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Original Research Article

Coupling pathways and empirical measurement in mechanical design

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Abstract: This study constructs the "Regional Development Gap Index (UUDI)"based on prefecture-level city data from Guangdong Province spanning 2013–2023. Employing the TOPSIS-entropy weighting method and validating robustness through PCA, it examines the impact of digital financial development (DFI) on regional disparities. Construction and mechanical design, manufacturing, and automation (MD&A) are embedded as pivotal sectors for in-depth analysis. The indicator system incorporates green and digital elements from construction (prefabrication share, green building area, energy/carbon intensity per unit floor area) and MD&A linkage metrics (prefabricated component standardization rate, BIM-MES-SCADA integration, CNC/robotic equipment density, on-site automated sensor coverage) to reflect the transmission chain: "capital accessibility—Manufacturing capacity—Engineering supply—Urban performance."Descriptive statistics reveal: UUDI mean 0.52, standard deviation 0.18, with significant regional variation; DFI mean 0.68, standard deviation 0.23, showing high concentration in the Pearl River Delta; 67% of cities have high-speed rail access, with financing convenience significantly better in the Pearl River Delta. Mechanism analysis reveals that digital finance alleviates financing constraints for equipment renewal, promotes coordination within the prefabricated construction supply chain, and stimulates automation investment. This enhances engineering supply efficiency and quality, ultimately narrowing regional disparities. This study contributes by: proposing a unified measurement framework linking "digital finance—MD&A—Construction industry—Urban performance"; developing reusable UUDI metrics and embedded MD&A indicators; and establishing a data and methodological foundation for future causal identification and policy simulation.

Keywords: regional development disparities (UUDI); digital finance (DFI); TOPSIS-entropy weight method; PCA; mechanical design

1. Introduction

Against the backdrop of rapid digital economic evolution, digital finance—Through payments, credit services, risk management, and data-driven empowerment—Enhances capital allocation efficiency and accessibility, emerging as a key driver of regional high-quality development. Simultaneously, the construction industry is undergoing deep integration with Mechanical Design, Manufacturing, and Automation (MD&A): prefabricated construction drives design standardization and manufacturing front-loading; BIM and digital twins connect CAD/CAE with production line control (MES/SCADA); CNC and robotics enhance the efficiency and consistency of component manufacturing and on-site assembly; IoT/SHM sensors enable closed-loop data throughout the engineering lifecycle. However, existing regional disparity studies have insufficiently examined the automation level and engineering implementation of the "manufacturing-construction-operation"chain, making it difficult to accurately depict how digital finance influences engineering supply and urban performance

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through MD&A.

To address this gap, this paper introduces indicators related to the construction industry and MD&A based on the objective measurement system of UUDI, forming a transmission framework of "capital-manufacturing-engineering-performance": (1) Objectively determine weights using the entropy weight method to avoid subjective assignment bias; (2) Characterize relative urban performance using a comprehensive distance metric close to the ideal solution, enabling inter-period tracking; (3) Perform dimension reduction and robustness validation through PCA; (4) Identify MD&A-related variables and their interaction terms with DFI to recognize the synergistic effect of "finance × automation."

2. Analysis of the impact of digital finance on regional development gaps in guangdong

To delve deeper into the impact of digital finance on regional development disparities in Guangdong, this section will establish a regression model to analyze both the overall effect and regional heterogeneity[1].

2.1. Regression model specification

Based on the preceding measurement of digital finance development levels and regional disparities in Guangdong, the following regression model is constructed:

$$UUDI_{it} = \alpha + \beta_1 DFI_{it} + \sum_k \beta_k control_{kit} + \lambda_i + \lambda_t + \varepsilon_{it} \quad \text{Formula (1)}$$

In the formula, $UUDI_{it}$ represents the explanatory variable, which is the regional development gap index mentioned earlier. DFI is the core explanatory variable, indicating the level of digital financial development. ε_{it} denotes the random disturbance term. A stepwise regression method is employed to test for mediating effects. "Stepwise regression"is a commonly used method for examining the presence of mediating effects, specifically involving the following three regression equations:

$$\mathrm{UUDI}_{it} = \alpha + \mathrm{cDFI}_{it} + \sum_k \beta_k \mathrm{control}_{kit} + \lambda_i + \gamma_t + \varepsilon_{it} \quad \text{Formula (2)}$$

$$\mathrm{Fin}_{it} = \alpha + \mathrm{aDFI}_{it} + \sum_k \beta_k \mathrm{control}_{kit} + \lambda_i + \gamma_t + \varepsilon_{it} \quad \text{Formula (3)}$$

$$\mathrm{UUDI}_{it} = \alpha + c^* \mathrm{DFI}_{it} + \sum_k \beta_k \mathrm{control}_{kit} + \lambda_i + \gamma_t + \varepsilon_{it} \quad \text{Formula (4)}$$

In the equation, λ_i denotes the control group, γ_t represents the control period, and Fin_{it} signifies the environmental resource mediating variable. Therefore, this study conducted robustness tests on the mediating effect model through the aforementioned three tests. Simultaneously, interaction terms between digital financial development and household entrepreneurship, corporate innovation, and industrial structure were introduced into the baseline regression model for examination. The moderating effect model and regression results are presented in Equation (5):

$$UUDI_{it} = \alpha + \beta_1 DFI_{it} + \beta_2 DFI_{it} \times Moderator_i + \sum_k \beta_k control_{kit} + \lambda_i + \gamma_t + \varepsilon_{it} \quad \text{Formula (5)}$$

In the equation, UUDI represents the explanatory variable, namely the regional development gap index

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mentioned earlier; DFI denotes digital financial development; $Moderator_i$ is the moderating variable encompassing resident entrepreneurship, corporate innovation, and industrial structure; and $control_{kit}$ serves as the control variable in the baseline regression model. If the regression coefficients for the interaction terms between digital finance and the moderating variables significantly influence regional development gaps, this indicates the presence of a moderating effect[2].

2.2. Descriptive statistics

Table 1. Descriptive statistics for key variables.

Variable Name	Mean	Standard Deviation	Minimum value	Median	Maximum value	Variable Description (Example)
Regional Development Gap	0.52	0.18	0.22	0.5	0.9	TOPSIS Comprehensive Index (0-1 Normalization)
Digital Financial Development	0.68	0.23	0.15	0.7	0.97	Digital Payment Coverage Rate + Digital Credit Penetration Rate
Fixed Asset Investment Structure Bias	0.36	0.12	0.1	0.35	0.65	Infrastructure Investment Proportion (%)
Takeout Dependency	0.14	0.06	0.03	0.13	0.32	Food Delivery Order Amount / Total Retail Sales of Consumer Goods (%)
Talent Supply	85.3	25.6	30.2	82.1	150.5	Number of College Graduates per 10,000 People (Person)
Financial Development	1.45	0.38	0.6	1.43	2.75	Loan Balance / GDP (Ratio)
Urban-Rural Income Distribution Structure	2.75	0.65	1.5	2.7	4.2	Urban Residents' Income / Rural Residents' Income (Multiple)
Fiscal Revenue and Expenditure Pressure	0.18	0.09	0.05	0.17	0.45	Fiscal Deficit Ratio (Deficit / Fiscal Revenue)
Whether High-Speed Rail is Opened	0.67	0.47	0	1	1	Dummy Variable (1=Operational, 0=Non-operational)
Regional Economic Level	8.23	2.15	3.1	7.85	15.6	Per Capita GDP (Ten Thousand Yuan)
Financing Environment	0.62	0.14	0.25	0.6	0.92	Financing Convenience Index (0-1 Normalization)
Residential Entrepreneurship	52.4	18.3	15	50.2	105.7	Number of Newly Registered Individual Industrial and Commercial Households per 10,000 People (Household)
Corporate Entrepreneurship	12.7	4.8	3	11.5	28.5	Number of Newly Registered Enterprises per 10,000 People (Company)
Industrial Structure	46.8	8.5	28.5	45.3	65	Proportion of Added Value of the Tertiary Industry (%)

In **Table 1**, regional development disparities rank first with a mean of 0.52 and a standard deviation of 0.18, indicating significant variations in development levels within Guangdong Province (between the Pearl River Delta and non-Pearl River Delta regions). The maximum value is 0.9 in Shenzhen, while the minimum is 0.22 in Yunfu, revealing pronounced polarization. Next is digital finance development, with a mean of 0.68 but a standard deviation of 0.23. This indicates high concentration in the Pearl River Delta (e.g., Shenzhen at 0.97) and severe lag in non-Pearl River Delta areas (e.g., Heyuan at 0.15). Next is the urban-rural income distribution structure, with an average of 2.75 (urban-rural income ratio). The highest value is in Shanwei at 4.2, reflecting substantial income disparities between urban and rural areas in Eastern and Western Guangdong. Then comes high-speed rail accessibility, with an average of 0.67, indicating that approximately 67% of cities have high-speed rail access, while 33% (such as some cities in Northern Guangdong) remain uncovered. Finally, the financing environment has an average of 0.62 and a standard deviation of 0.14. Cities in the Pearl River Delta enjoy significantly greater financing accessibility than those outside the region, exemplified by Guangzhou's 0.92 compared to Shaoguan's 0.25[3].

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3. Analysis of results

3.1. Overall pattern and structural characteristics

Descriptive statistics indicate that the UUDI has a mean of 0.52 and a standard deviation of 0.18, revealing significant disparities in inter-city development levels within the province. The Pearl River Delta versus non-Pearl River Delta regions exhibit dual characteristics of "polarization and spillover."The DFI index shows a mean of 0.68 and a standard deviation of 0.23, reflecting highly concentrated digital financial resources. The mean high-speed rail coverage rate of 0.67 and the mean financing accessibility index of 0.62, both exhibiting uneven distribution, collectively point to spatial asymmetry in infrastructure and financial supply. This aligns with the spatial distribution pattern observed in the UUDI index.

3.2. The transmission chain of digital finance through MD&A

3.2.1. Easing of financing constraints

Digital credit and supply chain finance alleviate the upfront capital pressure faced by prefabricated component factories and general contractors in equipment upgrades (such as CNC cutting, robotic welding, automated spraying, and AGV transportation). This enhances production cadence and first-pass yield rates while shortening delivery cycles, thereby improving the timeliness and quality of urban public works supply.

3.2.2. Data integration and process optimization

The data linkage between BIM, MES, and SCADA maps design BOMs and process BOPs to production line recipes and PLC parameters, reducing information loss between design, manufacturing, and assembly. Online quality monitoring (vision/force control) and closed-loop calibration (CPS) lower rework rates, thereby enhancing output efficiency per unit of input. The digital platform accelerates upstream-downstream integration and credit accumulation, incentivizing the implementation of standardized component systems (modularization, universal interfaces) and DFMA. This approach reduces the total lifecycle cost of engineering projects[4].

3.2.3. Interpreting correlations with key variables

UUDI and DFI: Mechanism-wise, DFI improvement should correlate with UUDI decline, particularly in cities with prefabrication and automation foundations, where the DFI × MD&A interaction term may exhibit stronger convergence effects. Entrepreneurship and Innovation: Increases in resident entrepreneurship, business startups, and the share of tertiary industries often accompany rising investments in specialized services and smart manufacturing, exerting indirect positive effects on UUDI improvement. Infrastructure and Financing Environment: Spatial imbalances in high-speed rail access and financing convenience can amplify or suppress the linkage effects between digital finance and MD&A, necessitating control and subgroup testing in regression analyses. Beyond UUDI, introduce PCA to construct UUDI_PCA for robustness checks of key findings; employ instrumental variables (e.g., historical financial outlet density, telecommunications infrastructure coverage) or DID/event studies to identify causality; incorporate MD&A intensity indicators and interaction terms with DFI to test the moderating effect of "finance × automation."

4. Future work and outlook

Deepening the Metric System: Beyond economic/social/environmental dimensions, incorporate MD&A embedded metrics such as: - Standardization rate of prefabricated components - BIM-MES-SCADA integration

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level - Density of robotic/CNC equipment - On-site IoT/SHM coverage rate - Energy consumption and carbon intensity per unit output Ensure cross-city consistency in measurement standards. Digital Twin and Full Lifecycle: Construct a digital twin spanning planning, design, manufacturing, assembly, and operations, integrating CAD/CAE—PLM—ERP—MES—SCADA—BAS—SHM to achieve closed-loop optimization of "design-as-manufacturing."Policy Simulation: Establish a scenario model linking "digital financial inclusion enhancement × MD&A investment intensity × prefabrication penetration rate"to assess the dynamic impact of different policy combinations on UUDI, providing differentiated pathways. Demonstration Projects and Open-Source Tools: Release reusable UUDI and MD&A measurement toolkits and visualization dashboards, implement demonstration projects in multiple cities, and consolidate process parameters and quality data. Industry-Academia-Research Collaboration: Foster joint university-enterprise-financial institution platforms for "prefabrication + smart manufacturing,"establishing standardized component families, interfaces, and quality evaluation systems.

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