

Original Research Article

Digital transformation, environmental regulations, and green innovation in manufacturing enterprises

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Abstract: Against China's "Dual Carbon" goals, digital transformation acts as a critical driver for corporate green innovation. Using panel data of A-share listed manufacturing firms from 2012 to 2023, this paper investigates how digital transformation affects green innovation and tests the moderating role of two types of environmental regulations. The results indicate that digital transformation significantly promotes enterprise green innovation. Both ex-ante guidance oriented and ex post penalty oriented environmental regulations positively moderate the above relationship. Such promotion effect is stronger for high-growth, non-heavily-polluting and high-tech enterprises. This study provides theoretical basis for governments to formulate differentiated digital and environmental policies and offers references for enterprises to implement targeted green-innovation practices.

Keywords: digital transformation; green innovation; environmental regulations

1. Introduction

Manufacturing enterprises bear key responsibilities for realizing the "Dual Carbon" goals. Restrained by high costs and long investment cycles of green innovation, many firms lack sufficient incentives for green transition. Digital transformation can optimize innovation-resource allocation and mitigate green-innovation risks, thus becoming a vital approach to improve corporate green innovation. As important institutional instruments, environmental regulations shape firms' green strategic choices. This paper incorporates environmental regulation and distinguishes ex-ante guidance-type and ex-post penalty-type regulation to explore their conditional moderating effects.

2. Theoretical analysis and research hypotheses

2.1. Digital transformation and corporate green innovation

From organizational capability theory, digital transformation improves green-innovation performance through three channels. Information-wise, it breaks information barriers and raises corporate information transparency. Resource-wise, digital technologies reorganize idle resources and alleviate resource misallocation (Shen and Yuan, 2020). Governance-wise, digital supervision reduces agency conflicts and motivates green-innovation activities (Shi and Chang, 2024). Therefore: H1: Digital transformation positively promotes corporate green innovation.

2.2. The regulatory role of environmental regulations

According to institutional theory, environmental regulation generates institutional pressure that reshapes corporate environmental strategies (Aguilera-Caracuel and Ortiz-de-Mandojana, 2013). It can be divided into ex-ante guidance and ex-post penalty categories (Guo, 2019). Ex ante guidance oriented regulation releases policy signals, reduces innovation uncertainty, and pushes firms to allocate digital resources toward energy conservation and emission reduction. Ex post penalty oriented regulation raises compliance and reputational risks. Firms will adopt digital governance to avoid penalties, and accumulated technical capacity will be transformed into green-innovation advantages. Thus, we propose: H2: Environmental Regulations Positively Moderate the Positive Impact of Digital Transformation on Green Innovation.

3. Research design

3.1. Sample selection and data sources

The empirical sample covers A-share listed manufacturing firms from 2012-2023. Dataset is obtained from CSMAR, CNRDS, *China Statistical Yearbook*, and Peking University Law Database.

3.2. Variable definition

Green Innovation (GI) is measured as the natural logarithm of the number of corporate green patent applications plus one. Digital Transformation (DT) is constructed by taking the natural logarithm of the total frequency of digital-transformation-related keywords extracted from corporate annual reports plus one. Ex ante guidance oriented environmental regulation (BER) is proxied by the logged number of local environmental regulations plus one, while ex post penalty oriented environmental regulation (AER) adopts the natural logarithm of environmental administrative penalty cases. A set of control variables are included: Firm size, firm age, asset-liability ratio, return on assets, operating cash flow, Tobin's Q, board size, proportion of independent directors, dual-role of chairman and CEO, management shareholding ratio, revenue growth rate, book-to-market ratio, largest shareholder shareholding, and fixed-asset ratio.

3.3. Model setup

Baseline regression model:

$$GI_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Controls_{it} + Ind_i + Year_t + \varepsilon_{it} \quad (1)$$

Moderating-effect model:

$$GI_{it} = \beta_0 + \beta_1 DT_{it} + \beta_2 DT_{it} \times ER_{it} + \beta_3 ER_{it} + \beta_4 Controls_{it} + Ind_i + Year_t + \varepsilon_{it} \quad (2)$$

Ind denotes industry fixed effect; Year denotes year fixed effect.

4. Empirical findings and analysis

4.1. Benchmark regression and moderation effect test

The coefficient of DT remains positive at the 1 % statistical level ($\alpha_1=0.0494, p<0.01$), supporting Hypothesis H1. The interaction terms $DT \times AER$ ($\beta_2=0.0153, p<0.01$) and $DT \times BER$ ($\beta_2=0.0263, p<0.05$) are both significantly positive. Both ex ante guidance type and ex post penalty type environmental regulations strengthen the green-innovation effect of digital transformation, which validates H2.

4.2. Heterogeneity analysis

Grouped regression results reveal that, compared with low-growth enterprises ($\alpha_1=0.0390, p<0.01$), heavy polluting enterprises ($\alpha_1=0.0008, p>0.1$), and non-high-tech enterprises ($\alpha_1=0.0156, p>0.1$), digital transformation generates stronger green-innovation promotion for high-growth enterprises ($\alpha_1=0.0588, p<0.01$), non-heavily-polluting enterprises ($\alpha_1=0.0604, p<0.01$) and high-tech enterprises ($\alpha_1=0.0616, p<0.01$). High-growth firms can rapidly deploy digital resources for green process improvement. Non-heavy-polluting firms suffer less regulatory legitimacy pressure. High-tech firms possess solid R&D foundations to realize digital-driven green-technology iteration.

5. Conclusions and recommendations

This paper conducts an empirical analysis based on 2012-2023 panel data of Chinese manufacturing companies. Results show that digital transformation significantly promotes corporate green innovation. Both ex-ante guidance-oriented and ex-post penalty-oriented environmental regulations positively moderate this relationship. The effect is more pronounced for high-growth, non-heavily-polluting and high-tech enterprises.

Corresponding policy suggestions are put forward. First, strengthen policy support for corporate digital transformation. Second, optimize environmental regulatory system and give full play to effect of ex ante guidance and ex post punishment. Third, implement differentiated policies: Provide targeted support for different firms while exerting the demonstration effect of advantageous enterprises, so as to narrow the green-innovation gap among manufacturing enterprises and promote overall green development under the "Dual Carbon" goals.

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