production efficiency of construction enterprises.

(2) Digital transformation elevates green production efficiency through two transmission channels: advancing corporate green technological innovation and alleviating financing constraints.

(3) The efficiency-enhancing effect of digital transformation is more pronounced for construction enterprises located in eastern China and state-owned enterprises.

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