

# Research on the Impact of Interlocking Director Network Centrality on the Green Innovation Efficiency of Heavily Polluting Enterprises

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## Abstract

Heavily polluting enterprises are key targets for environmental governance and core entities in industrial transformation. In the context of implementing the "dual carbon" goals, how to enhance the green innovation efficiency of heavily polluting enterprises is an essential aspect. The impact of interlocking director networks on green innovation efficiency is crucial. Based on the information on interlocking directors' concurrent positions in enterprises, this paper constructs an interlocking director network among heavily polluting enterprises. It innovatively explores the impact and mechanism of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises from a social network perspective, and further investigates the moderating effect of enterprise absorptive capacity. The study finds that the centrality of the interlocking director network positively impacts the green innovation efficiency of heavily polluting enterprises; absorptive capacity enhances the promoting effect of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. Mechanism testing reveals that the centrality of the interlocking director network promotes the improvement of green innovation efficiency in heavily polluting enterprises through resource and reputation mechanisms. Furthermore, this positive effect is more significant in heavily polluting enterprises located in the eastern region, those with a state-owned nature, and those in provinces with high environmental attention. This paper extends the research on director networks to the context of green innovation, which helps deepen the understanding of the pathways through which director networks enhance the green innovation efficiency of heavily polluting enterprises in China. It also provides decision-making references for regulatory authorities to guide the green transformation of heavily polluting enterprises.

**Keywords:** interlocking director network, network centrality, green innovation efficiency, heavily polluting enterprises

## 1. Introduction

Faced with increasingly severe global climate change and environmental pollution, the Chinese government has put forward the "dual-carbon" goals to promote the comprehensive green transformation of the economy and society. The issuance of *Opinions of the CPC Central Committee and the State Council on Accelerating the Comprehensive Green Transformation of Economic and Social Development* in July 2024 further clarified the core position of green and low-carbon development in the national strategy, and emphasized the responsibilities and missions of enterprises as the main body of green innovation. *Opinions of the State Council on Deepening the Reform of the Dual Control System of Carbon Emissions* issued in August 2024 marked the in-depth transformation of China's carbon emission management from "intensity constraint-oriented" to "total amount and intensity coordinated control". In this context, whether heavily polluting enterprises can achieve a win-win situation of "emission reduction and carbon reduction" and "quality and efficiency improvement" by improving green innovation efficiency is not only related to the implementation effect of the dual control goals but also becomes a key criterion to test the resilience of the low-carbon transformation of China's industrial system. Compared with non-heavily polluting enterprises, the green innovation activities of heavily polluting enterprises not only face the problem of effective allocation of innovation resources but also face the risk of reputation crises caused by illegal behaviors such as "greenwashing". Therefore, improving the quantity and quality of green outputs and strengthening the actual contribution of R&D investment to low-carbon transformation are inevitable choices for heavily polluting enterprises to build sustainable competitive advantages.

However, existing literatures mainly focus on regional green innovation efficiency, and research on the green innovation efficiency of heavily polluting enterprises, which are key subjects of green transformation, is still insufficient. At the same time, most studies on green innovation of heavily polluting enterprises focus on green outputs, environmental regulation, and other aspects. Based on the social network theory, the interlocking director network, as a bridge connecting internal and external corporate governance, can play the dual functions of information intermediary and resource integration, and become a core channel for heavily polluting enterprises to obtain heterogeneous innovation information and integrate key resources. Therefore, from the perspective of corporate governance based on the interlocking director network, the mechanism and impact effect of green innovation efficiency of heavily polluting enterprises need to be in-depth explored. This will help expand the theoretical achievements in the field of green development of heavily polluting enterprises, and build a theoretical support system and provide practical path references for corporate low-carbon transformation from the perspective of corporate governance.

In the field of corporate governance, directors, as individuals in the economy, play multiple social roles and are influenced by different social groups [1]. As important nodes in the inter-firm social network, interlocking directors have attracted increasing attention for their impact on the green innovation of heavily polluting enterprises. Compared with enterprises with high network centrality, heavily polluting enterprises located at the edge of the network often capture policy dynamics, market demands, and cutting-edge technological information more slowly, and respond more sluggishly to changes in environmental protection regulations and updates of technical standards. They are prone to fall into a vicious circle of "backwardness-elimination-rebound" in green transformation, and there is much room for improvement in their green innovation efficiency. Based on the resource dependence theory, enterprises can obtain information, capital, and other key resources through the interlocking director network, which is particularly important for green innovation. This theory holds that enterprises rely on external resources for survival, and the interlocking director network, as a governance mechanism, can help heavily polluting enterprises overcome the obstacles of high R&D costs and financing difficulties. Therefore, improving network centrality may become one of the important ways to enhance green innovation efficiency. A few scholars have begun to pay attention to the role of social networks in corporate innovation. Wang Fenmian et al. believe that interlocking directors with green experience can promote the "increase in quantity and improvement in quality" of corporate green innovation [2]. Therefore, it is necessary to further explore whether the positional advantages of the director network can have a positive impact on the green innovation efficiency of heavily polluting enterprises. If there is an impact, what is its mechanism? Exploring the above issues expands the research boundary of the interlocking director network and reveals its important significance in the field of environmental governance.

The marginal contributions of this paper are as follows: Firstly, existing studies mainly discuss regional green innovation efficiency, and the analysis of its influencing factors mostly focuses on external factors such as environmental regulation. However, existing studies on the green innovation efficiency of heavily polluting enterprises have not paid attention to the impact of the structural characteristics of the director network. To a certain extent, the interlocking director network of enterprises can help enterprises obtain external scarce resources and key information, which will inevitably have a certain impact on the green innovation efficiency of heavily polluting enterprises. Therefore, this paper constructs an interlocking director network among heavily polluting enterprises based on the information of interlocking directors' concurrent positions and calculates the network centrality index, which not only enriches the research on green innovation efficiency at the micro-enterprise level but also expands the application of social network theory in the field of green innovation. Secondly, it expands the research on the driving factors of green innovation efficiency of heavily polluting enterprises and provides new ideas for green innovation of heavily polluting enterprises from the perspective of corporate governance. The improvement of the centrality of the interlocking director network can enhance the enterprises' right to speak in the industry and promote the coordinated formulation and implementation of corporate green innovation strategies. Especially in the heavily polluting industry, this promoting role cannot be ignored, and its internal mechanism needs to be in-depth analyzed. This paper clarifies the role channels of the interlocking director network from the two perspectives of reputation effect and resource effect, and then breaks the "black box of action" between the centrality of the interlocking director network and the green innovation efficiency of heavily polluting enterprises, which is of great practical significance for accelerating the green and low-carbon transformation of China's heavily polluting enterprises. Finally, it expands the boundary conditions of the impact of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. This paper examines the moderating effect of the absorptive capacity of heavily polluting enterprises and finds that the absorptive capacity of enterprises can enhance the promoting effect of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. Further research finds that the positive effect of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises is more obvious

in heavily polluting enterprises with state-owned nature, located in the eastern region, and in provinces with high environmental attention. This shows that the role of director network embedding in the green innovation of heavily polluting enterprises should be viewed systematically. As an important mechanism of corporate governance, the interlocking director network also needs the support of enterprises' endogenous capabilities and external environment. This paper not only deepens the understanding of the complex relationship between corporate governance and environmental innovation from the perspective of the interlocking director network but also provides reference ideas and theoretical basis for heavily polluting enterprises to formulate green decisions and solve the dilemma of green transformation.

## 2. Literature Review and Research Hypotheses

### 2.1 Literature Review

As an important research object in the cross-field of corporate governance and social networks, the interlocking director network of enterprises has attracted widespread attention from the academic community in recent years. Regarding the measurement of the interlocking director network, it is usually based on graph theory and social network analysis framework, and interlocking directors and their relationships are regarded as nodes and connections in the network. It is possible to take individual directors as nodes in the network: if two directors serve on the same board of directors at least, there is a connection between them, indicating that there is a relationship between the two directors [3]; or take individual companies as nodes in the network: if two companies have at least one director serving concurrently, there is a connection between the two companies [4]. This paper adopts the second method for measurement. This network relationship plays a key role in many aspects such as corporate governance and fulfillment of social responsibilities. Existing studies have shown that when enterprises are in the central position or structural hole position of the interlocking director network, it helps to alleviate information asymmetry [5], optimize channels for sharing resources and information [6], promote enterprises to fulfill social responsibilities [7], and reduce inefficient investment of enterprises [8]. In terms of corporate innovation, interlocking directors integrate into the process of corporate knowledge acquisition, creation, and spillover through information exchange and sharing activities in their relationship networks, thereby promoting corporate breakthrough technological innovation [9]; moreover, there is a positive correlation between the interlocking director network and the breadth of cooperative innovation, and a negative correlation with the depth of cooperative innovation [10].

Against the background of increasingly severe global environmental problems and China's "dual-carbon" goals, improving corporate green innovation efficiency is crucial for sustainable economic development and environmental protection. Existing studies have explored the influencing factors of green innovation efficiency from two dimensions: region and enterprise. The research shows that regional green innovation efficiency is not only affected by external economic environment shocks such as trade frictions [11] but also by regional development strategies such as the opening of government public resources and industrial layout [12]. The influencing factors of corporate green innovation efficiency are mainly discussed from internal and external aspects of enterprises. From the external perspective, as a strategic support for China to promote high-quality development, the full release of the effectiveness of green innovation is highly dependent on environmental regulation. Some scholars have noticed the role of command-and-control environmental regulation and emphasized the role of ecological rule of law. For example, Tang Liang et al. found that the implementation of the new *Environmental Protection Law* can significantly improve the quantity, quality, and efficiency of green technological innovation of heavily polluting enterprises, and the punishment mechanism plays a leading role [13]. Other scholars have discussed from the perspective of market-incentive environmental regulation. Wang Pei et al. found that the value-added tax (VAT) credit refund policy can improve corporate green innovation efficiency by alleviating financing constraints [14]. However, Fan Jingbo et al. verified the "Porter Hypothesis" and found that there is an inverted U-shaped relationship between command-based environmental regulation and the green innovation efficiency of heavily polluting enterprises, while the positive effect of market-incentive environmental regulation weakens after the regulation intensity exceeds the inflection point [15]. From the internal perspective, the development of big data and the advancement of the digital economy have provided new opportunities for corporate green innovation. Big data can improve the quality and efficiency of corporate green technological innovation through various mechanisms such as promoting corporate digital transformation, alleviating corporate financing constraints, and improving the government's environmental governance capacity [16]. In addition, corporate environmental, social, and governance (ESG) has a bottom-up environmental governance effect. Corporate ESG performance can promote the improvement of corporate green innovation efficiency by reducing corporate financial leverage and corporate rent-seeking [17].

To sum up, this paper believes that there is still room for expansion in existing studies: First, existing literatures have not paid attention to the role of the interlocking director network in the field of green innovation, nor have they carried out targeted discussions combined with the governance particularities of heavily polluting industries. Second, although the academic community has conducted systematic research on the factors affecting corporate green innovation efficiency, the research on how to improve the green innovation efficiency of heavily polluting enterprises from the perspective of corporate governance still needs to be further explored. Third, there is no literature analyzing the impact of the interlocking director network on the green innovation efficiency of heavily polluting enterprises, and there is still research space for its mechanism and heterogeneous impact.

## *2.2 Theoretical Analysis and Research Hypotheses*

### *2.2.1 Interlocking Director Network Centrality and Green Innovation Efficiency*

As key objects of environmental governance, the improvement of the green innovation efficiency of heavily polluting enterprises depends not only on the accumulation of internal resources but also on the acquisition of key information and scarce resources through external networks. Based on the resource dependence theory, enterprises with high network centrality can quickly obtain industry trends, market conditions, policy information, and green technology knowledge through director connections, thereby reducing the high-risk and high-cost characteristics of green innovation. As an important connection mechanism between enterprises [18], the interlocking director network not only alleviates corporate financing constraints through the resource effect but also improves corporate reputation through information transmission, further driving the improvement of corporate green innovation efficiency. On the one hand, enterprises with high centrality in the interlocking director network can obtain more resource sharing through informal communication with more connected enterprises in the network [19], alleviate financing constraints by reducing information asymmetry between enterprises, and thus improve their green innovation efficiency. This is called the "resource effect" of the centrality of the interlocking director network; on the other hand, enterprises with high centrality will actively strengthen their market image through green innovation practices to maintain their reputation status in the network, forming the "reputation effect" of the centrality of the interlocking director network.

From the perspective of the resource effect of the interlocking director network, enterprises in the center of the network are more likely to obtain resources and dynamic information from the external capital market, thereby optimizing their financing strategies and helping to improve their green innovation efficiency. At the same time, enterprises with high centrality can more efficiently disseminate "soft information" such as their credit status and project prospects [20]. This information advantage helps enterprises establish a more transparent credit image in the credit market, reduce adverse selection risks, and thus more easily obtain low-cost financing. On the one hand, enterprises with high network centrality have multi-dimensional information aggregation, which can obtain diversified financing channels such as green credit and digital inclusive finance [21], breaking through traditional financing limitations. On the other hand, enterprises with high network centrality are more likely to obtain low-cost funds through the financial background or industry resources of directors, providing stable support for high-investment and long-cycle green technology R&D and improving corporate green innovation efficiency.

From the perspective of the reputation effect of the interlocking director network, one of the important factors for an enterprise to stand out in the fierce market competition is to have a good reputation, and the social relationship network is a main way to obtain reputation [22]. Precisely because heavily polluting enterprises in the central position of the network have more connection relationships than those in the edge of the network, they usually receive more attention, so their motivation for green innovation is stronger [23]. On the one hand, the higher the corporate network centrality, the greater the external pressure it faces. Therefore, interlocking directors have more responsibilities and motivations to urge listed companies to fulfill their social responsibilities [24]. In addition, the existence of the interlocking director network effectively reduces the supervision cost among network members [25]. On the other hand, enterprises with high network centrality will actively increase green innovation investment to maintain their reputation status in the industry, so as to gain the recognition and trust of stakeholders such as the government and investors. This is conducive to enterprises obtaining key resources needed for their own development [26], forming a "reputation premium", attracting more green investment. Therefore, in order to maintain their own reputation and the potential benefits brought by it, enterprises with higher centrality have greater motivation to carry out green innovation practices to improve their green innovation efficiency. To sum up, this paper puts forward the following hypotheses:

Hypothesis 1: The centrality of the interlocking director network has a promoting effect on the green innovation efficiency of heavily polluting enterprises.

Hypothesis 1a: The centrality of the interlocking director network promotes the green innovation efficiency of heavily polluting enterprises through the resource effect.

Hypothesis 1b: The centrality of the interlocking director network promotes the green innovation efficiency of heavily polluting enterprises through the reputation effect.

### 2.2.2 The Moderating Role of Corporate Absorptive Capacity

Cohen et al. believe that absorptive capacity refers to the ability of enterprises to identify, digest, and utilize external resources [27]. Only when heavily polluting enterprises acquire and absorb diversified knowledge and fully transform and utilize it can they promote the improvement of green innovation efficiency. On the one hand, enterprises with high centrality in the interlocking director network can obtain broader industry knowledge, technical information, and policy dynamics by occupying the core position of the network [28]. However, these external resources need to be transformed into internal innovation capabilities through the absorptive capacity of enterprises. Enterprises with strong absorptive capacity can more efficiently identify, screen, and integrate green technology knowledge in the network. Higher absorptive capacity helps enterprises organically integrate green knowledge with original knowledge [29], quickly respond to external environmental governance needs and market changes, and enhance their environmental adaptability [30]. On the other hand, high network centrality provides enterprises with channels to access green innovation resources, but absorptive capacity determines whether these resources can be effectively transformed and utilized [31]. High absorptive capacity bridges the gap between network resources and internal capabilities through "knowledge re-creation", thereby improving the marginal effect of green innovation efficiency. Based on this, this paper puts forward the following hypothesis:

Hypothesis 2: Corporate absorptive capacity positively moderates the relationship between the centrality of the interlocking director network and the green innovation efficiency of heavily polluting enterprises.

## 3. Research Design

### 3.1 Sample Selection and Data Sources

This paper selects A-share listed companies in China's heavily polluting industries from 2014 to 2023 as the research sample. According to the *Guidelines on Environmental Information Disclosure of Listed Companies* issued by the former Ministry of Environmental Protection in 2010, the heavily polluting industries are identified with reference to the 2012 version of the industry classification standard of the China Securities Regulatory Commission (CSRC). At the same time, the samples are screened in accordance with the following principles: (1) Excluding companies marked with S, ST, and PT; (2) Excluding listed companies in the financial industry; (3) Excluding samples with missing data. Finally, 5,940 sample observation data of 594 enterprises are obtained. The green patent data in this paper are from the CNRDS database, and the interlocking director network and other data are from the CSMAR database. The data processing software is Stata 17.

### 3.2 Variable Definition

#### 3.2.1 Dependent Variable

Green innovation efficiency (Efficiency). This paper draws on the research idea of Liu Chang et al. [32] and uses the ratio of green innovation output to green innovation input to measure corporate green innovation efficiency. Since the green innovation input data of listed companies are not publicly disclosed in detail, this paper uses the company's annual R&D expenditure as an approximate substitute for green innovation input. The green innovation output of listed companies is measured by the natural logarithm of the total number of applications for green invention patents, utility model patents, and design patents independently applied by listed companies in the current year plus 1. In the robustness test, the measurement method of this variable is changed, and the ratio of the current green innovation output to the previous green innovation input is used for measurement.

#### 3.2.2 Independent Variable

Degree centrality of the interlocking director network (Degree). To construct the interlocking director network of enterprises in heavily polluting industries, this paper first exports the director appointment data of sample companies from 2014 to 2023 from the executive personal information files in the CSMAR database, uniquely identifies the list of interlocking directors with concurrent positions in enterprises by personnel ID by year, and then converts the "enterprise-director" two-mode relational matrix into an "enterprise-enterprise" one-mode relational matrix through Ucinet 6 software and calculates the degree centrality index of the corporate interlocking director network. Its calculation formula is as follows:

$$Degree_i = \frac{\sum_{i \neq j} X_{ji}}{g-1}$$

Among them,  $i$  represents a certain enterprise, and  $j$  represents other enterprises except  $i$  in the current year. If there is at least one interlocking director between two enterprises,  $X_{ji} = 1$ ; otherwise,  $X_{ji} = 0$ .  $g$  is the number of enterprises in the director network in the current year, and  $g-1$  is used for standardization. Degree centrality describes the sum of the number of other heavily polluting enterprises directly connected to a certain heavily polluting enterprise. The larger the value of Degree, the more enterprises directly connected to the enterprise, and it is often in the core position of the network.

### 3.2.3 Mediating Variables

Resource effect (WW). This paper selects the WW index as the proxy indicator of financing constraints, and the specific calculation method refers to the CSMAR database. This indicator can more comprehensively reveal the financing constraint status of enterprises by systematically measuring their profitability, financial health, and external financing dependence.

Corporate reputation (REPU). By drawing on the research of Guan Kaolei and Zhang Rui [33], this paper constructs a reputation evaluation system to measure the reputation (REPU) of heavily polluting enterprises. Factor analysis is used to process 12 corporate reputation evaluation indicators, and the corporate reputation score is calculated; then, the enterprises are divided into ten groups according to the reputation score from low to high, and each group is assigned REPU from 1 to 10 in turn.

### 3.2.4 Moderating Variable

Absorptive capacity (ABS). Since the process of enterprises identifying and capturing knowledge and transforming and integrating it into themselves can be reflected in R&D activities, most scholars currently use the proportion of R&D expenditure to represent the absorptive capacity of enterprises. Therefore, this paper uses the proportion of R&D expenditure in the current operating income to measure it.

### 3.2.5 Control Variables

With reference to existing research results, this paper selects enterprise size (Asset), ownership concentration (Shrcr), asset-liability ratio (Debtasset), return on net assets (Grow), current ratio (Liquid), and proportion of independent directors (Id) as control variables. In addition, this paper controls the time fixed effect and industry fixed effect. The specific description of variables is shown in Table 1.

Table 1. Variable Definition

Variable Type	Variable Name	Symbol	Measurement Method
Dependent Variable	Green Innovation Efficiency	Efficiency	Green Innovation Output / Green Innovation Input
Independent Variable	Interlocking Director Network Centrality	Degree	See Formula (1)
Moderating Variable	Absorptive Capacity	ABS	R&D Expenditure / Operating Income
Mediating Variable	Resource Effect	WW	WW Index
	Corporate Reputation	REPU	See the above text
Control Variable	Enterprise Size	Asset	Natural Logarithm of Total Corporate Assets
	Ownership Concentration	Shrcr	Proportion of the Top Ten Shareholders of the Company
	Asset-Liability Ratio	Debtasset	Total Liabilities / Total Assets
	Return on Net Assets	Grow	Net Profit / Net Assets
	Current Ratio	Liquid	Current Assets / Current Liabilities
	Proportion of Independent Directors	ID	Number of Independent Directors / Total Number of Directors

### 3.3 Model Setting

To test the impact of the centrality of the interlocking director network on corporate green innovation efficiency, the model is set as shown in Formula (2):

$$Efficiency_{it} = \alpha_0 + \alpha_1 Degree_{it} + \alpha_2 C_{it} + m_i + n_i + \varepsilon_{it}$$

Among them, the dependent variable is green innovation efficiency (Efficiency), the core independent variable is the degree centrality of the interlocking director network (Degree),  $C$  is the aforementioned control variable, and  $\varepsilon$  is the random error term of the model. To reflect the heterogeneous characteristics of enterprises and the impact of macroeconomic conditions, this paper controls the dummy variables of time ( $\$m\_i\$$ ) and industry ( $\$n\_i\$$ ) at the same time.

$$Efficiency_{it} = \alpha_0 + \alpha_1 Degree_{it} + \alpha_2 ABS_{it} + \alpha_3 Degree_{it} \times ABS_{it} + \alpha_4 C_{it} + m_i + n_i + \varepsilon_{it}$$

To test the moderating role of absorptive capacity in the relationship between the centrality of the interlocking director network and corporate green innovation efficiency, an interaction term is introduced, and the model is set as follows:

If  $\alpha_3$  in Formula (3) is significantly positive, Hypothesis 2 is valid, that is, absorptive capacity has a positive moderating effect between the centrality of the interlocking director network and corporate green innovation efficiency.

To test the impact mechanism of reputation and resources on the relationship between the centrality of the interlocking director network and corporate green innovation efficiency, this paper adopts the three-step method of mediating effect test, and sets the model on the basis of the benchmark model as follows:

$$M_{it} = \alpha_0 + \alpha_1 Degree_{it} + \alpha_2 C_{it} + m_i + n_i + \varepsilon_{it}$$

$$Efficiency_{it} = \alpha_0 + \alpha_1 Degree_{it} + \alpha_2 M_{it} + \alpha_3 C_{it} + m_i + n_i + \varepsilon_{it}$$

Among them,  $M$  is the mediating variable, representing the reputation level and financing constraint respectively. Other variables are the same as those in Formula (2).

## 4. Empirical Results and Analysis

### 4.1 Descriptive Statistics

Table 2 shows the descriptive statistics of the variables in this paper. The mean value of Efficiency is 0.086, slightly larger than the median value of 0.082, which means that more than half of the heavily polluting enterprises have green innovation efficiency below the average value, and the minimum value is 0, indicating that China's heavily polluting industry needs to further improve green innovation efficiency. The maximum value of Degree is 13 and the minimum value is 0, indicating that there are great differences in the connections between heavily polluting enterprises through interlocking directors, which provides a basis for the empirical analysis of this paper.

Table 2. Descriptive Statistics

Variable	Sample Size	Mean	Median	Standard Deviation	Minimum	Maximum
Efficiency	5,939	0.086	0.082	0.08	0	0.372
Degree	5,940	1.446	1	1.693	0	13
ABS	5,940	0.034	0.03	0.039	-0.089	1.23
REPU	5,176	6.402	7	2.773	1	10
WW	5,262	-1.043	-1.04	0.078	-1.974	-0.788
Shrcr	5,940	54.98	53.91	15.57	12.34	98.59
Debtasset	5,940	0.423	0.413	0.206	0.014	2.849
Asset	5,940	22.72	22.49	1.357	0	28.64
Grow	5,940	0.034	0.034	0.105	-3.2	1.408
ID	5,940	37.43	33.33	5.419	16.67	66.67
Liquid	5,940	2.189	1.537	2.778	0.094	78.41

### 4.2 Benchmark Regression Analysis

The benchmark regression results of the impact of the centrality of the interlocking director network on the green innovation efficiency of enterprises in heavily polluting industries are shown in Table 3. Columns (1) and (2) show

that whether control variables are added or not, the centrality of the interlocking director network has a significantly positive impact on the green innovation efficiency of enterprises in heavily polluting industries at the 1% level. Columns (3) and (4) further control the time and industry fixed effects. The results show that the centrality of the interlocking director network still has a significantly positive impact on the green innovation efficiency of enterprises in heavily polluting industries at the 1% level. This means that heavily polluting enterprises in the central position of the director network can help enterprises obtain external scarce resources and key information to a certain extent, and have a positive impact on the green innovation efficiency of heavily polluting enterprises. Therefore, Hypothesis H1 is verified.

Table 3. Benchmark Regression Results

	-1	-2	-3	-4
	Efficiency	Efficiency	Efficiency	Efficiency
Degree	0.003***	0.002***	0.003***	0.002***
	-4.3	-2.74	-4.56	-3.01
Shrcr		0.000***		0.000**
		-4.67		-2.31
Debtasset		-0.013*		-0.021***
		(-1.91)		(-3.17)
Asset		0.007***		0.007***
		-7.96		-7.4
Grow		0.031***		0.027***
		-2.85		-2.59
ID		0		0
		-1.43		(-0.58)
Liquid		-0.001***		-0.001**
		(-2.60)		(-2.41)
Cons	0.083***	-0.104***	0.083***	-0.071***
	-60.3	(-5.22)	-64.24	(-3.4)
Year	No	No	Yes	Yes
Industry	No	No	Yes	Yes
N	5,939	5,939	5,936	5,936
R-squared	0.003	0.034	0.148	0.164

Note: \*\*\* indicates  $p < 0.01$ , \*\* indicates  $p < 0.05$ , \* indicates  $p < 0.1$ ; *t*-values are in parentheses, the same below.

### 4.3 Robustness Test

#### 4.3.1 Replacing the Dependent Variable

This paper uses the ratio of the natural logarithm of the total number of green patent applications plus 1 to the previous period's R&D expenditure (Eff1) to replace the dependent variable. The regression results are shown in Column (1) of Table 4. The centrality of the interlocking director network is significantly positive at the 1% level, which further verifies Hypothesis 1.

#### 4.3.2 Replacing the Independent Variable

This paper uses structural holes (SH) to replace the degree centrality of the independent variable. Structural holes represent key positions or connection points in the interlocking director network, that is, connecting parts that had no direct connection originally. A larger number of structural holes indicates that the enterprise has a more important position in the network. The regression results are shown in Column (2) of Table 4. The structural holes are significant at the 1% level, indicating that the previous regression results are still robust.

#### 4.3.3 Lagging Variables by One Period

This paper brings the independent variables and control variables lagged by one period into the model for regression. The regression results are shown in Column (3) of Table 4, indicating that the centrality of the interlocking director network still has a significant role in promoting the corporate green innovation efficiency after lagging by one period.

#### 4.3.4 Adding Fixed Effects

Since heavily polluting enterprises may be affected by other factors, this paper further controls the provincial fixed effect. The regression results are shown in Column (4) of Table 4, indicating that the benchmark regression results are robust.

Table 4. Robustness Test Results

	-1	-2	-3	-4
	Eff1	Efficiency	Efficiency	Efficiency
Degree	0.002***			0.002***
	-3.44			-2.9
SH		0.009***		
		-3.86		
Degree1			0.002***	
			-2.84	
Cons	-0.065***	-0.084***	-0.119***	-0.088***
	(-3.1)	(-4.02)	(-5.02)	(-3.86)
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
N	5,935	5,936	5,343	5,452
R-squared	0.164	0.165	0.173	0.188

#### 4.4 Endogeneity Test

##### 4.4.1 Instrumental Variable Method

To solve endogeneity problems such as omitted variables, this paper uses the instrumental variable method for testing. Referring to Chen Danlin's idea of constructing instrumental variables[21], the instrumental variable (DG) of the centrality of the interlocking director network is composed of two parts: DG1 and DG2. Among them, DG1 represents the annual-industry average of the centrality of the interlocking director network, and DG2 represents the difference between the centrality of a single enterprise and the industry average. Since the fluctuation of the centrality of the interlocking director network of a single enterprise has a relatively small impact on the industry average, the change of the industry average is unlikely to be the result of the endogenous selection of a single enterprise, which can meet the requirement of exogeneity.

The regression results are shown in Table 5. It can be found that the Cragg-Donald Wald F statistic in the first stage is greater than the critical value, which indicates that the original hypothesis is rejected, there is no weak instrumental variable problem, and the correlation of the instrumental variable is guaranteed. In the second stage, the centrality of the interlocking director network is significantly positive at the 1% level and the coefficient increases, which further indicates that Hypothesis H1 of this paper is still robust after excluding endogeneity interference.

Table 5. Endogeneity Test Results

	-1	-2
Variable	First Stage	Second Stage
	Degree	Efficiency
DG	0.878***	
	-58.66	
Degree		0.005***
		-5.09

Cons	-4.451*** (-11.27)	-0.093*** (-4.15)
Cragg-Donald Wald F statistic	3,441.23	3,441.23
Stock-Yogo weak ID test critical values 10%	16.38	16.38
Control	Yes	Yes
Year	Yes	Yes
Industry	Yes	Yes
N	5,939	5,939
R-squared	0.403	0.033

#### 4.4.2 Propensity Score Matching (PSM) Method

According to the mean value of the centrality of the interlocking director network, this paper divides the full sample into enterprises with more interlocking directors and enterprises with fewer interlocking directors. The enterprises with more interlocking directors are taken as the treatment group, and the others are taken as the control group. The control variables are used as covariates in the matching process, and 1:1 matching is performed on the samples. The results in Table 6 show that the standardized deviation of covariates after matching is less than 10%, which passes the balance test. This paper uses the matched samples for regression. The results are shown in Table 7. Column (2) shows that the marginal effect of the information technology background of interlocking directors is still significantly positive, which is consistent with the above research conclusions.

Table 6. Sample Balance Test Results Based on PSM

Covariate Name	Unmatched (U) / Matched (M)	Mean (Treatment Group)	Mean (Control Group)	Standard Error (%)	Absolute Reduction Standard (%)	Value of t-value	p-value
Shrcr	U	56.03	54.38	10.7	70.6	3.95	0
	M	56.03	55.55	3.1		1.01	0.312
Debtasset	U	0.433	0.417	7.8	80.4	2.89	0.004
	M	0.433	0.436	-1.5		-0.51	0.61
Asset	U	22.91	22.61	22.7	95.1	8.42	0
	M	22.91	22.9	1.1		0.38	0.707
ROA	U	0.0401	0.0308	9.2	92.6	3.29	0.001
	M	0.0401	0.0408	-0.7		-0.27	0.786
ID	U	37.22	37.55	-6.3	61.6	-2.33	0.02
	M	37.22	37.08	2.4		0.82	0.415
Liquid	U	2.107	2.236	-4.6	86.8	-1.73	0.083
	M	2.107	2.089	0.6		0.21	0.834

Table 7. PSM Test Results

Variable	-1	-2
Degree	Origin 0.0018***	PSM 0.0019**
Cons	-3.01 -0.0708*** (-3.397)	-2.424 -0.1270*** (-4.039)
Control	Yes	Yes
Year	Yes	Yes
Industry	Yes	Yes
N	5,936	2,957
R-squared	0.164	0.164

## 5. Further Analysis

### 5.1 Mediating Effect

#### 5.1.1 Resource Effect

Table 8 shows the mediating effect test results of the resource effect. Degree in Column (1) is significantly negative at the 5% level, indicating that the higher the centrality of the interlocking director network, the smaller the corporate financing constraint. It can be seen from Column (2) of Table 8 that Degree is significantly positive at the 1% level; the coefficient of WW is significantly negative at the 1% level, indicating that corporate financing constraint plays a mediating role in the process of the impact of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. It is confirmed that the centrality of the director network helps to alleviate corporate financing constraints, thereby improving the green innovation efficiency of heavily polluting enterprises, which supports Hypothesis H1a proposed in this paper. Further, the Sobel test is used to analyze the mediating mechanism of corporate reputation. The results show that  $Z=2.087$  and  $p<0.05$ , indicating that the resource effect plays a mediating role in the process of the impact of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. The embedding of the interlocking director network reduces the information asymmetry between enterprises and financial institutions, improves the availability of financing, and helps heavily polluting enterprises overcome the obstacles of high R&D costs and financing difficulties in green innovation activities.

#### 5.1.2 Reputation Effect

Table 8 shows the mediating effect test results of corporate reputation. Degree in Column (3) is significantly positive at the 1% level, indicating that the higher the centrality of the interlocking director network, the better the corporate reputation. It can be seen from Column (4) that Degree is significantly positive at the 5% level; the coefficient of REPU is significantly positive at the 1% level, indicating that corporate reputation plays a mediating role in the process of the impact of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. It is confirmed that the centrality of the director network helps to improve corporate reputation, thereby improving the green innovation efficiency of heavily polluting enterprises, which supports Hypothesis H1b proposed in this paper. Further, the Sobel test is used to analyze the mediating mechanism of corporate reputation. The results show that  $Z=4.065$  and  $p<0.01$ , indicating that corporate reputation plays a mediating role in the process of the impact of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises. Enterprises with high centrality in the interlocking director network obtain information advantages through the cross-enterprise appointments of directors, which not only enhances their green innovation capabilities but also converts good reputation into "green premium" by improving their reputation in the industry, attracting more resources to invest in green innovation, and reducing the risk of reputation loss caused by environmental violations. This process provides a new governance path for the green transformation of heavily polluting industries.

Table 8. Mediating Effect Test Results

	-1	-2	-3	-4
Variable	Resource Effect	Resource Effect	Reputation Effect	Reputation Effect
Degree	WW -0.001**	Efficiency 0.002***	REPU 0.075***	Efficiency 0.001**
REPU	0	-0.001	-0.014	-0.001
WW		-0.119***		-0.001
Cons	-0.106***	-0.069***	-31.580***	0.068**
Sobel Test	0.001 ( $z=2.087$ , $p=0.037$ )	0.001 ( $z=2.087$ , $p=0.037$ )	0.001 ( $z=2.087$ , $p=0.000$ )	0.001 ( $z=4.065$ , $p=0.000$ )
Control	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
N	5,259.00	5,258.00	5,173.00	5,172.00

R-squared	0.644	0.172	0.621	0.173
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### 5.2 Moderating Effect

To ensure data consistency, this paper centralizes the independent variables and moderating variables before multiplying them. Table 9 shows the moderating effect test results of absorptive capacity. The interaction term between the centrality of the interlocking director network and absorptive capacity in Column (2) is significantly positive at the 1% level, indicating that corporate absorptive capacity positively moderates the promoting effect of the centrality of the director network on the green innovation efficiency of heavily polluting enterprises, which supports Hypothesis H2 proposed in this paper. Heavily polluting enterprises usually face high environmental regulation pressure. Heavily polluting enterprises with strong absorptive capacity are better at integrating policy information, heterogeneous technologies introduced by the director network with the internal R&D system. This process reflects the complementarity between enterprises' internal capabilities and external network resources, providing an important path for heavily polluting industries to break through the "technological bottleneck" in green transformation.

Table 9. Moderating Effect Test Results

	-1	-2
	Efficiency	Efficiency
Degree	0.002***	0.002***
Degree×ABS	-3.01	-3.62
ABS		0.083***
Cons		-3.91
		0.200***
		-6.89
	0.000**	-0.088***
	-2.31	(-4.22)
Control	Yes	Yes
Year	Yes	Yes
Industry	Yes	Yes
N	5,936.00	5,936.00
R-squared	0.164	0.171

### 5.3 Heterogeneity Analysis

#### 5.3.1 Grouped Regression by Enterprise Location

According to the provinces where the enterprises are located, this paper divides the samples into two groups: central and western regions, and eastern region, and conducts regression. The results are shown in Columns (1) and (2) of Table 10. The coefficient of Degree in the eastern region is significantly positive at the 1% level, while it is not significant in the central and western regions. The p-value of the Bootstrap inter-group difference coefficient is <0.01, indicating that the sample grouping is effective. The possible reason is that the economy in the eastern region is more developed, and enterprises can more conveniently obtain various resources in the interlocking director network, understand the latest green innovation technology trends in the industry, and introduce advanced environmental protection equipment and technologies in a timely manner, thereby improving green innovation efficiency. However, the competition among enterprises in the central and western regions is relatively weak, and the market environment is relatively closed. Enterprises may pay more attention to short-term economic benefits and have insufficient motivation to invest in green innovation. Even enterprises with high centrality in the interlocking director network may lack the sense of urgency to promote green innovation due to the relatively small market competition pressure, resulting in the insignificant impact of the centrality of the interlocking director network on green innovation efficiency.

#### 5.3.2 Grouped Regression by Enterprise Nature

According to the nature of enterprises, this paper divides heavily polluting enterprises into state-owned enterprises and non-state-owned enterprises and conducts regression. The results are shown in Table 10. The coefficients of Degree in Columns (3) and (4) are both significantly positive at the 5% level. The impact of the centrality of the

interlocking director network on the green innovation efficiency of state-owned heavily polluting enterprises is more significant. The p-value of the Bootstrap inter-group difference coefficient is  $<0.05$ , indicating that the sample grouping is effective. The possible reason is that due to the close connection between state-owned enterprises and the government, they are more likely to obtain guarantees in terms of funds and policy support, and are also given more social responsibilities. Compared with non-state-owned enterprises, the interlocking director network can further strengthen their resource acquisition capabilities.

### 5.3.3 Grouped Regression by Provincial Environmental Attention

There are differences in the degree of environmental attention among provinces, and the pressure of green innovation faced by heavily polluting enterprises also varies accordingly. Based on the 6-dimensional keywords provided by the CNRDS database, including protecting and improving the environment, preventing and controlling pollution and other public hazards, resource conservation, coordinated development and environmental co-governance, promoting ecological civilization construction, and promoting sustainable economic and social development, this paper calculates the proportion of keyword frequency in the government work reports of various prefecture-level cities, and divides the samples into groups with high environmental attention and low environmental attention in the provinces where the enterprises are located.

It can be seen from Columns (5) and (6) of Table 10 that when the government of the province where the enterprise is located has higher environmental attention, Degree is significantly positive at the 1% level; otherwise, it is not significant. The p-value of the Bootstrap inter-group difference coefficient is  $<0.05$ , indicating that the sample grouping is effective. When the government of the province where the enterprise is located has higher environmental attention, it tends to tilt policy formulation and resource allocation towards the green environmental protection field, and at the same time implement more stringent environmental supervision policies, which forms strong external pressure on heavily polluting enterprises and urges them to actively carry out green innovation to meet environmental protection requirements. Interlocking directors can obtain more information on environmental protection policies and technological innovation through the network, helping enterprises better respond to strict environmental supervision.

Table 10. Heterogeneity Test Results

	Central and Western Regions	Central and Western Regions	Eastern Region	Non-State-Owned Enterprises	State-Owned Enterprises	Low Environmental Attention	High Environmental Attention
	-1	-1	-2	-3	-4	-5	-6
	Efficiency	Efficiency	Efficiency	Efficiency	Efficiency	Efficiency	Efficiency
Degree	-0.000598	-0.000598	0.00343**	0.001**	0.002**	0.00113	0.00237***
	(-0.64)	(-0.64)	-4.5	-1.98	-2.36	-1.22	-3.08
Cons	0.0271	0.0271	-0.142***	-0.027	-0.172***	-0.0288	-0.0924***
	-0.84	-0.84	(-5.16)	(-1.07)	(-4.48)	(-0.85)	(-3.47)
p-value	0	0	0	0.022	0.022	0.046	0.046
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2,372.00	2,372.00	3,563.00	3,889.00	2,044.00	2,527.00	3,402.00
R-squared	R-squared	0.2	0.181	0.172	0.165	0.19	0.155

## 6. Conclusions and Implications

Based on the panel data of A-share listed companies in China's heavily polluting industries from 2014 to 2023, this paper uses social network analysis to construct the interlocking director network of listed companies and measure the position of enterprises in the network, explores the impact mechanism of the interlocking director network on the green innovation efficiency of heavily polluting enterprises, and conducts empirical analysis,

mechanism testing, and heterogeneity analysis. The research finds that the centrality of the interlocking director network has a positive impact on the green innovation efficiency of heavily polluting enterprises, and further clarifies the improvement mechanism of director network embedding on green innovation efficiency. Firstly, enterprises with high network centrality have multi-dimensional information and can obtain diversified financing channels to reduce financing costs, helping enterprises obtain low-cost funds for green technology R&D. Secondly, green innovation has a "reputation effect", and enterprises in the central position are more inclined to maintain their market reputation through green innovation practices, thereby improving corporate green innovation efficiency. This paper also finds that absorptive capacity can strengthen the promoting effect between the centrality of the interlocking director network and the green innovation efficiency of heavily polluting enterprises. The reason is that enterprises with high centrality in the interlocking director network can obtain a large amount of heterogeneous resources through director connections, and enterprises with high absorptive capacity can quickly and efficiently identify, screen, and transform external knowledge into internal innovation capabilities. Heterogeneity analysis shows that due to resource endowments and development characteristics, the centrality of the interlocking director network has a more significant positive effect on the green innovation efficiency of heavily polluting enterprises that are state-owned and located in the eastern region; and when the government of the province where the enterprise is located has higher environmental attention, the impact of the centrality of the interlocking director network on the green innovation efficiency of heavily polluting enterprises is stronger.

Based on the above analysis, this paper draws the following implications for corporate governance and government supervision:

- (1) The embedding of the interlocking director network has a positive impact on the green innovation efficiency of heavily polluting enterprises. The strategic value of network positional advantages in green innovation should be emphasized, and the role of directors as information bridges formed by cross-organizational appointments in efficiently integrating external heterogeneous resources should be strengthened. Specifically, heavily polluting enterprises should focus on building a diversified interlocking director network, especially connections with financial institutions and upstream and downstream enterprises in the industrial chain, and make full use of key information and scarce resources in the network to install an "accelerator" for corporate green innovation efficiency. In addition, the government can build cross-industry and cross-regional interlocking director exchange platforms, so that more heavily polluting enterprises have the opportunity to join them, accelerate the diffusion of green technologies and resource sharing, help heavily polluting enterprises with weak networks break through the dilemma of "high pollution and low innovation", and continuously establish an incentive mechanism for knowledge sharing in the director network to strengthen the collaborative innovation willingness of network nodes.
- (2) Absorptive capacity enhances the promoting effect of the interlocking director network on green innovation efficiency through three dimensions: knowledge screening, transformation, and application. Potential absorptive capacity such as R&D investment and technical personnel reserves determines the sensitivity of enterprises to external knowledge, while realized absorptive capacity affects the practical application effect of knowledge. Therefore, enterprises should not only actively recruit directors with green technology backgrounds or environmental protection experience, but also improve the management's awareness of green innovation through regular training, industry-university-research cooperation, and other methods, and enhance the ability to identify and transform green innovation resources in the network. They can also establish knowledge integration platforms, connect the technical knowledge transmitted by the director network with the internal knowledge base of the enterprise, and automatically match innovation needs with external resources through AI algorithms.
- (3) The green innovation of heavily polluting enterprises is a systematic project with both long-term and complexity. Appropriate green innovation strategies should be formulated based on the endogenous capabilities and external environment of enterprises. Non-state-owned enterprises and enterprises in the central and western regions in the heavily polluting industry should give priority to establishing connection relationships with state-owned enterprises and enterprises in the eastern region, and rely on their resource advantages and policy sensitivity to further exert the promoting effect. At the same time, the government should encourage state-owned enterprises to transmit green technology standards and financing experience to heavily polluting enterprises through the interlocking director network, and promote the diffusion of technology spillover effects to the central and western regions. Of course, the government should also strictly enforce environmental protection regulations, exert transformation pressure on high-pollution enterprises, and at the same time provide tax incentives or subsidies to enterprises with significant green innovation results, so as to promote the steady and win-win development of the heavily polluting industry in green development.

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