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A Study on the Relationship Between Digital Transformation and Corporate Green Innovation Levels—Based on the Mediating Role of Corporate Investment Efficiency

Junrui Gao

School of Management, Beijing Institute of Technology, Beijing, China
13641304806@163.com

Abstract. Dual Period: Digital & Environmentally Friendly Development Era. If we take digital transformation as a major catalyst that can push firms along the road where they will continue to make greener innovations, then such an idea does appear rather interesting both academically and commercially at this time. Use China A-shares listed companies from 2015-2024 for testing whether our theory holds true. We see that(1)Digital transformation makes corporate green innovation higher; every extra piece of digitization within any company leads to about .047% increase in its own particular worth.(2)Test on mediation says digital transformation raises corp green innov level via increasing inv efficiecy; (3). Analysis shows difference is good for people who don't pollute much, lots of R&D spending helps make things less bad. And these kinds of discoveries tell you some underlying reasons or causes why such a thing actually happens because of this type of change coming into being through improvements related to how much one might consider putting money towards something.

Keywords: Digital transformation, Corporate green innovation levels, Corporate investment efficiency, Corporate governance

1. Introduction

In recent years, ecological and environmental issues such as global warming, resource depletion, and biodiversity loss have become increasingly prominent, posing major challenges to sustainable economic and social development. To address this severe situation, China explicitly set strategic goals in 2020 to achieve "carbon peaking" by 2030 and "carbon neutrality" by 2060, aiming to drive a comprehensive green transformation of economic and social development.As the primary micro-level agents of resource consumption and pollution emissions, enterprises' levels of green innovation are directly linked to the harmonious integration of ecological protection and economic benefits.Green innovation is not only about making environmental progress such as developing new ways to make things cleaner, controlling how much pollution there is, and using less energy so that we don't have too many emissions; it also means improving the worthiness of our company's goods by increasing what people want and selling them more easily while making fewer negative effects on nature. A measure of whether a firm has sustainable development capability. But in fact

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companies usually run into real problems when they go for green innovation because it costs lots, takes ages to get back some money, and you just can't afford all this stuff. Therefore, how to effectively motivate enterprises to improve their green innovation abilities has become a major issue for both policymakers and corporate managers. At the same time, digital technology represented by big data, artificial intelligence, internet of things, and blockchain are greatly changing industrial structure and economic operation. Digital transformation was originally an option for manufacturing companies, but currently it has become necessary for enhancing production processes, increasing management efficiency, reorganizing business models and reducing operating costs. The extensive application of digital technologies offers new technical opportunities for enterprises to accomplish "cost reduction, quality improvement and efficiency enhancement". Nevertheless, if this change can also raise the degree of green innovation in enterprises at the same time, it will attract attention from scholars and practitioners [1]. Therefore, how does digital transformation influence corporate green innovation? What are the underlying transmission mechanisms? Do firms with various features such as heavily polluting ones versus non-polluting ones, or those with high versus low research and development (R&D) investments, exhibit significant differences in this procedure? Clarifying these issues will enable us to comprehend the logical relationship between digitalization and greening from a theoretical perspective, fill the gap in the existing literature on micro-level mechanism verification, and provide practical empirical evidence and decision-making suggestions to guide enterprises to take advantage of digital opportunities and formulate customized strategies to achieve the 'dual carbon' targets. Based on this, this paper takes Chinese A-share listed companies from 2015 to 2024 as a sample to empirically investigate the effect of digital transformation on the green innovation level of enterprises and the mediating role of corporate investment efficiency.

2. Theoretical analysis and research hypotheses

2.1. The impact of digital transformation on corporate green innovation levels

Digital transformation can profoundly alter the way enterprises identify, develop, and apply green technologies, providing new technical conditions and organizational foundations for enhancing green innovation levels [2].

Digital transformation enhances the capability of enterprises to collect, process and analyze environmental information, providing precise data support for green innovation. The present research and development of green technology mainly relies on post-event statistics or a few samples, which is not beneficial for continuously monitoring the energy consumption, pollutant emissions and the utilization efficiency of resources during the production process. By applying Internet of Things (IoT) sensors, industrial internet platforms and big data analysis methods, enterprises can monitor the environmental performance indicators at each production stage in real time, identify the major processes with high energy consumption and emissions, and therefore pinpoint the appropriate places for the enhancement of green technology [3]. This data-driven innovative approach decreases the cost and uncertainty in green R&D, making enterprises more willing and capable of investing in green innovation activities like clean production processes and end-of-pipe pollution control. Digital transformation promotes the exchange of both internal and external knowledge and technical resources, overcoming the problems caused by the lack of integration of resources and knowledge isolation which hamper green innovation. Green innovation usually involves different disciplines such as materials science, chemical engineering, energy and environmental engineering, and it is hard for one enterprise to possess all the required expertise. Digital technologies have led to collaborative tools like open innovation platforms and cloud-based

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R&D cooperation systems, allowing enterprises to efficiently interact with universities, research institutes, technology service providers and even upstream and downstream partners. Through digital platforms, enterprises can quickly obtain information about green technology patents, advanced research results or effective solutions and integrate them into their own green innovation outputs [4]. At the same time, digital systems break down the barriers between internal departments such as research and development, production and environmental protection, which makes it convenient for all links of the chain to cooperate from generating green ideas to implementing process improvements, thus speeding up the realization of green innovations. Based on the above discussion, this paper proposes the following hypotheses:

H1: Digital transformation can improve a company's level of green innovation.

2.2. The mediating role of corporate investment efficiency digital transformation raises corporate green innovation levels by boosting investment efficiency

Digital transformation helps to improve corporate investment efficiency. Digital technology integration changes how information is gathered, handled, and sent inside companies, helping to lessen problems with getting enough info and people not acting right when they should be spending money [5]. On one hand, big data and cloud computing platforms can integrate various types of data such as production, sales, inventory, and energy consumption to create real-time, accurate operation profiles so that managers can better understand the marginal returns and capital invested in each part of the business.Data driven decision making system help manager to find investment project that have long term return potential, avoid missing opportunity or blindly expand because of information delay or cognitive bias. On the contrary, digital tools like ERP and SCM systems make it easier to track and monitor investment projects all through their life cycle, allowing online management from budgeting and allocating funds to periodic performance assessments. This kind of open process cuts down on how much middle- and lower-level bosses can hide stuff or try to get extra money by doing things they shouldn't, which means there's less cost for someone else taking care of things (agency costs) and more money goes where it should – towards really good work. And also digital platform connects with outside capital market so it lowers info asymmetry between lender and borrower, helps company get fund cheaper, and lessen underinvestment due to finance restriction. Therefore, digital transformation systematically improves corporate investment efficiency by increasing information transparency, improving decision-making processes, and decreasing agency costs.

At the same time, improved investment efficiency helps promote the level of green innovation within enterprises. Green innovation is characterized by high investment, long cycles, and high risk, and its R&D process requires continuous and stable capital injections. If a company's investment efficiency is low and a large amount of capital is tied up in inefficient or ineffective projects, this will inevitably squeeze the budget for green R&D. Conversely, when investment efficiency improves, enterprises can allocate more of the freed-up financial resources and managerial attention to green technology development activities that generate positive externalities [6]. Specifically, high investment efficiency means that enterprises can accurately identify green innovation projects that, while offering low short-term returns, possess significant strategic value, and decisively provide them with financial support. Furthermore, efficient monitoring and feedback mechanisms can promptly detect deviations during the R&D process, reduce trial-and-error costs, and thereby increase the success rate of green innovation.Furthermore, improved investment efficiency reflects an enhancement in a company's overall resource allocation capabilities. This capability also applies to the allocation of innovation factors such as environmental protection talent, laboratory equipment, and technical intelligence, helping to accelerate the entire process from the inception to the

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implementation of green innovations [7]. Therefore, investment efficiency serves as a key bridge connecting digital transformation and green innovation. Consequently, this paper proposes the following hypothesis:

H2: Corporate investment efficiency mediates the relationship between digital transformation and the level of corporate green innovation.

3. Model construction

3.1. Data sources

China A-share listed companies from 2015 to 2024 were taken as the starting point of this paper. We have applied these standards: exclude those with "ST,*ST,PT" or any financial corporation; do not use those who gave me incomplete data. Finally we got 4361 pieces of listed company information, the sum is around 25603. The data sources used in this study are obtained from CSMAR and CRDNS. Trim top/bottom 1% out so that outliers can be reduced, then continue working with continuous values for the rest.

3.2. Variable definitions

Dependency: CorpGreInnov level(green). ln((current year + number of independent green invention patents in this year) + (current year+number of independent green utility patent application in current year)+1) [8].

Explanatory variable: Digital transformation (Dig1). Following the approach of previous scholars [9], this study constructs a corporate digital transformation index based on the frequency of digital-related keywords appearing in listed companies' annual reports. Word frequency analysis is currently the mainstream method for measuring digital transformation; it is highly feasible, and the usage of vocabulary in annual reports can reflect a company's strategic characteristics and development plans. Specifically, this study defines keywords related to corporate digitalization across five dimensions: artificial intelligence, big data, blockchain, cloud computing, and digital technology application. Using Python, we perform word frequency analysis on keywords across these dimensions and ultimately use the total word frequency to measure the degree of a firm's digital transformation. Due to the "right-skewed" nature of the data, we add 1 to the data and then take the natural logarithm.

Controlling variable: Drawing upon prior studies regarding firms' levels of green innovation [10]. In this paper it selects Firm ages(Age), natural logs about all kinds of asset values(Sizes) such as lev which stands for debt/equity ratio; tops refer to how much each individual owns, dual role director means that people have two roles and independent directors proportion,indiv. We wanted more than just making companies less unique we also wanted some decrease in the Digital Transform & Green Innov Level connection.

Mediating Variable: Drawing on scholars' methods for measuring corporate investment efficiency [11], a higher value of inveff indicates lower investment efficiency.

3.3. Model design

As per the theory as shown by above, there is a certain base model (1) which would give us an idea on how Digital transformation could influence Green Innovation. j and t represent industry and year respectively here.

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$$green_{i,t} = \alpha_0 + \alpha_1 Dig1_{i,t} + \sum \gamma Controls_{i,t} + Industry_i + Year_t + \epsilon_{i,t} \quad (1)$$

This study establishes mediation models (2) and (3) to test the mediating role of investment efficiency.

$$inveff_{i,t} = \alpha_0 + \alpha_1 Dig1_{i,t} + \sum \gamma Controls_{i,t} + Industry_i + Year_t + \epsilon_{i,t} \quad (2)$$

$$green_{i,t} = \alpha_0 + \alpha_1 Dig1_{i,t} + \alpha_2 inveff_{i,t} + \sum \gamma Controls_{i,t} + Industry_i + Year_t + \epsilon_{i,t} \quad (3)$$

4. Empirical analysis

4.1. Baseline regression

Table 1 shows the results from baseline regressions about how DT is connected with companies at different levels of GI. Col(1): Including controls as well as industry & year FE; dt's coeff was 0.0473, sig pos at p<0.01 which supports hypothesis 1.

Table 1. Regression results

	(1)	(2)
	green	green
Dig1	0.0473***	
	(0.00467)	
Dig2		0.0367***
		(0.00501)
Age	-0.00891***	-0.00878***
	(0.000758)	(0.000760)
Size	0.191***	0.193***
	(0.00516)	(0.00518)
Levw	0.0959***	0.0898***
	(0.0304)	(0.0304)
Topw	0.000336	0.000197
	(0.000358)	(0.000358)
dual	-0.0137	-0.0105
	(0.0111)	(0.0111)
indirw	0.000410	0.000490
	(0.000933)	(0.000934)
_cons	-4.148***	-4.149***
	(0.132)	(0.132)
Ind/year	yes	yes
N	25,603	25,603
R^2	0.182	0.181
adj. R^2	0.179	0.178

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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4.2. Robustness analysis

So we need to make sure that those regression results will be reliable, by using another way of doing the digit transform. In column(2) from table 1, coefficient of digital transformation with respect to firm's level of green innovation is +0,0367 at level of significance more than or equal to one percent(p=). Regression co-efficient remains significant which means our finding are valid.

4.3. Testing for mediation effects

And paper also discusses about the mediation section, which is corporation's investment efficiency and in table 2 there are numbers for those relevant regression coefficients. The first column gives us results where we use Corporate Investment Efficiency as our Dependent Variable and Digital Transformation as an Independent Variable. Here it turns out that digital changes have been quite a strong -ve influence on corp's invstmnt effecnsity @0.5%, so maybe if digital trans could get better at making corp invest more effectively, then H-2 might actually work? Column two adds corporate investments to base line before doing any regression analysis. We can see from these coeffients that -0.629 was significant at 1% level, this indicates Corp's investment efficacy will increase Comp's Green Innovation capacity; therefore, the mediating role played by Corp investment effect between Digital Trans and Firm GI levels has some support through Hypothesis H-2 being accepted upon considering only such effects.

Table 2. Mediation regression

	(1)	(2)
	inveff	green
Dig1	-0.000571**	0.0470***
	(0.000276)	(0.00466)
Age	-0.000780***	-0.00940***
	(0.0000448)	(0.000762)
Sizew	-0.000839***	0.191***
	(0.000305)	(0.00516)
Levw	0.00698***	0.100***
	(0.00180)	(0.0304)
Topw	-0.0000475**	0.000306
	(0.0000212)	(0.000358)
dual	0.00222***	-0.0123
	(0.000656)	(0.0111)
indirw	0.0000761	0.000458
	(0.0000551)	(0.000932)
inveff		-0.629***
		(0.106)
_cons	0.0675***	-4.106***
	(0.00778)	(0.132)
Ind/year	yes	yes
N	25,603	25,603

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Table 2. (continued)

R^2	0.066	0.184
adj. R^2	0.062	0.180

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

4.4. Heterogeneity test

4.4.1. Heterogeneity of pollution levels

In terms of dividing up the samples according to whether they fall into heavy polluting companies or not, which can be seen in column (1) of Table 3; for those more highly contaminated businesses when it came time for some real action on doing things with Digital changes there wasn't much going on. But take column(2): It's somewhat better: non-polluted ones' digital coeff was quite large at .0614 and pretty close but just a little bit larger than before under the same condition(i.e., the one right after %). Which means that digital transition helps increase green innovation among firms that don't make too much pollution compared to those making lots of pollution.

Table 3. Heteroskedasticity regression

	(1)	(2)	(3)	(4)
	green	green	green	green
Dig1	-0.00319	0.0614***	0.0682***	0.0163***
	(0.00745)	(0.00576)	(0.00695)	(0.00621)
Age	-0.00365***	-0.0114***	-0.0137***	-0.00647***
	(0.00102)	(0.000998)	(0.00129)	(0.000899)
Sizew	0.147***	0.211***	0.256***	0.149***
	(0.00726)	(0.00667)	(0.00853)	(0.00630)
Levw	-0.0803*	0.163***	0.275***	-0.0107
	(0.0430)	(0.0392)	(0.0466)	(0.0392)
Topw	0.000661	0.000366	0.0000657	0.00168***
	(0.000509)	(0.000460)	(0.000558)	(0.000452)
dual	-0.0709***	0.00920	0.00236	-0.0439***
	(0.0162)	(0.0141)	(0.0159)	(0.0152)
indirw	0.00121	0.000196	0.000188	0.000548
	(0.00136)	(0.00118)	(0.00143)	(0.00118)
_cons	-3.182***	-4.612***	-5.314***	-3.300***
	(0.177)	(0.163)	(0.229)	(0.156)
Ind/year	yes	yes	yes	yes
N	7,600	18,003	12832	12771
R^2	0.197	0.172	0.190	0.192
adj. R^2	0.191	0.168	0.184	0.186

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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4.4.2. Heterogeneity in R&D expenditures

The sample is split up into two groups: firms that make lots of money for their R&D efforts, and firms that don't spend much at all on R&D projects. The third column and the fourth column in Table 1 shows: when it comes to high investment firm's digital transformation coefficient will be 0.0682 which is significant at level and if we take lower investment firm then its digital transformation coefficient would be 0.0163 and it is also significant at same level this means that higher levels of digitization has bigger impact on green innovation compared to those with less investments.

5. Conclusions and recommendations

Based on the data of Chinese A-list company from 2015-2024, we check out the digital transformation of firms' green innovations empirically. And find how it happens: Findings are as follows, First: Digital Transformation greatly improves companies' level of Green Innovation; when there was a small increase (one hundred per mille), i.e., +1/100/100, then Corporate Green Innovations increased by approximately four thousand seven hundred three ten-thousandths (0.0473). Second is mediator test - digital transformation raises corporate level green innovation due to investment being more effective. Thirdly with respect to differentiations which were discovered in our study, it has become apparent that digital conversion had a greater beneficial impact on less polluted business entities and R&D investments than others. With those results in mind, here are my recommendations:

(1) Enterprises should proactively seize opportunities for digital transformation, deeply integrating digital technologies with traditional business operations. Install sensors, build digital operational platform to monitor carbon emissions in real time so as to improve investment and operation efficiency, freeing up resources for green innovation. Different companies need different approaches: if they're already pretty techy and investing lots into new ideas, maybe go deeper on things like developing greener tech stuff and making those cool inventions from nature easier to use; but others who aren't super high-tech or don't spend much money researching should just slowly try putting some more money towards computers and see what makes sense for them personally. Non-heavy-polluting enterprises can achieve rapid breakthroughs in green innovation by means of digitization; Heavy polluters will have no choice but to rely on environmental regulation and digital tools for pollution control improvement in order to gradually improve their own level of green innovation.

(2) The government has to do its top-level design work well, it's also got to refine stuff like tax breaks and R&D helpings, get finance flowing straight at places that matter most. At the same time tighten environment rules, increase penalties when exceeding emission limit and invest industrial pollution reduction which forces heavily polluting company to improve their carbon performance via digitizing. And we could try speeding up how fast we make our digital infrastructure, setting up a joint working area where industries, schools, and research groups would be able to give each other advice about technical fixes and training people, helping businesses work together with universities and labs. Small & medium-sized enterprises lacking strong R&D strength may receive targeted support measures aimed at cutting down both digitalization and green innovation expenses, amplifying intermediary transmission effects of investment efficiency, thus contributing toward achieving "dual carbon" targets.

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