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Exploring the long-term impact of top management team interlocking networks on green innovation through regression analysis methods

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Abstract Under the guidance of the concept of sustainable development, green innovation becomes the key to corporate transformation. Based on the data of Chinese Shanghai and Shenzhen A-share companies from 2012 to 2024, this study explores the impact of top management team interlocking network on corporate green innovation and the moderating role of organizational redundancy and government subsidies through multiple linear regression models. The study adopts word frequency analysis to measure the environmental attention of the top management team interlocking network, and the number of green patent applications to measure the level of green innovation. The results show that the executive team interlocking network is significantly positively correlated with corporate green innovation, indicating that the higher the executive team's attention to environmental issues, the stronger the firm's green innovation ability. Further analysis reveals that organizational redundancy plays a positive moderating role in this relationship, and when firms have higher organizational redundancy, the interlocking network of the executive team promotes green innovation more strongly. Similarly, government subsidies significantly enhance the positive relationship. The conclusions remain consistent through endogeneity tests of exogenous shock event and instrumental variable methods, as well as multiple robustness tests. The study reveals the importance of executive team interlocking networks in promoting corporate green innovation and confirms the moderating role of internal and external resource allocation in this process, providing new ideas for corporate green innovation strategies.

Index Terms Top management team interlocking network, Green innovation, Organizational redundancy, Government subsidies, Environmental attention, Green patents

I. Introduction

The global environmental crisis and industrial transformation pressure are profoundly affecting the sustainable development of modern enterprises, and it is particularly urgent and important to protect the ecological environment and actively promote the green transformation and upgrading of enterprises [1]. Green innovation will resource conservation, ecological civilization and other green development concepts into the actual production and operation activities of enterprises, the use of new technologies, new processes to reduce the degree of environmental pollution, improve the efficiency of resource utilization, is an important source of power and an inevitable way to achieve sustainable development and enhance the competitive advantage of enterprises [2]-[5]. However, as green innovation focuses on environmental performance while pursuing economic benefits, it will produce the double externalities of knowledge spillover and environmental spillover, which seriously affects the enthusiasm of enterprise green innovation [6]-[8]. Therefore, it is particularly important to conduct an in-depth exploration of the enterprise green innovation driving factors.

Enterprises provide products and services to the society and the public through their own operation management, and obtain value in the process [9]. Operation management is a key link in the core competitiveness of an enterprise, which determines the profit effect and survival and development of an enterprise, and the interlocking network structure of top management is an important carrier for the implementation of operation management in an enterprise [10]-[12]. How to achieve the green sustainable operation and management demand of taking into account the economy, environment and society through the means of network optimization design and analysis in the process of enterprise operation and management, and construct all-round green sustainable competitiveness has become a major challenge for enterprises [13]-[16].

Global climate change and environmental degradation are posing serious challenges to human society, and the impact of production and operation on the environment is particularly important for enterprises as the main body of economic activities. In the face of increasingly stringent environmental policies and public demand for sustainable development, corporate green innovation has become a key strategy for solving environmental problems and

maintaining competitive advantages. Green innovation not only helps to reduce the negative impacts of corporate activities on the environment, but also improves the efficiency of resource utilization, reduces production costs, and enhances the market competitiveness of enterprises. However, corporate green innovation activities are often characterized by high risk and uncertainty, and require substantial resource investment and long-term strategic commitment. Therefore, it is of great significance to identify the key factors affecting corporate green innovation. As the core of corporate strategic decision-making, the characteristics, perceptions and behaviors of the top management team have a decisive impact on corporate strategic choices. By constructing interlocking networks, the executive team is able to access external information, resources and knowledge, and these cross-boundary linkages may have a profound impact on corporate green innovation strategies. Although studies have explored the relationship between executive team characteristics and corporate innovation, there is still limited research on how executive team interlocking networks influence corporate green innovation and what factors regulate this influence mechanism.

Based on the upper echelon theory and the resource base view, this study will explore the influence mechanism of the top management team interlocking network on corporate green innovation and examine the moderating roles of organizational redundancy and government subsidies, which are two factors representing the internal and external resources of the firm, in this process. The study measures the top management team interlocking network's concern for environmental issues through word frequency analysis, measures the level of green innovation by the number of corporate green patent applications, and constructs a multiple linear regression model for empirical analysis. The data of A-share listed companies in Shanghai and Shenzhen from 2012 to 2024 are selected, and the balanced panel data are formed after excluding special samples. This study will systematically explore the relationship between executive team interlocking network and corporate green innovation from the aspects of theoretical analysis, research design, empirical analysis, etc., and ensure the reliability of the research conclusions by combining the endogeneity test and robustness test, so as to provide theoretical guidance and practical references for corporations to promote green innovation.

II. Theoretical analysis

At this stage, China's rapid economic development has brought about increasingly serious environmental pollution problems, resource constraints and environmental pollution double pressure on traditional enterprises to maintain the crude economic growth mode. With the call for environmentally friendly technologies gradually growing in all sectors of society, manufacturing enterprises and other major pollution producers have become the focus of public attention, and changing the development mode and realizing green development have become the urgent needs of Chinese enterprises. The concept of sustainable development provides a roadmap for the green development of China's economy and the construction of an ecological civilization. In this context, green innovation strategy has become a key way for enterprises to promote green transformation.

II. A. Senior management team interlock network

II. A. 1) Top management team

The term “top management team” (TMT) first appeared in the 1970s in the study of strategic management, and the top management team plays a crucial role in the organizational leadership of enterprises. As the highest management team in the enterprise, the TMT has great management decision-making and control power in the daily management work, and is responsible for the strategic decision-making of the whole enterprise and the organization and coordination between various departments, etc. The decision-making will affect the enterprise's performance and the direction of future development, and it has an irreplaceable role in the enterprise compared with the general management [17].

According to the enterprise resource base theory researchers regard the enterprise senior management team as a group that adds value to the enterprise, they combine in a unique way and influence the development direction of the enterprise through decision-making, which is the core competitiveness of the enterprise, and is conducive to improving the performance of the enterprise. By organizing and reading the literature, it can be seen that scholars all have different understandings of the top management team, which leads to the definition of the top management team has not been unified, and the conclusions of the research are vastly different and not universal. Since the data collection is mainly secondary data, for the reliability of data collection as well as availability, drawing on the definitions of the top management team by various researchers, this paper defines the top management team personnel as the top managerial group responsible for the organizational coordination and performance of the entire enterprise, and has great decision-making power in the operation and management, and is the highest strategy formulation and implementation of the enterprise, including the CEO, the chairman of the board of directors, the general manager, Deputy General Manager, President, Vice President, Chief Financial Officer, Chief Engineer, etc.

II. A. 2) TMT interlocking network

A general consensus in the current academic community is that managers' social interlocking network relationships are closely related to the firm's strategic choices and performance. As a result, some researchers have linked social ties to organizational strategy and firm performance, defining social ties as executives' boundary-crossing activities and their related interactions with external entities. Further, scholars have further subdivided social interlocking network relationships into business ties and political ties. In this context, business ties are connections with other business executives, suppliers, customers, and competitors, etc., and these types of ties contribute to the operation and growth of the firm in the marketplace. Political linkages are those established with government officials, and political linkages can help firms better understand and adapt to policy changes and obtain necessary policy support and resources [18].

Currently, some researchers have proposed that social interlocking network relationships are a key way for firms to utilize diversified channels to access social capital through high-level personal networks, including both support relationships and business connections. In this study, supportive relationships cover non-commercial type of relationships with government officials and with social institutions such as universities. In contrast, business ties exclusively refer to relationships established between managers and other business executives, emphasizing direct economic interactions between firms. Combining the above definitions, this paper defines executive team social interlocking network relationships as managers' efforts to cross boundaries and their corresponding activities with external entities to help executives better conduct their business activities by leveraging favorable relationships with other participants in the value chain or by obtaining favorable government protection.

II. B. Green Innovation and Drivers

II. B. 1) The concept of green innovation

Green innovation refers to technological or managerial innovations that are characterized by the novelty and value of innovation and that achieve resource conservation and environmental improvement. Green innovation is a new approach aimed at solving environmental problems while improving productivity and efficiency and promoting economic transformation and sustainable development. Green innovation includes not only energy saving and emission reduction and green technology innovation, but also any innovative activities that can promote resource saving and environmental improvement [19].

Enterprise green innovation in this paper refers to the enterprise's ability to uphold the concept of environmental protection when carrying out innovation activities, and to promote green improvement and enhancement of products, services, processes and other aspects through scientific and technological innovation and management innovation, so as to realize the goal of sustainable development. The green innovation ability of enterprises is not only reflected in the greening of products and services, but also includes the greening of the internal management and operation process of enterprises, such as energy saving and emission reduction, resource recycling and utilization. The enhancement of enterprise green innovation capability requires enterprises to possess environmental awareness and responsibility, strengthen cooperation with stakeholders, continuously enhance technological innovation and management innovation, and continuously promote green improvement and enhancement to realize the goal of sustainable development. In order to encourage the development of green innovation, many countries and regions have introduced corresponding policies and support measures, such as the provision of R&D funding, tax breaks, market access facilitation, etc., so as to incentivize enterprises and research institutions to participate in green innovation activities. In this paper, based on previous research, we select the top management team interlocking network to explore the impact on corporate green innovation.

II. B. 2) Green innovation drivers

Since the Industrial Revolution, global problems such as resource scarcity, environmental degradation and the rising number of extreme weather conditions caused by economic development have been intensifying, and how to protect the environment while maintaining economic development has become a topic of concern for countries around the world. Innovation is the first power driving the development strategy, and green is the basic requirement to promote the harmonious coexistence of human and nature. Existing research on the driving factors of enterprise green innovation mainly focuses on the internal perspective and external perspective of enterprises.

(1) Enterprise internal perspective. With the increasingly severe environmental problems, scholars pay more attention to the value of green innovation from an ecological perspective, rather than analyzing the importance of green innovation only from the perspective of economic value. The implementation of green production, marketing and other management activities can improve the efficiency of resource utilization and reduce the negative impact on the environment, so some scholars have begun to pay attention to the internal characteristics of the enterprise, such as the resources and capabilities of the organization, to explore its impact on green innovation.

(2) External perspective of enterprises. Based on organizational legitimacy theory, new institutional theory and stakeholder theory, the existing literature studies the external drivers of corporate green innovation. Based on stakeholder theory, the existing literature focuses on the impact of the needs of external stakeholders, such as the government, the media, and upstream and downstream enterprises in the supply chain, on the green innovation of enterprises.

II. C.Design of relevant research hypotheses

II. C. 1) Impact of TMT interlocking networks on green innovation

The executive team, as the formulators and implementers of corporate strategy, is crucial to corporate strategic decision-making and corporate development. Based on the theory of sustainable development, the implementation of an enterprise's green innovation strategy involves three steps, namely attention, interpretation and action. Executive teams have limited time and energy, and they tend to focus their limited time and energy on selective attention to the information they consider important for corporate development. When the executive team focuses on this information in the process of building the interlocking network, the information is interpreted and given significance. Ultimately, the interpretation of this information is reflected in the strategic behavior of the executive team.

In the face of the current state of the natural environment, where pollution is a growing problem, many firms are concerned about the adverse effects of environmental pollution on the sustainable development of their firms. The natural resource-based view holds that the sustainable competitive advantage of an enterprise comes from a series of natural resources owned by the enterprise, and the green innovation strategy, as a way for enterprises to cope with environmental problems, can improve the status quo of the natural environment and realize the sustainable development of the enterprise, so the executive team will pay more attention to it when constructing the interlocking network. When the executive team's interlocking network expands and devotes limited time and energy to environment-related issues, they may associate environmental protection with bringing sustainable competitive advantages, efficient use of resources, cost savings, and obtaining stakeholders' support, thus assigning significance to the green innovation strategy of the enterprise.

On the one hand, they may assign significance to corporate green innovation strategy in terms of bringing sustainable competitive advantage, efficient resource utilization, cost saving, and gaining stakeholder support. On the other hand, the green innovation strategy of the company can make the company easily cope with the competitive pressure from the external market and competitors, and the technological innovation also provides the impetus for the development of the company. Therefore, the executive team interlocking network is an effective guarantee for the green innovation strategy of the enterprise, and the interaction of the two drives the enterprise to adopt the green innovation strategy. In summary, this paper proposes the following hypotheses:

H1: There is a significant positive correlation between executive team interlocking network and enterprise green innovation strategy.

II. C. 2) Moderating effects of organizational redundancy

The decision-making behavior of the executive team towards the organization does not only depend on how they configure their interlocking networks, but also on the context and situation they are in. For companies, the way an executive team configures its interlocking networks and focuses its attention is only a personal level factor; in addition, the company's large organizational structure, the external conditions that are responsible for the variability of the company, etc., all influence the decision-making behavior of the executive team. Overall, the executive team takes both contextual and situational factors into account when deciding whether and how to proceed with green innovation orientation.

Organizational redundancy is a resource-related concept that reflects the specifics of whether or not a firm has excess resources, and refers to the gap between all the resources available to the firm and the resources necessary for the firm to sustain its production operations, i.e., idle resources that are not being utilized. Investing R&D funds and strengthening scientific management are the reliance for green innovation, in addition to the efficient utilization of existing resources is also the way to realize green innovation. Organizational redundancy indicates that an enterprise is relatively rich in existing resources, which can reduce the internal and external pressures on the enterprise in implementing new decisions, and increase the autonomy of the enterprise to allocate surplus resources independently and efficiently, which greatly promotes the success rate of the enterprise's new decisions into action. Research on organizational redundancy has shown that it can provide companies with surplus resources to explore new opportunities and new solutions to problems, thus effectively promoting organizational innovation.

When the executive team intends to implement green innovation within the organization, there will be relatively little resistance from relevant interest groups. Green innovation is undoubtedly resource- and environment-friendly, but due to its high risk and uncertainty, the corresponding economic risk is relatively high, and organizational

redundancy can effectively mitigate the risk of failure of green innovation borne by the enterprise and the executive team. As a result, this paper proposes the following research hypothesis:

H2: Organizational redundancy plays a positive moderating role in the relationship between executive team interlocking network and green innovation.

II. C. 3) Moderating effects of government subsidies

As an effective environmental regulatory policy, government subsidies are the main incentive for the government to promote enterprises to carry out green innovation, encourage and promote heavily polluting enterprises to carry out environmental management by means of subsidies, improve the efficiency of resource use in the production process of enterprises, and prompt enterprises to shift to green production and green operation. However, from the perspective of existing research, the moderating effect of government subsidies on the interlocking network of executive teams and corporate green innovation has still not reached a unified conclusion.

On the one hand, based on the resource allocation theory, government subsidies can help enterprises alleviate the financial pressure, so that they have sufficient funds to carry out green innovation activities and have the ability to resist the risks of capital chain breakage and lack of key technical personnel in the process of innovation. In addition, signaling theory suggests that when a company receives government subsidies, it will be “government certified”. Government subsidies help enterprises gain the trust of investors and other stakeholders, improve their reputation, and enable them to further improve their financing ability. Thus, by receiving government subsidies, firms can signal to the outside world that they have a good relationship with the government, which can help them improve their innovation performance. Further, a good relationship with the government can further promote cooperation with external resources and enhance the firm's own competitive advantage, thus promoting the long-term sustainable development of the firm. In this context, government subsidies can further increase managers' attention and focus on green innovation, thus improving enterprises' ability in green innovation.

On the other hand, based on the resource curse theory, some scholars point out that government subsidies weaken the relationship between the interlocking network of executive teams and green innovation. Government support to firms would force firms to allocate resources under the government's preference, which in turn reduces the awareness and motivation of firms to innovate. This perspective emphasizes that government subsidies change the configuration of the interlocking network of the executive team of the enterprise, affect its top-down interlocking network processing, and reduce the enthusiasm of the executive team for green innovation. At this time, although the interlocking network of the executive team still stays on green innovation, its focus will be more on obtaining subsidies through green innovation activities, obtaining the “certification effect” from the government, and obtaining benefits for the enterprise, rather than focusing on green innovation itself. At the same time, government subsidies may lead to rent-seeking behavior of enterprises and their executive teams, which may restrict green innovation by reallocating resources to meet government expectations. As a result, although government subsidies can reduce the financial pressure of green innovation to a certain extent, the resources and efforts spent by the executive team in order to obtain government subsidies and maintain a good relationship with the government will hinder their green innovation. Based on this, this paper proposes the following research hypotheses:

H3: Government subsidies positively regulate the relationship between executive team interlocking networks and corporate green innovation.

III. Study design

While China's economy is growing rapidly, the ecological and environmental problems brought about by business development are becoming more and more prominent. For this reason, the state proposes green innovation as a key entry point to solve environmental problems and realize green development. However, it is difficult to rely only on the technical experience and knowledge accumulation of enterprises to carry out green innovation, and breaking through the organizational boundaries to search for a wide range of heterogeneous knowledge is a more effective way to carry out green innovation. The interlocking network relationship of the executive team is of high value, which can help enterprises to obtain resources and benefits that are difficult to be realized only by their own accumulation. Forming a stable and long-lasting interlocking network of executives and acquiring the knowledge needed for green innovation is a reliable way for enterprises to carry out green innovation.

III. A. Data sources and sample processing

III. A. 1) Data sample selection

This paper selects the data of Shanghai and Shenzhen A-share companies from 2012 to 2024 and organizes the raw data according to the following principles:

(1) Excluding samples such as banks and insurance, the accounting standards of financial institutions have their uniqueness, so they are excluded.

(2) Excluding samples subject to ST, *ST during the sample period.
(3) Samples with asset loading ratio greater than 1 are excluded to satisfy the going concern basis.
(4) Excluding the data of enterprises listed within one year with serious lack of data.
(5) In order to make the findings of the study more reliable, all continuous variables were subjected to two-sided 1% shrinkage.

The various raw financial data used are derived from the Cathay Pacific Repository (CSMAR), and data on corporate innovation and financing constraints are collected with CSMAR and then supplemented and validated using the Wind database. The raw data for the executive team interlocking network is taken from CSMAR, and the missing parts are supplemented and validated using the Wind database as well as Sina Finance and other websites to manually search for data related to the executive team interlocking network.

III. A. 2) Sample data processing

(1) Data Smoothing Processing

The core idea of the simple sliding average algorithm is to solve for an average of two or more neighboring terms as a smoothing value in the original sequence of enterprise green innovation data, and recompose a new sequence. The simple sliding average calculation formula is:

$$\overline{A}_t = \frac{A_{t-n} + \cdots + A_t + \cdots + A_{t+n}}{M}, t \geq M \tag{1}$$

where $M = 2n+1$, denotes the window width, A_t denotes the actual value at moment t, and $\overline{A}_t$ denotes the value obtained after smoothing the original data. For example, the simple sliding average of $(M = 5)$ for a window width of 5 is calculated as:

$$\overline{A}_t = \frac{A_{t-2} + A_{t-1} + A_t + A_{t+1} + A_{t+2}}{5} \tag{2}$$

(2) Data standardization

In the fusion analysis of multi-source data, due to the different sources of data, resulting in differences in the data outline and magnitude, in order to make these data comparable, it is necessary to use standardization methods to eliminate these differences. Data standardization refers to scaling the original data according to a certain ratio and removing the unit limitations, converting them into pure dimensionless values, so that all types of data with different units or scales are at the same level of quantity for comparison and weighting.

Z-Score standardization method is based on the mean and standard deviation of the original data to standardize the data, which is applicable to the case where the maximum and minimum values of the original data are unknown, or there are outlier data beyond the range of values.

Transform the sequence $x_1, x_2, \cdots, x_n$, i.e:

$$y_i = \frac{x_i - \overline{x}}{s} \tag{3}$$

Among them:

$$\begin{cases} \overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \\ s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2} \end{cases} \tag{4}$$

Then the new sequence $y_1, y_2, \cdots, y_n$ is the standardized sequence which has mean 0 and variance 1, satisfies normal distribution and is dimensionless.

III. B. Regression model and parameter estimation

III. B. 1) Multiple linear regression

Multiple linear regression (MLR) is a method of statistical analysis that is widely used in various fields and aims to explore the intrinsic connection between one indicator and multiple other indicators and to explain this connection by solving for the coefficients of multiple indicators [20].

Multiple linear regression model as the name suggests is to study the relationship between a dependent variable and multiple independent variables, if the assumption that the dependent variable is y, need to explore the linear relationship between the dependent variable y and n independent variables $x_1, x_2, \cdots, x_n$, then its general multiple linear regression formula is:

$$y = \sum_{i=1}^{n} b_i x_i + b_0 + \varepsilon \tag{5}$$

where b_i denotes the partial regression coefficient of its corresponding independent variable in the sample, which means the amount of change in the dependent variable y averaged over a unit change in the independent variable. b_0 is a constant that represents the intercept. ε is the random error after removing the effect of n independent variables on the dependent variable y, also known as the residual, which is an unobservable random variable. If m sets of observations are available, they are obtained by substituting them into the general formula:

$$\begin{cases} y_1 = b_0 + b_1 x_{11} + b_2 x_{12} + \cdots + b_n x_{1n} + \varepsilon_1 \\ y_2 = b_0 + b_1 x_{21} + b_2 x_{22} + \cdots + b_n x_{2n} + \varepsilon_2 \\ \vdots \\ y_m = b_0 + b_1 x_{m1} + b_2 x_{m2} + \cdots + b_n x_{mn} + \varepsilon_m \end{cases} \tag{6}$$

Write it in vector form as:

$$\begin{cases} y = \begin{bmatrix} y_1 & y_2 & \cdots & y_m \end{bmatrix}^T \\ X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \\ & & \vdots & & \\ 1 & x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \\ b = \begin{bmatrix} b_0 & b_1 & \cdots & b_n \end{bmatrix}^T \\ \varepsilon = \begin{bmatrix} \varepsilon_1 & \varepsilon_2 & \cdots & \varepsilon_m \end{bmatrix}^T \end{cases} \tag{7}$$

Then equation (6) can be written as:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \\ & & \vdots & & \\ 1 & x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \tag{8}$$

The above equation can then be expressed as:

$$y = Xb + \varepsilon \tag{9}$$

where the vector of partial regression coefficients b is the unknown parameter and ε is the residual. In general X is referred to as an information matrix of order $m*(n+1)$, assuming that X is column-full rank, i.e:

$$rank(X) = 1 + n \tag{10}$$

The above equation denotes the rank of the matrix X, and equation (9) is a classical linear algebra formula that we aim to solve for the vector of partial regression coefficients b in the model.

III. B. 2) Model parameter estimation

The greatest difficulty in using the multiple linear regression method for statistical analysis is parameter estimation, and the accuracy of parameter estimation directly affects the model fit. As in the case of the same multiple linear regression method, the most commonly used parameter estimation method for this statistical method is also the least squares (OLS) method, and the basic idea of OLS is to minimize the sum of squares of the residuals. Although some independent variables may have covariance problems in real life, this does not mean that these data do not satisfy the basic assumptions of the model, so the parameter estimates obtained using the least squares method

are still linear unbiased estimates [21]. The specific procedure for parameter estimation by ordinary least squares is as follows:

$$\begin{aligned} Q &= \sum \left[Y_i - \left(\beta_0 + \beta_1 X_i \right) \right]^2 = (Y - X\beta)^T (Y - X\beta) \\ &= \left(Y^T - \beta^T X^T \right) (Y - X\beta) \\ &= Y^T Y - \beta^T X^T Y - Y^T X\beta + \beta^T X^T X\beta \\ &= Y^T Y - 2\beta^T X^T Y + \beta^T X^T X\beta \end{aligned} \tag{11}$$

The partial derivation of Q with respect to β can be obtained:

$$\begin{aligned} &\frac{\partial Q}{\partial \beta} = -2X^T Y + 2X^T X\beta = 0 \\ &\Rightarrow X^T X\beta = X^T Y \\ &\Rightarrow (X^T X)^{-1} X^T X\beta = (X^T X)^{-1} X^T Y \end{aligned} \tag{12}$$

Since $(X^T X)^{-1} X^T X = I$ and $I\beta = \beta$, an estimate of the parameter β can be obtained as:

$$\hat{\beta} = \left(X^T X \right)^{-1} X^T Y \tag{13}$$

From this, the multiple linear regression model can be obtained as:

$$Y = X\hat{\beta} \tag{14}$$

III. C. Variable selection and model construction

III. C. 1) Selection of research variables

(1) Explained Variables

Corporate green innovation (GTI) is the core explanatory variable of this study. Referring to the research of existing scholars, it is characterized by the number of green patent applications of listed companies plus 2 to take the natural logarithm.

(2) Explanatory Variables

The executive team interlocking network (TMT) is the explanatory variable of this study. The content of CSR reports involving environmental issues can reflect the focus on the environment in the interlocking network of the executive team, and by analyzing the environment-related words in these reports, the degree of the executive team's commitment to and attention to environmental issues can be measured. In this study, word frequency analysis is used to measure the attention to the environment in the interlocking network of executive teams. Referring to the existing related studies, the social responsibility reports of A-share listed companies in Shanghai and Shenzhen from 2012 to 2024 are analyzed by word frequency analysis with the frequency of environment-related words as the keywords and the environmental attention of the interlocking network of executive teams is measured by using the text data platform of Wenjian Finance. Through the constructed word list of environmental attention keywords, the ratio of the word frequency of environmental keywords to the total word frequency in the reports of the studied companies is counted to assess the degree of attention to environmental issues in the executive team interlocking network. Both exact and extended words were considered when using the word frequency method.

(3) Moderating variables

Organizational redundancy (Org) is the moderating variable in this paper, and some researchers have classified organizational redundancy into three parts, i.e., sunk redundancy, non-sunk redundancy, and potential redundancy. In this paper, “(Administrative Expenses + Selling Expenses)/Operating Income” is used as a proxy variable for sedentary redundancy, and the larger the ratio, the more sedentary redundancy the firm can be reconfigured. "Current assets/current liabilities" is used as a proxy variable for non-precipitation redundancy, and the larger the ratio, the more non-precipitation redundancy. Use "Total Shareholders' Equity/Total Liabilities" as a proxy variable for potential redundancy, and the larger the ratio, the more potential redundancy. Calculate the mean of all three to measure organizational redundancy.

Government subsidies (Sub) is the moderating variable of this paper, this paper collects the amount of government subsidies received by enterprises according to the notes to the financial statements of each enterprise, and verifies its moderating effect by taking the natural logarithm and using the data of the lagged period as the moderating variable.

(4) Control variables

Referring to the existing studies, this study chooses the following control variables, i.e., firm size (Size), firm age (Age), gearing ratio (Lev), ownership ratio of the largest shareholder (OS), return on assets (ROA), management level (MAN), and total asset turnover (TAT).

III. C. 2) Research modeling

Based on the research hypotheses, the following sets of models were constructed and STATA was used for hypothesis testing:

Based on hypothesis H1, the following models were constructed:

$$GTI_{i,t} = \beta_0 + \beta_1 TMT_{i,t-1} + \beta_2 Control_{i,t-1} + \varepsilon_{i,t} \tag{15}$$

Based on assumptions H2 and H3, the following model is constructed:

$$\begin{aligned} GTI_{i,t} &= \beta_0 + \beta_1 TMT_{i,t-1} + \beta_2 Org_{i,t-1} \\ &+ \beta_3 TMT_{i,t-1} \times Org_{i,t-1} + \beta_4 Control_{i,t-1} + \varepsilon_{i,t} \end{aligned} \tag{16}$$

$$\begin{aligned} GTI_{i,t} &= \beta_0 + \beta_1 TMT_{i,t-1} + \beta_2 Sub_{i,t-1} \\ &+ \beta_3 TMT_{i,t-1} \times Sub_{i,t-1} + \beta_4 Control_{i,t-1} + \varepsilon_{i,t} \end{aligned} \tag{17}$$

Among them, the explanatory variable is corporate green technology innovation (GTI), due to the lag in the impact of different government environmental protection on the innovation output of enterprises, and in order to eliminate the possible endogeneity of the impact of the explanatory variables, moderating variables, and a series of control variables are lagged one period. Eq. (15) tests for the main effect, the effect of a chain network of top management teams on corporate green innovation, with the coefficient β_1 indicating the magnitude of this effect. Eq. (16) tests the moderating effect of organizational redundancy, adding the interaction term between top management team interlocking network and organizational redundancy on the basis of Eq. (15), and if the coefficient of β_3 is positive, it indicates that organizational redundancy can enhance the positive relationship between top management team interlocking network and corporate green innovation. Eq. (17) tests the moderating role of government subsidies, if the β_3 coefficient is positive, it indicates that government subsidies can enhance the positive relationship between the interlocking network of executive team and corporate green innovation, if the β_3 coefficient is negative, it indicates that it plays a weakening role. In the model, $Control$ represents a number of control variables, including firm size (Size), firm age (Age), gearing ratio (Lev), the ratio of the first largest shareholder's shareholding (OS), return on assets (ROA), management level (MAN), total asset turnover (TAT), year dummy variable (Year) and industry dummy variable (Industry).

IV. Empirical analysis

Over the past few decades, human productivity had risen significantly with the accelerated pace of industrialization, but that process had also been accompanied by the massive consumption of resources and the gradual deterioration of the ecological environment. China emphasizes the balance between environmental protection and economic development and actively advocates the concept of green development. Although innovation is the core driving force for economic growth and sustainable development, it is not enough to rely solely on innovation to achieve high-quality economic development. We must incorporate the concept of green development into our innovation activities, so that innovation and development and environmental protection can promote and complement each other. Green innovation is precisely such a combination of concept and practice, which aims to protect the environment while promoting economic development, and is therefore the key to solving current environmental problems.

IV. A. Benchmark regressions and moderating effects

IV. A. 1) Benchmark regression results

In studying the impact of top management team on corporate green innovation, the research sample of this paper is selected from the balanced panel data of Shanghai and Shenzhen A-share listed companies from 2012 to 2024.The results of Hausman test show that the p-value significantly rejects the original hypothesis, which suggests that there is a significant difference between the fixed-effects model and the random-effects model at the time of estimation. Therefore, the fixed effect model is more appropriate when conducting a specific study.

Table 1 shows the results of regression analysis for main effects. Models (1) to (4) are the results of regression analysis without adding control variables and fixed effects, fixed effects, adding control variables without controlling

fixed effects, and control variables with fixed effects, respectively. In the table, *, **, and *** indicate significant correlation at the 10%, 5%, and 1% levels, respectively, with t-values in parentheses.

In the comparative data of model (1) and model (2), the regression impact coefficients of top management team interlocking network (TMT) on corporate green innovation (GTI) without control variables and after categorical control for time and industry are 0.573 and 0.528, respectively, and both of them are positive at the 1% significance level (P<0.01). This suggests that the higher the level of environmental concern in the top management team interlocking network, the stronger the firm's implementation of green innovation strategy will be accordingly, and hypothesis H1 is verified. After controlling for time and industry variables, it is clear that the coefficient of influence of top management team interlocking network (TMT) on corporate green innovation (GTI) becomes smaller. In addition, after adding control variables (models (3)~(4)), the regression impact coefficient of top management team interlocking network (TMT) on corporate green innovation (GTI) is positively and significantly enhanced at the 1% level (P<0.01), regardless of controlling for time and industry. A higher level of environmental concern among different executives in the top management team interlocking network significantly contributes to better results in green innovation activities of the firms.

Table 1: The regression analysis results of the main effect

Variable	Model (1)	Model (2)	Model (3)	Model (4)
(Con_)	0.712***(5.176)	0.694***(4.891)	0.581***(4.483)	0.546***(4.065)
TMT	0.573***(6.941)	0.528***(5.752)	0.537***(5.991)	0.502***(5.181)
Size	-	-	0.026***(6.214)	0.029***(5.795)
Age	-	-	0.045**(3.127)	0.041**(3.052)
Lev	-	-	-0.028(-0.071)	-0.025(-0.061)
OS	-	-	0.005(0.194)	0.005(0.189)
ROA	-	-	0.028(0.183)	0.024(0.172)
MAN	-	-	0.034*(2.795)	0.031*(2.561)
TAT	-	-	0.161*(1.836)	0.169*(1.724)
Year	NO	YES	NO	YES
Industry	NO	YES	NO	YES
R^2	0.8261	0.8392	0.8153	0.8078

IV. A. 2) Analysis of moderating effects

Since the interaction term between the independent variable and the moderator variable may cause covariance in the absence of any treatment, it is necessary to construct the interaction term based on the values of the independent variable and the moderator variable after centering them separately. Therefore, before designing the moderating effect test model, it is necessary to construct the interaction term based on the centered values of the independent variables and the moderating variables separately, and judge whether the moderating effect can be established based on the significance of the interaction term. Table 2 shows the regression results of the moderating effects of organizational redundancy and government subsidies on the relationship between top management team interlocking networks and corporate green innovation.

Based on model (1) in the table, the coefficient of the interaction term between environmental concern and organizational redundancy in the TMT interlocking network is 1.418, which is significant at 10% level (t=3.489, P<0.1), indicating that the redundant resources within the enterprise can indeed positively regulate the relationship between environmental concern and green innovation strategy in the TMT interlocking network, the regression results support the hypothesis H2. Through the model (2) in the table to test the moderating role of government subsidies, that is, the government subsidies as an external resource assistance, in the process of the enterprise TMT interlocking network of environmental concerns into the green innovation strategy of the conversion process can be put to the best use, have an impact? The interaction term between TMT interlocking network and government subsidy (TMT*Sub) is added in model (2), and from model (2), the interaction term between TMT interlocking network's concern for environmental issues and government subsidy is significant at 10% level (t=55.428, P<0.05), which indicates that government subsidy in the conversion of TMT interlocking network's concern for environmental issues to green innovation strategy in the process can also play a catalytic role, and the regression results support hypothesis H3.

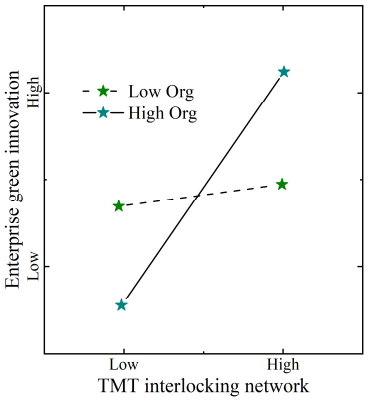
Table 2: Analysis of moderating effect

Variable	Model (1)	Model (2)
(Con_)	0.582***(4.393)	0.516***(4.495)
TMT*Org	1.418*(3.489)	-
TMT*Sub	-	55.428**(28.716)
Size	-0.025(2.014)	-0.024(1.878)
Age	0.003(1.785)	0.005(1.634)
Lev	0.063(3.268)	0.059(3.052)
OS	0.005(0.189)	0.004(0.171)
ROA	0.148(3.156)	0.135(2.958)
MAN	0.005(3.071)	0.004(2.779)
TAT	0.106(2.847)	0.106(2.847)
Year	YES	YES
Industry	YES	YES
R^2	0.8041	0.8092

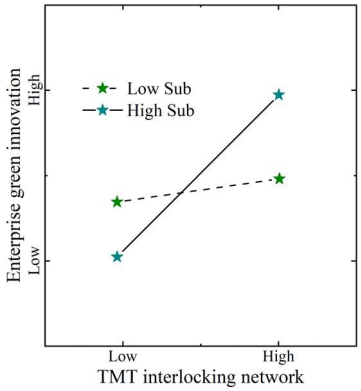
In order to better understand the moderating effect of the two resources of organizational redundancy and government subsidies on the main effect, this paper draws the moderating effect diagrams of organizational redundancy and government subsidies by using Stata software in order to visualize their effects. Figure 1 shows the results of regulation effect comparison, in which Figure 1(a)~(b) are the regulation effect of organizational redundancy and government subsidies, respectively.

As can be seen from Figure 1(a), when the level of corporate organizational redundancy is low, the effectiveness of the implementation of corporate green innovation strategy increases slowly with the increase of environmental concern in TMT interlocking network, but the slope of this positive relationship is low, indicating that in the case of low level of corporate redundancy resources, the transformation of environmental concern in the TMT interlocking network into green innovation strategy is weak. And when the level of corporate organizational redundancy is high, the positive relationship between TMT interlocking network environmental problem concern and green innovation strategy is enhanced, and redundant resources play a significant role in prompting the conversion of corporate TMT interlocking network environmental problem concern into green innovation strategy, which is also reflected in model (1) of Table 2 of the regression results after adding the interaction term of TMT interlocking network environmental problem concern with the The significance of the main effect increases after adding the interaction term of organizational redundancy. Organizational redundancy, as an important resource support within the firm, will strengthen the risk-taking level of the executive team and add to the implementation of the firm's green innovation strategy.

From Figure 1(b), it can be seen that a high level of government subsidy will increase the slope between environmental concern and green innovation strategy in TMT interlocking networks compared to a low level of government subsidy. That is to say, when the more government support a firm receives, the more obvious the effect of converting TMT interlocking network environmental problem concern into green innovation strategy. When government subsidies are a large financial input for firms, executive teams concerned about environmental issues will be more cautious in utilizing this money to implement green innovation strategies to ensure the best use of the money.



(a) Organizational redundancy



(b) Government subsidy

Figure 1: Comparison results of moderating effects

IV. B. Endogeneity and robustness tests

IV. B. 1) Endogeneity test

The empirical results of this paper may be affected by a series of endogenous issues. On the one hand, if firms actively engage in green technology innovation, their executive teams will naturally pay attention to environmental problems and allocate more attention to environmental issues and solutions. On the other hand, although this paper has selected control variables from multiple perspectives, there are still some difficult-to-measure omitted variables that may affect the empirical results. In order to alleviate the possible endogeneity problem, this paper adopts the exogenous shock event and instrumental variable method to re-test.

(1) Exogenous shock event method

When a company receives administrative punishment from the government for negative environmental behavior, it not only has to pay a huge fine, but also has a negative impact on the reputation of its executives. In order to restore their reputation, the executive team will increase their environmental attention when constructing interlocking networks, and show a new good image to the outside world by adopting green behaviors. Based on this, this paper takes the environmental administrative penalty as an exogenous shock event to test the influence of environmental concern on the interlocking network of the executive team on the green technological innovation of the enterprise. A dummy variable (Punish) is constructed for the environmental administrative penalty, which is assigned as P1 if the enterprise receives the environmental administrative penalty for the first time during the sample period, and P0 for the rest of the sample.Meanwhile, a dummy variable (Post) is constructed for the time, which is assigned as T1 for the year when the enterprise receives the environmental administrative penalty and the year after that, and T0 for the rest of the year.The data are collected through the announcement of the environmental penalty issued by the enterprise.

(2) Instrumental variables method

Considering the relevant requirements of instrumental variables and referring to the relevant practices of existing studies, the mean value of environmental concerns of the executive team interlocking network of other listed enterprises in the same industry (TMT Mean) is selected as the instrumental variable of the executive team interlocking network. Generally speaking, the strategic positioning and the market environment faced by enterprises in the same industry are similar, and the concern of the executive team interlocking network on environmental issues will also show a high degree of consistency, but the executive team interlocking network of other enterprises in the same industry will not have an impact on the green technology innovation of this enterprise, so this instrumental variable meets the requirements of relevance and exogeneity. Mainly, two-stage least squares (2OLS) is used for coefficient estimation.

Table 3: Endogeneity test results

Variable	Model (1)	Model (2)-TMT	Model (3)-GDI
		First stage	Second stage
Punish×Post	0.156**(2.178)	-	-
TMT Mean	-	1.273**(3.748)	-
TMT	-	-	3.892***(5.886)
F	-	27.426***(3.561)	41.763***(3.915)
Control	YES	YES	YES
Year	YES	YES	YES
Industry	YES	YES	YES
Adj.R^2	0.7291	0.6164	0.8035

Table 3 shows the results of the endogeneity test, where model (1) is the test result of the exogenous shock event method and models (2) to (3) are the results of the instrumental variable method. From the test results of model (1) in the table, it can be seen that when enterprises are subjected to environmental administrative punishment, the level of green innovation of enterprises will be significantly improved. That is, under the cross-multiplication term of the dummy variable environmental protection administrative punishment and time, its impact coefficient on the green innovation activities of enterprises is 0.156 and shows positive significance at the 5% level. It shows that the conclusion that executive team interlocking network has a positive impact on corporate green innovation still holds when exogenous shock events are used to represent the increase in attention to environmental issues in the construction of executive team interlocking network in the ancient city. In addition, model (2) demonstrates the first-stage estimation results, the regression coefficient of TMT Mean is 1.273 and significantly positive at the 5% level, indicating that the executive team interlocking network of other enterprises in the same industry can indeed positively influence the concern of the executive team of this enterprise on environmental issues, and the results of

the test of weak instrumental variables show that the F-value is 27.426, which is significantly greater than 8, which indicates that the instrumental variables selected in this paper are reasonable. Model (3) is the result of the second stage estimation, from which it can be seen that the regression coefficient of executive team interlocking network (TMT) on the level of green innovation of the enterprise is 3.892, which is significantly positive at the level of 1%, and still supports the above conclusion.

IV. B. 2) Robustness Tests

In order to further illustrate the reliability of the regression results in this paper, this paper carries out a robustness test. Table 4 shows the results of the robustness test. The specific methods are as follows:

(1) Replacement of corporate green innovation measurement variables. Drawing on existing relevant studies, this paper measures the level of green innovation by the ratio of the number of green patent applications to the number of all its patent applications in the year (GrepatRatio), which is similarly divided into the ratio of green invention-based patent applications (GreInRatio) and the ratio of green utility-based patent applications (GreUpRatio). This paper further adopts the natural logarithm of the number of green patents granted plus one (GreAll) to measure green innovation, and divides it into the number of green invention patents granted (GreInvig) and the number of green utility patents granted (GreUmig).

(2) Replacement of executive team interlocking network measurement variables. Referring to the existing related research, if the past experiences of corporate executives include teaching in colleges and universities, engaging in research in scientific research institutions or associations, etc., the dummy variable Academic for executives' academic experience takes the value of A1, or else it is A0.

(3) Replace the measurement model. This paper replaces the measurement model with the PLS regression model to re-regress, as a way to explore the impact of the measurement model.

After the robustness test through the above three methods, it can be seen that when replacing the corporate green innovation measurement variables, no matter how they are measured, the research findings always present a significant positive impact at the 1% level, i.e., the research findings are robust. In addition, when replacing the executive team interlocking network variable and under the measurement model, its impact coefficient on the level of corporate green innovation is 0.237 and 0.453, respectively, both presenting a significant positive impact at the 1% level, which further indicates that the research conclusions of this paper are robust.

Table 4: Robustness test results

Replace the measurement variables of green innovation in enterprises						
Variable	GrepatRatio	GreInRatio	GreUpRatio	GreAll	GreInvig	GreUmig
TMT	0.053*** (2.894)	0.065*** (2.876)	0.058*** (2.932)	0.631*** (5.428)	0.716*** (4.475)	0.486*** (4.189)
Academic	Model (1)-GTI 0.237***(5.739)			-	-	-
TMT	Model (2)-GTI 0.453***(5.428)			-	-	-
Control	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES	YES
Adj.R^2	0.3162	0.1384	0.1751	0.1462	0.1462	0.1408

V. Conclusion

The top management team interlocking network has a significant contribution to corporate green innovation strategy. The empirical results show that environmental concern in the executive team interlocking network is significantly and positively related to the level of corporate green innovation (β=0.573, P<0.01), and the effect remains robust after controlling for time and industry factors (β=0.528, P<0.01). At the resource allocation level, organizational redundancy strengthens the positive relationship between executive team interlocking network and green innovation, with an interaction term coefficient of 1.418 (P<0.1); meanwhile, government subsidy as external support also significantly enhances this relationship (β=55.428, P<0.05). When facing the exogenous shock event of environmental penalties, the level of corporate green innovation is significantly enhanced (β=0.156, P<0.05), which confirms the facilitating effect of the interlocking network of executive team on green innovation. The instrumental variables test further supported the robustness of the main effect (β=3.892, P<0.01). Multi-perspective robustness tests showed that the findings remained consistent regardless of the green innovation measure or econometric model used. These findings reveal the important influence mechanism of executive team interlocking network on corporate green innovation, and enterprises should strengthen the attention of executive team to environmental

issues, make reasonable use of organizational redundancy resources and government subsidy support to build a good green innovation ecosystem and promote the sustainable development of enterprises.

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