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Board Networks and Firms' Technological Innovation Output: The Moderating Roles of Shareholder Networks and CEO Networks

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Abstract: In the field of firms' technological innovation, a large body of research has emphasized the roles of interlocking directors and the associated board networks in which they are embedded. By integrating the process perspective of absorptive capacity theory with stakeholder network theory, this study investigates the influence of board networks on firms' technological innovation output, with particular attention given to the moderating effects of shareholder networks and CEO networks. The theoretical hypotheses suggest that degree centrality within board networks positively influences firms' technological innovation output, and that this positive effect is weakened by degree centrality within both shareholder networks and CEO networks. While board networks facilitate information acquisition for technological innovation, shareholder networks and CEO networks may serve as substitutes. Furthermore, they may shape the motivations of shareholders and CEOs, potentially hindering the exploitation of information acquired through board networks. Using longitudinal data on Chinese A-share listed companies from 2005 to 2023, we construct three distinct types of interorganizational networks and annually measure firms' degree centralities within each network type. Employing fixed-effects panel models, this study empirically verifies the proposed hypotheses. Practically, the findings offer important implications for firms seeking to align interorganizational networks with their technological innovation management strategies. We recommend that future research further explore the roles of diverse stakeholder networks in interorganizational contexts to enhance the understanding of how interactions across multilayer networks affect firms' technological innovation output.

Keywords: board networks; shareholder networks; CEO networks; technological innovation output; absorptive capacity theory; social network analysis



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1. Introduction

Technological innovation plays a critical role in enabling firms to gain a competitive advantage and achieve sustainable long-term success. However, technological innovation is inherently risky and demands a high tolerance for costly failures, as it emerges from a continuous process of exploratory learning [1]. This inherent risk frequently results in information asymmetry between firms and the market [2]. Consequently, absorbing innovation-related information has become essential for improving firms' technological innovation output. A growing body of research has explored the roles of various interorganizational networks in facilitating information absorption, including board networks [3,4],

shareholder networks [5], CEO networks [6,7], collaboration networks [8–10], and alliance networks [11,12], among others.

The primary focus of this study is on board networks, which are defined as the interorganizational networks formed through director interlocks. Within board networks, when a director simultaneously serves on the boards of two or more firms, the director is called an interlocking director, and the firms involved are considered interlocked [13–16]. The influences of board networks on firms' technological innovation have been widely discussed in prior research [17–19]. For example, Chuluun et al. [20] find that firms embedded in more centralized board networks tend to exhibit higher technological innovation output. Based on a study of U.S. public firms in high-tech industries, Li [21] finds that board networks increase firms' likelihood of successful technological exploration. Similarly, drawing upon an empirical analysis of over 50,000 Swedish start-up firms, Baum et al. [22] demonstrate that board networks facilitate bidirectional interorganizational knowledge flow. Compared with other types of interorganizational networks, board networks offer unique advantages in information absorption. On one hand, interlocking directors can engage in discussions about future technological developments during board meetings [21], enabling them to acquire timely insights into emerging technologies and investment directions. On the other hand, as key decision makers and strategic leaders, interlocking directors can rapidly exploit acquired information to formulate innovation strategies [23]. By facilitating both information acquisition and exploitation, interlocking directors and the associated board networks play a particularly crucial role in innovation-driven contexts.

Although prior empirical research has widely acknowledged the important role of board networks in facilitating firms' technological innovation—particularly in the context of information absorption—limited attention has been paid to how information absorption may be moderated by other interorganizational networks. In addition, existing studies have not disentangled the distinct processes involved in information absorption. To extend this line of inquiry, we integrate stakeholder network theory [24] with absorptive capacity theory [25] to investigate how two critical stakeholder networks—shareholder networks and CEO networks—moderate the roles of board networks in firms' information absorption. Specifically, this study seeks to unpack the “black box” of absorptive capacity in the relationship between board networks and firms' technological innovation output by distinguishing between potential and realized absorptive capacity, which correspond to information acquisition and information exploitation. Shareholder networks and CEO networks are defined as interorganizational networks formed through common shareholding and CEOs' shared employment histories or educational backgrounds, respectively. Together with board networks, these two types of interorganizational networks may generate combined effects on firms' technological innovation output [7,26].

On one hand, shareholder networks and CEO networks represent critical channels through which firms can acquire valuable information, potentially serving as substitutes for board networks. Specifically, with regard to shareholder networks, prior studies have emphasized their roles in disseminating industry-specific knowledge, including investment expertise, managerial insights, and strategic information [5,27–29]. Moreover, shareholder networks are typically characterized by large-scale and non-redundant weak ties [7,30], which enable firms to acquire diverse and heterogeneous information [31]. With regard to CEO networks, they facilitate the dissemination of strategic decisions and day-to-day operational information among firms. They also provide real-time insights into market dynamics and technology trends [32–34]. In addition, CEO networks can serve as effective channels for the dissemination of knowledge, ideas, and business information, as they are formed based on CEOs' employment histories and educational backgrounds [35]. In summary, the diverse information disseminated through shareholder networks and CEO

networks may also contribute to firms' technological innovation output, thereby generating substitutive effects that influence the role of board networks.

On the other hand, shareholder networks and CEO networks may also shape the motivations of shareholders and CEOs, respectively, thereby influencing firms' exploitation of information acquired through board networks. With regard to shareholder networks, firms that are deeply embedded within these networks typically have shareholders who hold stakes in multiple firms. Such shareholders often possess strong incentives to actively engage in firms' strategic decision making to safeguard their investment interests. For instance, they may pursue profit-maximizing strategies across their investment portfolios and potentially engage in collusive behaviors aimed at securing monopoly profits [36–38]. Under such circumstances, firms may encounter shareholders' reluctance to recognize the value of investments in technological innovation, thereby triggering conflicts between directors and shareholders during the implementation of innovation strategies. With regard to CEO networks, firms that are deeply embedded within these networks typically have CEOs who possess extensive industry expertise. These CEOs often possess elevated reputational status, granting them considerable informal power [26,39,40]. Such reputational status and informal power may foster CEO overconfidence, making them more inclined to trust and leverage information from CEO networks rather than board networks [6,41]. In summary, the motivations of shareholders and CEOs shaped by the deep embeddedness within shareholder networks and CEO networks may hinder firms' exploitation of information acquired from board networks.

Taken together, by explicating the two processes of absorptive capacity and highlighting the underlying mechanisms, we investigate the influence of board networks on firms' technological innovation output. Furthermore, this study addresses the following question: do shareholder networks and CEO networks moderate the impact of board networks by shaping two processes of absorptive capacity? To examine this issue, we develop a set of hypotheses and empirically test them using longitudinal data on Chinese A-share listed companies from 2005 to 2023. Specifically, we construct three distinct types of interorganizational networks on an annual basis—board networks, shareholder networks, and CEO networks. Following prior research, we construct board networks based on shared interlocking directors across firms [13–16], shareholder networks based on common shareholding relationships among principal shareholders [5], and CEO networks based on CEOs' shared employment histories and educational backgrounds [35,42]. Drawing upon degree centrality, a widely used measure for evaluating network embeddedness [43,44], this study examines the influence of board networks on firms' technological innovation output, as well as the moderating effects of the shareholder networks and CEO networks on this relationship.

Adopting a process-based perspective on absorptive capacity, this study makes two contributions to the literature on interorganizational networks and firms' technological innovation. First, we explore the substitutive effects among different sources through which firms acquire information via distinct types of interorganizational networks. These information sources do not function independently; rather, they interact in substitutive ways to explain significant organizational outcomes [7,9,45]. However, the extant research predominantly examines the impact of a singular network in isolation [1,5,46], overlooking broader interactions among multilayer networks [47]. Such a perspective may obscure the contextual mechanisms through which singular interorganizational networks exert their influence. This study investigates the moderating effects of shareholder networks and CEO networks on the influence of board networks, thereby extending our understanding of the boundary conditions under which board networks influence firms' technological innovation output.

Second, this study emphasizes that interorganizational networks in which firms are embedded not only shape the sources through which firms acquire information but also affect the motivations of actors who constitute these networks, potentially influencing the firms' exploitation of the acquired information. Given that actors embedded within networks exhibit agency [48], we argue that shareholders and CEOs can strategically leverage the advantages derived from relevant networks. These motivations can be interpreted as stemming from self-interested, utility-maximizing reasoning, potentially leading to inconsistent demands [48]. By considering shareholders' collusion motivations as well as the CEOs' overconfidence, this study advances the understanding of the motivations of distinct actors shaped by various interorganizational networks and the potential conflicts these motivations may trigger during firms' technological innovation processes. From a practical perspective, our findings may assist firms in designing more effective resource allocation and technological innovation strategies when constructing various types of interorganizational networks.

The remainder of this paper is organized as follows: Section 2 presents the theory and hypotheses. Section 3 describes the data and methodology, including the research samples, variable definition and measurement, and analytical methods. Section 4 reports the empirical results, and Section 5 discusses the theoretical implications, practical implications, and research limitations.

2. Theory and Hypotheses

As Powell et al. [49] suggest, the trajectory of innovation is more likely to unfold within interorganizational networks than within individual firms. Similarly, Chang [50] argues that the most advanced innovations often emerge from interorganizational networks rather than solely from individual firms' internal R&D efforts. The crucial roles of interorganizational networks in firms' innovation have been widely attributed to their influence on firms' absorptive capacity [51,52]. Absorptive capacity is defined as "the ability to value, assimilate, and utilize new external information" [53,54] and is widely regarded as a core component of a firm's technological capability [55]. Adopting a process-based perspective, Zahra and George [25] conceptualize absorptive capacity as a dynamic capability and further distinguish it into two sub-dimensions: potential absorptive capacity and realized absorptive capacity. Potential absorptive capacity primarily concerns the acquisition of information, aligning with Cohen and Levinthal's [53] characterization of a firm's ability to value and obtain external information. By contrast, realized absorptive capacity centers on the exploitation of acquired information and reflects a firm's ability to apply this information to generate technological innovation output. According to Zahra and George [25], high potential absorptive capacity alone does not necessarily lead to improved innovation. It is also critical to consider realized absorptive capacity—the effective exploitation of acquired information—which, in conjunction with potential absorptive capacity, drives the enhancement in technological innovation output.

The influence of board networks on firms' technological innovation output is closely linked to both potential and realized absorptive capacities, that is, to the acquisition and exploitation processes underlying absorptive capacity. Specifically, board networks could accelerate the acquisition of innovation-related information through interlocking directors' participation in board activities. By leveraging their strategic leadership roles, interlocking directors could also facilitate the exploitation of such information, thereby enhancing the organization's capabilities to systematically integrate and creatively transform external knowledge, ultimately driving technological innovation output.

Shareholders and CEOs, as primary stakeholders whose interests are either influenced by instrumental to the achievement of corporate objectives [56], are embedded within a

broader stakeholder network. Drawing on Rowley's [24] network theory of stakeholders, actors embedded within stakeholder networks exhibit varying positional characteristics, which in turn shape the extent of their influence. Moreover, Ertug et al. [57] emphasize that the interplay between multilayer networks and the combinations of multiplexity is crucial for understanding organizational outcomes. Therefore, we posit that shareholder networks and CEO networks may influence a firm's absorptive capacity by differentially affecting the underlying potential and realized absorptive capacities. First, in the process of information acquisition, information acquired from shareholder and CEO networks may serve as substitutes for that acquired from board networks. As revealed by Xu and Tian [9], multilayer interorganizational networks exert substitutive influences on firms' absorptive capacity. In our study, the industry-specific and heterogeneous information provided by shareholder networks, along with the firm-specific operational and individual information provided by CEO networks, offers firms richer channels for information acquisition. However, information overload may overwhelm decision makers due to their limited cognitive abilities [58], thereby increasing the likelihood of substitution among different information sources. Second, in the process of information exploitation, shareholders and CEOs may experience potential conflicts with directors due to divergent motivations. Shareholders' profit-maximizing incentives across investment portfolios may activate collusion mechanisms that suppress innovation-related investments, thereby diminishing the strategic implementation of board networks. In addition, CEOs' informal power and overconfidence bias may foster path dependency on personally sourced information, leading to the marginalization of information acquired from board networks in decision making.

This study constructs a theoretical analytical framework to explore the influence of board networks on firms' technological innovation output. It further investigates the moderating roles of shareholder networks and CEO networks, with a particular emphasis on their substitutive functions and motivational impacts. Drawing on social network analysis, centrality is widely recognized as the most direct measure of a node's embeddedness within a network [33,35,43,44,59]. Accordingly, this study employs degree centrality to capture firms' embeddedness in three types of interorganizational networks. A systematic investigation of these interaction mechanisms promises to advance the theoretical understanding of the organizational absorptive capacity [60]. The theoretical analytical framework is illustrated in Figure 1.

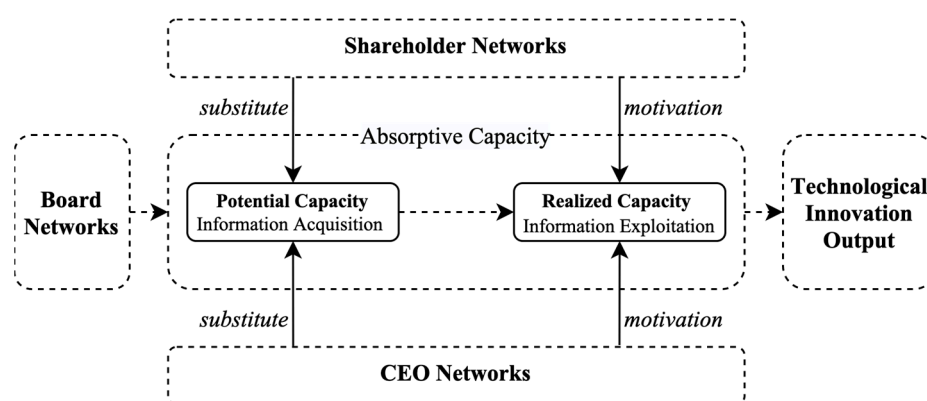


Figure 1. Theoretical analytical framework.

2.1. The Impact of Board Network Centrality on Firms' Technological Innovation Output

According to network theory, actors with high centrality typically possess greater access to and potential control over critical resources [20,61,62]. Centrality within board networks is particularly crucial in technological innovation activities characterized by high levels of uncertainty and information asymmetry [63,64]. Across the two sub-dimensions of

absorptive capacity—potential absorptive capacity and realized absorptive capacity—high centrality within board networks structurally enables firms to (1) achieve privileged acquisition of cutting-edge innovation information and technological insights and (2) effectively exploit the acquired information through the formulation of innovation strategies.

From the perspective of potential absorptive capacity, directors of centrally positioned firms are better equipped to engage in strategic discussions during board meetings. Through their extensive board affiliations, firms can acquire multi-sourced information related to operational environments, industry trends, supply chain dynamics, market conditions, and regulatory factors [1,21]. These help firms optimize decision making regarding technological innovation projects and boost their technological innovation output. Notably, the temporal dimension of innovation information further amplifies these advantages. Given the lengthy process from technology investment to exploration and eventual patent disclosure [65], directors of centrally positioned firms may acquire cutting-edge technological innovation information before it becomes publicly available. Such a timely acquisition of cutting-edge information enables firms to remain aligned with influential technological advancements and seize emerging innovation opportunities [66].

From the perspective of realized absorptive capacity, directors of centrally positioned firms tend to possess higher reputations [62]. As a result, these directors are more likely to diligently fulfill their duties. When exposed to cutting-edge information, conscientious directors, driven by the desire to maintain their reputations and enhance their prospects in the external labor market [67], are more likely to facilitate the effective exploitation of such information, thereby promoting the implementation of technological innovation strategies. Based on the above analysis, this study proposes the following hypothesis:

Hypothesis 1: *Firms with higher board network centrality are more likely to achieve higher levels of technological innovation output.*

2.2. The Moderating Effect of Shareholder Network Centrality

As a representative form of equity-based networks, shareholder networks emerge when shareholders hold equity stakes in multiple firms simultaneously [5]. The centrality of a firm within shareholder networks is positively associated with the number of firms held by its principal shareholders. Although board networks could serve as a source of potential absorptive capacity for firms' technological innovation, their role in information acquisition may be compromised when firms acquire heterogeneous and complex information through alternative channels. First, shareholders can invest in multiple firms with relatively few constraints, which makes the shareholder networks predominantly composed of weak ties. This allows centrally embedded firms within shareholder networks to acquire heterogeneous information from diverse backgrounds and sectors [7]. Such heterogeneous information is crucial for firms' technological innovation development, as it provides novel insights, ideas, and problem-solving approaches [68]. Second, interactions among firms within shareholder networks facilitate the exchange of views on economic conditions and investment experience, which enables firms to acquire information that differs from that acquired through board networks [27,28]. Given the importance of heterogeneous information in fostering technological innovation, firms may increasingly rely on the information advantages offered by shareholder networks.

Additionally, from the perspective of realized absorptive capacity, a firm's centrality within shareholder networks may undermine its exploitation of information derived from board networks. Shareholders with equity stakes in many firms typically maintain diversified investment portfolios [7]. However, the presence of agency problems and self-interested tendencies among these shareholders may expose affiliated firms to the risk of collusion. The collusion motivations refer to the tendency of shareholders to maximize

the returns on their investment portfolio by promoting cooperation among the firms they invest in, thereby reducing competitive tensions and even forming industry-wide interest alliances [69]. Such collective action enhances market bargaining power, diminishes the effectiveness of market-based price mechanisms, and contributes to the generation of monopoly profits [36]. Consequently, shareholders with stakes in many firms may prioritize maximizing portfolio returns over enhancing the value of any single firm [70]. This inclination to balance interests across portfolio firms may lead to underinvestment in innovation at the individual firm level [71]. By intentionally slowing innovation investments to mitigate competition among their portfolio firms, such shareholders may also undermine the exploitation of innovation-related information derived from board networks. In the context of technological innovation, the collusion motivation may reduce firms' sensitivity to innovation investment opportunities, thereby undermining the effective exploitation of information acquired from board networks [72,73]. Based on the above analysis, this study proposes the following hypothesis:

Hypothesis 2: *Higher shareholder network centrality weakens the positive effect of board network centrality on firms' technological innovation output.*

2.3. The Moderating Effect of CEO Network Centrality

CEO network centrality captures a firm's position within CEO networks, typically measured by the extent to which its CEO is connected to other CEOs through shared educational backgrounds or employment histories [33,35]. Similar to, yet distinct from, shareholder networks, CEO networks influence the role of board networks in shaping firms' potential and realized absorptive capacity through information substitution and exploitation motivations. From the perspective of potential absorptive capacity, firms with high CEO network centrality are better positioned to acquire proprietary information, such as idiosyncratic data sets and beliefs regarding future economic activity, from other firms [74]. Innovation-related information is often highly proprietary and exclusive, characterized by limited acquisition channels and high acquisition costs [75]. However, centrally positioned firms can leverage their CEOs' alumni or prior employment relationships to acquire more individualized information and otherwise restricted information. These informal connections may help lower information barriers and facilitate the effective communication of highly proprietary information [32,33,74]. These unique information sources reduce the firms' reliance on board networks for information acquisition.

From the perspective of realized absorptive capacity, a firm's high centrality in CEO networks may enhance the informal power and overconfidence of its CEO, thereby diminishing firms' propensity to exploit information acquired from board networks. Firms with high network centrality typically have CEOs with elevated status, which endows them with greater personal reputational status and informal power [76]. CEOs with greater reputational status and informal power may develop overconfidence in their managerial capabilities due to their extensive experience, which can lead to an overestimation of the value of the information they possess [41]. As a result, CEOs may prefer to rely on their individual and specific information when making innovation-related decisions while neglecting the exploitation of information derived from board networks. Based on the above analysis, this study proposes the following hypothesis:

Hypothesis 3: *Higher CEO network centrality weakens the positive effect of board network centrality on firms' technological innovation output.*

Following a deductive reasoning and grounded in prior theoretical research, this study integrates absorptive capacity theory and stakeholder network theory to develop a series of

hypotheses incorporating moderating effects, thereby decomposing the research problem into a set of empirically verifiable propositions. The hypothesis framework of this study is illustrated in Figure 2.

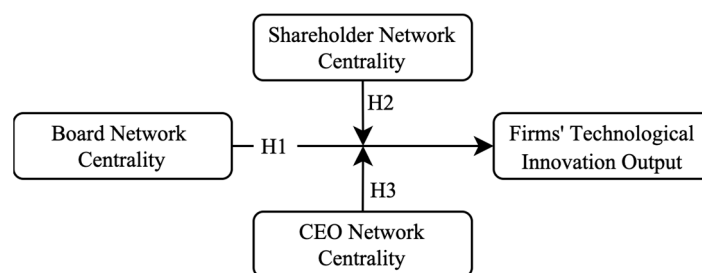


Figure 2. Hypotheses framework.

3. Data and Methodology

3.1. Data

Our empirical analysis is based on Chinese A-share listed firms, excluding firms in the financial sector and under special treatment status (PT/ST/*ST), in order to minimize potential biases arising from regulatory heterogeneity and financial distress [5]. The industry classification in this study adheres to the 2012 China Securities Regulatory Commission (CSRC) industry standards. Specifically, secondary industry codes are applied to manufacturing sectors, whereas primary codes are used for non-manufacturing sectors, thereby ensuring a more granular and consistent sectoral alignment [77]. The data are obtained from the China Stock Market & Accounting Research Database (CSMAR) and Chinese Research Data Services Platform (CNRDS), covering the period from 2005 to 2023. These databases provide comprehensive information on the characteristics of directors, the top ten shareholders and CEOs of listed firms, and patent citation data and corresponding financial indicators. All data processing and analysis are conducted using Python 3.11.9 and STATA 17.

Following the approaches of Chuluun et al. [20], El-Khatib et al. [35], and Liu et al. [7], this study constructs three types of interorganizational networks: board networks, shareholder networks, and CEO networks. Board networks are constructed based on interlocking directors within a three-year moving window. Specifically, the bipartite module of Python's NetworkX package is employed to construct undirected, binary firm–director bipartite networks based on board memberships. Firm–firm board networks are subsequently derived using a one-mode projection approach. Given that information dissemination and the influence of network relations typically persist for three to five years [78], a moving time window approach is commonly adopted in social network research. Therefore, this study employs a three-year moving window to construct board networks for overlapping periods (e.g., 2005–2007, 2006–2008, ..., 2021–2023), which are then matched with financial data from the corresponding years (e.g., 2007, 2008, ..., 2023).

Similarly, the firm–shareholder bipartite networks, constructed using data on each firm's top ten shareholders, are transformed into firm–firm one-mode shareholder networks by applying the same three-year moving window approach. For CEO networks, we directly construct firm–firm one-mode networks based on CEOs' employment histories and educational backgrounds. In CEO networks, firms are represented as nodes, and a tie is established between two firms if their CEOs share a common employment history or educational background prior to a given year.

3.2. Methodology

3.2.1. Variable Definition and Measurement

1. Dependent variable

To reflect firms' technological innovation output, this study employs the number of net forward citations received by invention patent applications as the dependent variable (*Cite*). Patent data are widely used to measure technological innovation owing to their high availability, completeness, and accuracy [1]. Among various patent-based indicators, citation counts are particularly effective in capturing the extent to which a firm's technological innovation output is recognized and utilized as well as reflecting its technological influence and economic value [79]. Consistent with prior studies, a three-year citation window is applied to account for the time lag in patent recognition [80]. To address skewness and mitigate the influence of outliers, the natural logarithm of citation counts plus one is used.

2. Independent variable

Board network centrality (*Bdegree*) refers to the number of listed firms that are directly connected to the focal firm within board networks. A higher *Bdegree* indicates that the directors of the focal firm also serve on the boards of a greater number of other listed firms [20]. Following Freeman [59], this study calculates *Bdegree* as shown in Equation (1).

$$Bdegree_{it} = \sum_{j=1}^n BW^t(i, j) \quad (1)$$

where BW^t denotes the adjacency matrix representing the board network in year t . $BW^t(i, j) = 1$ indicates that firms i and j are connected in the board network in year t ; otherwise, $BW^t(i, j) = 0$.

3. Moderating variables

Shareholder network centrality (*Sdegree*) refers to the number of listed firms that are directly connected to the focal firm within shareholder networks. A higher *Sdegree* indicates that the top ten shareholders of the focal firm also hold the top ten shareholder positions in a greater number of other listed firms [7]. Following Freeman [59], this study calculates *Sdegree* as shown in Equation (2).

$$Sdegree_{it} = \sum_{j=1}^n SW^t(i, j) \quad (2)$$

where SW^t denotes the adjacency matrix representing the shareholder network in year t . $SW^t(i, j) = 1$ indicates that firms i and j are connected in the shareholder network in year t ; otherwise, $SW^t(i, j) = 0$.

CEO network centrality (*Cdegree*) refers to the number of listed firms that are directly connected to the focal firm within CEO networks. A higher *Cdegree* indicates that either the alumni of the focal firm's CEO also hold CEO positions in a greater number of other listed firms, or the focal firm's CEO has previously served as CEO of multiple listed firms [35]. Following Freeman [59], this study calculates *Cdegree* as shown in Equation (3).

$$Cdegree_{it} = \sum_{j=1}^n CW^t(i, j) \quad (3)$$

where CW^t denotes the adjacency matrix representing the CEO network in year t . $CW^t(i, j) = 1$ indicates that firms i and j are connected in the CEO network in year t ; otherwise, $CW^t(i, j) = 0$.

4. Control variables

Firms may differ across a range of characteristics that could influence their technological innovation output; thus, we include the following control variables to mitigate potential confounding effects.

Debt-to-Asset Ratio (Lev). The availability of slack resources plays a critical role in shaping a firm's propensity for change. We employ the debt-to-asset ratio as a proxy for financial slack, where elevated leverage may constrain a firm's capacity to allocate resources toward technological innovation [21].

Return on Assets (ROA). We include ROA as a control variable to capture firm performance, as profitability directly influences a firm's capacity to support technological innovation initiatives [21].

R&D Intensity (RDI). We control for RDI, as it directly affects a firm's capability to process and exploit innovation-related information [1].

State Ownership (SOE). Given the substantial differences in innovation behavior between state-owned and non-state-owned enterprises [81], we include state ownership as a control variable in the analysis.

Firm Size (Size). We control for firm size, as it influences both resource availability and risk-bearing capacity associated with innovation investments [21]. Larger firms generally have more resources but may encounter different innovation challenges compared to smaller firms.

Board Size (Board). The size of the board of directors may influence the breadth of information and expertise available for innovation-related decision making. Therefore, we include board size as a control variable [1].

Proportion of Independent Directors (Indep). Following Sierra-Morán et al. [82], we control for the proportion of independent directors, given their important monitoring role in corporate governance, which may directly influence technological innovation output.

Board Duality (Duality). The concurrent holding of CEO and board chair positions reflects a concentration of executive power [20]. Therefore, we control for CEO duality across all models.

Firm Age (Age). Following Zhang et al. [81], we include firm age as a control variable, recognizing that younger firms may exhibit greater flexibility in technological adoption, whereas older firms may leverage accumulated knowledge to sustain innovation capabilities.

Industry and year fixed effects are also included in all regression models. Detailed definitions and measurement approaches for all variables are presented in Table 1.

Table 1. Description and measurement of variables.

Variable Symbol	Variable Name	Variable Definition and Measurement
Cite	Technological innovation output	The natural logarithm of one plus the number of net forward citations received by invention patent applications.
Bdegree	Board network centrality	The number of listed firms to which the focal firm is directly connected within the board network.
Sdegree	Shareholder network centrality	The number of listed firms to which the focal firm is directly connected within the shareholder network.
Cdegree	CEO network centrality	The number of listed firms to which the focal firm is directly connected within the CEO network.
Lev	Debt-to-asset ratio	The ratio of total liabilities to total assets.
ROA	Return on assets	The ratio of net profit to total assets.
RDI	R&D intensity	The ratio of research and development (R&D) expenditure to total assets.

Table 1. Cont.

Variable Symbol	Variable Name	Variable Definition and Measurement
SOE	State ownership	A dummy variable indicating the nature of the firm's controlling shareholder, coded as 1 if the firm is state-owned and 0 otherwise.
Size	Firm size	The total number of employees, measured in thousands.
Board	Board size	The total number of directors serving on the board.
Indep	Proportion of independent directors	The ratio of independent directors to the total number of board members.
Duality	Board duality	A dummy variable indicating whether the roles of board chairman and CEO are held by the same individual, coded as 1 if the positions are dual-held and 0 otherwise.
Age	Firm age	The natural logarithm of one plus the number of years since the firm's establishment.

3.2.2. Analytical Methods

To account for firm-specific, time-invariant characteristics, this study employs a fixed-effects panel model to examine the impact of board network centrality on firms' technological innovation output and the moderating effects of shareholder network centrality and CEO network centrality. Drawing on the relevant studies by Chang and Wu [1], Chuluun et al. [20], and Xu and Tian [9], this study further addresses potential endogeneity concerns arising from reverse causality by lagging all independent, moderating, and control variables by one period. Following Guan and Yan [82], we standardize the independent and moderating variables using Z-score before generating the interaction terms to mitigate potential multicollinearity. Specifically, the model used to test Hypothesis 1 is presented in Equation (4), while the models for Hypotheses 2 and 3 are shown in Equations (5) and (6), respectively.

$$\text{Cite}_{i,t} = \alpha_t + \beta_0 \text{Bdegree}_{i,t-1} + \gamma \text{Control}_{i,t-1} + \text{Industry}_i + \text{Year}_t + \varepsilon_{i,t} \quad (4)$$

$$\begin{aligned} \text{Cite}_{i,t} = \alpha_t + \beta_0 \text{Bdegree}_{i,t-1} + \beta_1 \text{Sdegree}_{i,t-1} + \beta_2 \text{Bdegree}_{i,t-1} \times \text{Sdegree}_{i,t-1} \\ + \gamma \text{Control}_{i,t-1} + \text{Industry}_i + \text{Year}_t + \varepsilon_{i,t} \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Cite}_{i,t} = \alpha_t + \beta_0 \text{Bdegree}_{i,t-1} + \beta_1 \text{Cdegree}_{i,t-1} + \beta_2 \text{Bdegree}_{i,t-1} \times \text{Cdegree}_{i,t-1} \\ + \gamma \text{Control}_{i,t-1} + \text{Industry}_i + \text{Year}_t + \varepsilon_{i,t} \end{aligned} \quad (6)$$

where $\text{Cite}_{i,t}$ denotes the technological innovation output of firm i in year t . $\text{Bdegree}_{i,t-1}$, $\text{Sdegree}_{i,t-1}$, and $\text{Cdegree}_{i,t-1}$ represent the board network centrality, shareholder network centrality and CEO network centrality of firm i in year $t - 1$, respectively. $\text{Control}_{i,t-1}$ denotes the set of control variables. Industry_i and Year_t represent industry and year dummy variables, respectively. α_t captures firm-specific time-invariant characteristics, and $\varepsilon_{i,t}$ represents the random error term.

In the subsequent robustness tests, since the R&D investment indicator emphasizes financial capital input and potential levels of technological innovation output, we follow Chang and Wu [1] by using R&D expenditure as an alternative proxy for technological innovation output. Additionally, prior research suggests that network relationships may either decay or persist over time. An excessively long time window might obscure interaction dynamics, while an overly short window may overlook significant connections [68]. Therefore, for robustness testing, we alternatively employ a 4-year moving window to construct the networks. Regarding the econometric model, we use the count of net forward citations received by patent applications three years after filing as the dependent variable. To accom-

moderate the large sample size, we employ a random-effects estimation approach, specifically adopting a random-effects negative binomial panel model for robustness checks [83].

4. Results

4.1. Descriptive Statistics and Correlation Analysis

Table 2 reports descriptive statistics for the main variables. The data reveal a significant variation in technological innovation output among Chinese listed firms, with a maximum value of 10.1777, a minimum of 0, and a standard deviation of 1.7553. By applying an exponential transformation, the average net forward citation count of firms' invention patent applications is calculated as $5.5745 (e^{1.8832} - 1)$. This metric highlights the relatively limited recognition and influence of technological innovation output among Chinese listed firms. Board network centrality ranges from 0 to 36, with a mean of 7.2988 (SD = 4.9243). This indicates that while some firms benefit from interlocking directors across multiple firms, others occupy periphery positions within board networks or remain entirely isolated. Shareholder network centrality exhibits even greater dispersion, with a maximum value of 1668, a minimum of 0, and a mean of 368.3559 (SD = 425.8610). This reflects both a high volume of and substantial variation in equity-based connections. The descriptive statistics for CEO network centrality show a maximum value of 310, a minimum of 0, and a mean of 9.6942 (SD = 26.4203), indicating the generally sparse nature of the CEO networks.

Table 2. Descriptive statistics.

Variable	N	Mean	Std. Dev.	Min	Median	Max
Cite	21,117	1.8832	1.7553	0.0000	1.6094	10.1777
Bdegree	21,117	7.2988	4.9243	0.0000	7.0000	36.0000
Sdegree	21,117	368.3559	425.8610	0.0000	179.0000	1668.0000
Cdegree	21,117	9.6942	26.4203	0.0000	0.0000	310.0000
Lev	21,117	0.3959	0.1992	0.0506	0.3848	0.8997
ROA	21,117	0.0444	0.0569	−0.2585	0.0420	0.2087
RDI	21,117	0.0222	0.0213	0.0000	0.0184	0.5818
SOE	21,117	0.3040	0.4600	0.0000	0.0000	1.0000
Size	21,117	4.7500	9.0156	0.0900	1.9250	63.1740
Board	21,117	8.5758	1.6743	3.0000	9.0000	18.0000
Duality	21,117	0.3043	0.4601	0.0000	0.0000	1.0000
Indep	21,117	0.3740	0.0527	0.3077	0.3333	0.5714
Age	21,117	2.7761	0.3845	0.0000	2.8332	3.9703

Table 3 presents the correlation matrix of the main variables used in this study. As shown in Table 3, all correlation coefficients are below the commonly accepted threshold of 0.8. Furthermore, the results of the multicollinearity test based on the variance inflation factor (VIF) indicate that all VIF values are below the conventional threshold of 10, with a mean VIF of 1.25. Therefore, the regression models employed in this study are not subject to multicollinearity concerns. In the bivariate correlations, the coefficients show that board network centrality and shareholder network centrality are positively associated with firms' technological innovation output, whereas CEO network centrality and firms' technological innovation output are negatively correlated.

Table 3. Correlation analysis.

Variable	Cite	Bdegree	Sdegree	Cdegree	Lev	ROA	RDI	SOE	Size	Board	Duality	Indep	Age
Cite	1												
Bdegree	0.124 ***	1											
Sdegree	0.136 ***	0.251 ***	1										
Cdegree	−0.013 **	0.069 ***	0.079 ***	1									
Lev	0.052 ***	0.138 ***	0.110 ***	−0.016 ***	1								
ROA	0.044 ***	−0.072 ***	0.023 ***	−0.049 ***	−0.377 ***	1							
RDI	0.114 ***	−0.038 ***	−0.038 ***	0.074 ***	−0.191 ***	0.138 ***	1						
SOE	0.069 ***	0.115 ***	0.181 ***	−0.105 ***	0.299 ***	−0.098 ***	−0.163 ***	1					
Size	0.324 ***	0.148 ***	0.304 ***	0.015 ***	0.252 ***	0.020 ***	−0.081 ***	0.223 ***	1				
Board	0.102 ***	0.158 ***	0.092 ***	−0.069 ***	0.162 ***	0.013 ***	−0.092 ***	0.290 ***	0.183 ***	1			
Duality	−0.003	−0.066 ***	−0.092 ***	0.080 ***	−0.162 ***	0.057 ***	0.107 ***	−0.310 ***	−0.075 ***	−0.183 ***	1		
Indep	0.009 *	−0.001	0.036 ***	0.038 ***	−0.014 ***	−0.028 ***	0.024 ***	−0.069 ***	0.070 ***	−0.470 ***	0.112 ***	1	
Age	−0.119 ***	0.186 ***	0.207 ***	0.069 ***	0.151 ***	−0.133 ***	−0.067 ***	0.098 ***	−0.001	−0.019 ***	−0.068 ***	0.005	1

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.2. Baseline Regression

Based on the fixed-effects panel regression model, the regression results of this study are presented in Table 4. Model 1 includes only the control variables, Model 2 incorporates board network centrality as the independent variable, Models 3 and 4 introduce shareholder network centrality and CEO network centrality as moderating variables, respectively, and Model 5 includes all variables. The results of Model 2 show that board network centrality is significantly and positively associated with firms' technological innovation output ($\beta_0 = 0.012$, $p < 0.01$), supporting Hypothesis 1. Holding all other factors constant, a one-unit increase in board network centrality leads to an approximately 1.2% increase in technological innovation output. This finding corroborates the crucial role of board networks in facilitating the acquisition and exploitation of information [1,20,21]. Specifically, board networks serve as channels for cutting-edge information acquisition. Moreover, directors of centrally positioned firms are incentivized by reputational concerns to diligently exploit innovation-related information in the implementation of innovation strategies, thereby enhancing firms' technological innovation output.

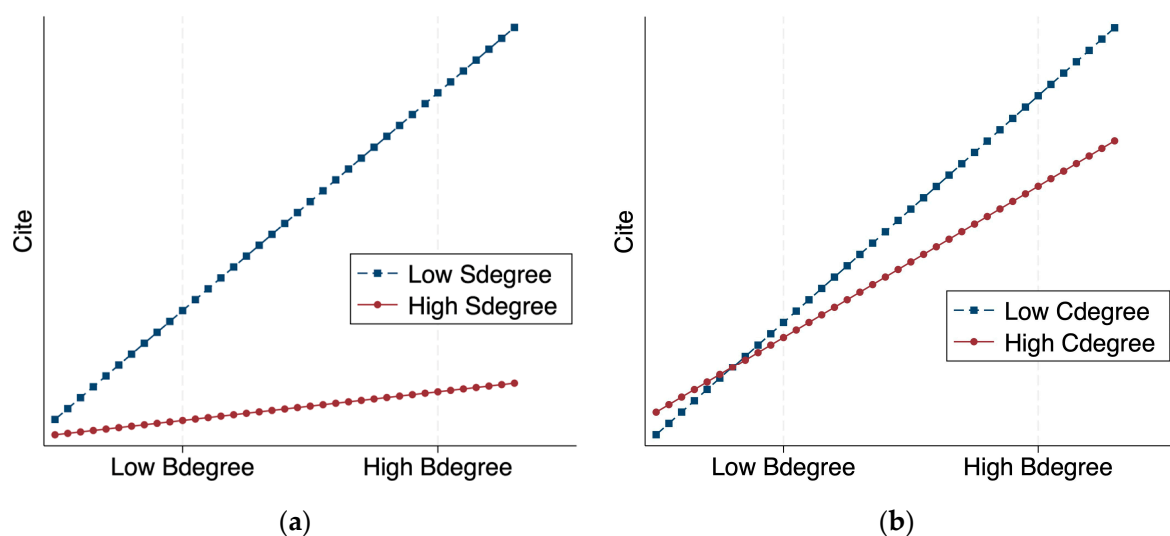
The results of Model 3 reveal that shareholder network centrality negatively moderates the positive effect of board network centrality ($\beta_2 = -0.0508$, $p < 0.01$), supporting Hypothesis 2. This finding aligns with prior research, which suggests that shareholder networks—predominantly composed of weak ties—provide heterogeneous and diverse information at high centrality levels [7], thereby substituting for the information acquired through board networks. Additionally, the collusion motivation associated with highly central shareholders may lead to the neglect of information acquired through board networks, thereby weakening the relationship between board network centrality and firms' technological innovation output. Model 4 demonstrates that CEO network centrality negatively moderates the positive effect of board network centrality ($\beta_2 = -0.0266$, $p < 0.05$), supporting Hypothesis 3. This implies that the individualized information available to CEOs reduces firms' reliance on information acquired through board networks. Moreover, high CEO network centrality may lead to greater reputational power and overconfidence, prompting CEOs to prioritize information acquired from CEO networks, further diminishing the exploitation of information acquired from board networks. Model 5, which incorporates all variables, provides further support for the three hypotheses.

To further illustrate the moderating effects of shareholder network centrality and CEO network centrality, Figure 3 depicts the relationship between board network centrality (Bdegree) and firms' technological innovation output (Cite) at mean and high levels (mean plus one standard deviation) of the moderators Sdegree and Cdegree, respectively. In Figure 3a,b, the horizontal axis represents board network centrality, while the vertical axis represents the technological innovation output. As shown, the positive relationship between Bdegree and Cite weakens when Sdegree and Cdegree are at higher levels, indicating negative moderating effects of Sdegree and Cdegree.

Table 4. Baseline regression results for the impact of board networks.

	Model 1	Model 2	Model 3	Model 4	Model 5
Bdegree		0.0120 *** (0.0024)	0.0117 *** (0.0024)	0.0116 *** (0.0024)	0.0114 *** (0.0024)
Sdegree			−0.0002 *** (0.0000)		−0.0002 *** (0.0000)
Bdegree × Sdegree			−0.0508 *** (0.0124)		−0.0491 *** (0.0124)
Cdegree				−0.0002 (0.0004)	−0.0002 (0.0004)
Bdegree × Cdegree				−0.0266 ** (0.0126)	−0.0216 * (0.0126)
Lev	0.2491 *** (0.0781)	0.2312 *** (0.0781)	0.2206 *** (0.0780)	0.2297 *** (0.0781)	0.2198 *** (0.0780)
ROA	1.0575 *** (0.1695)	1.0663 *** (0.1694)	1.1060 *** (0.1692)	1.0594 *** (0.1698)	1.0984 *** (0.1696)
RDI	1.4192 ** (0.6586)	1.4552 ** (0.6582)	1.5685 ** (0.6573)	1.4855 ** (0.6582)	1.5936 ** (0.6574)
SOE	0.0660 (0.0735)	0.0567 (0.0735)	0.0651 (0.0734)	0.0606 (0.0735)	0.0682 (0.0734)
Size	0.0196 *** (0.0026)	0.0192 *** (0.0026)	0.0209 *** (0.0026)	0.0196 *** (0.0026)	0.0213 *** (0.0026)
Board	0.0401 *** (0.0098)	0.0371 *** (0.0098)	0.0368 *** (0.0098)	0.0370 *** (0.0098)	0.0367 *** (0.0098)
Duality	0.0831 *** (0.0260)	0.0849 *** (0.0260)	0.0881 *** (0.0259)	0.0858 *** (0.0260)	0.0888 *** (0.0259)
Indep	0.2849 (0.2573)	0.2501 (0.2572)	0.2881 (0.2569)	0.2463 (0.2572)	0.2848 (0.2569)
Age	0.2708 *** (0.0920)	0.2553 *** (0.0920)	0.2642 *** (0.0922)	0.2524 *** (0.0920)	0.2628 *** (0.0922)
Firm	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	21,117	21,117	21,117	21,117	21,117
adj. R ²	0.700	0.701	0.702	0.701	0.702

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

**Figure 3.** The moderating effects of Sdegree and Cdegree.

4.3. Robustness Tests

4.3.1. Alternative Measure of Dependent Variable

Following Chang and Wu [1], this study replaces the measure of firms' technological innovation output with the natural logarithm of R&D expenditure plus one to capture potential technological innovation output. The regression results are reported in Table 5. As shown in Model 2, board network centrality is positively associated with the R&D expenditure ($\beta_0 = 0.0027$, $p < 0.05$). Models 3 and 4 reveal that shareholder network centrality ($\beta_2 = -0.0349$, $p < 0.01$) and CEO network centrality ($\beta_2 = -0.0149$, $p < 0.05$) continue to negatively moderate this relationship, providing further support for the robustness of the main findings.

Table 5. Robustness test using an alternative measure of the dependent variable.

	Model 1	Model 2	Model 3	Model 4	Model 5
Bdegree		0.0027 ** (0.0013)	0.0026 * (0.0013)	0.0025 * (0.0013)	0.0025 * (0.0013)
Sdegree			−0.0000 ** (0.0000)		−0.0000 ** (0.0000)
Bdegree × Sdegree			−0.0349 *** (0.0070)		−0.0340 *** (0.0070)
Cdegree				0.0007 *** (0.0002)	0.0006 ** (0.0002)
Bdegree × Cdegree				−0.0149 ** (0.0070)	−0.0119 * (0.0071)
Lev	0.4363 *** (0.0445)	0.4322 *** (0.0445)	0.4236 *** (0.0445)	0.4320 *** (0.0445)	0.4236 *** (0.0445)
ROA	1.7646 *** (0.0957)	1.7671 *** (0.0957)	1.7787 *** (0.0957)	1.7837 *** (0.0959)	1.7948 *** (0.0959)
RDI	11.9666 *** (0.4076)	11.9765 *** (0.4076)	12.0175 *** (0.4074)	11.9898 *** (0.4076)	12.0274 *** (0.4074)
SOE	0.0288 (0.0422)	0.0265 (0.0422)	0.0302 (0.0421)	0.0290 (0.0422)	0.0323 (0.0421)
Size	0.0419 *** (0.0015)	0.0418 *** (0.0015)	0.0425 *** (0.0015)	0.0418 *** (0.0015)	0.0424 *** (0.0015)
Board	0.0371 *** (0.0056)	0.0365 *** (0.0056)	0.0362 *** (0.0056)	0.0363 *** (0.0056)	0.0360 *** (0.0056)
Duality	0.0249 * (0.0146)	0.0253 * (0.0146)	0.0268 * (0.0146)	0.0248 * (0.0146)	0.0261 * (0.0146)
Independent	0.0778 (0.1461)	0.0697 (0.1462)	0.0742 (0.1461)	0.0719 (0.1461)	0.0767 (0.1461)
Age	−0.0101 (0.0535)	−0.0132 (0.0535)	−0.0217 (0.0537)	−0.0166 (0.0535)	−0.0243 (0.0537)
Firm	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	20,512	20,512	20,512	20,512	20,512
adj. R ²	0.866	0.866	0.866	0.866	0.866

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.3.2. Robustness Test Using Four-Year Moving Window

Prior research indicates that the influence of network relationships can persist for three to five years [78]. Accordingly, this study reconstructs board networks and shareholder networks based on a four-year moving window. Table 6 reports the results of this robustness test. Board network centrality remains positively associated with firms' technological innovation output under the four-year moving window ($\beta_0 = 0.0108$, $p < 0.01$), while

shareholder network centrality ($\beta_2 = -0.0731$, $p < 0.01$) and CEO network centrality ($\beta_2 = -0.0356$, $p < 0.01$) continue to weaken this effect. These findings provide additional support for the robustness of this study's conclusions.

Table 6. Robustness test using a four-year moving window.

	Model 1	Model 2	Model 3	Model 4	Model 5
Bdegree		0.0108 *** (0.0022)	0.0113 *** (0.0022)	0.0104 *** (0.0022)	0.0110 *** (0.0022)
Sdegree			−0.0001 *** (0.0000)		−0.0001 *** (0.0000)
Bdgree × Sdgree			−0.0731 *** (0.0126)		−0.0708 *** (0.0127)
Cdegree				−0.0001 (0.0005)	−0.0001 (0.0005)
Bdgree × Cdegree				−0.0356 *** (0.0128)	−0.0288 *** (0.0128)
Lev	0.2491 *** (0.0781)	0.2285 *** (0.0781)	0.2059 *** (0.0782)	0.2259 *** (0.0781)	0.2046 *** (0.0782)
ROA	1.0575 *** (0.1695)	1.0686 *** (0.1694)	1.1038 *** (0.1692)	1.0632 *** (0.1698)	1.0969 *** (0.1696)
RDI	1.4192 ** (0.6586)	1.4307 ** (0.6581)	1.5158 ** (0.6573)	1.4701 ** (0.6582)	1.5485 ** (0.6574)
SOE	0.0660 (0.0735)	0.0582 (0.0735)	0.0637 (0.0734)	0.0628 (0.0735)	0.0674 (0.0734)
Size	0.0196 *** (0.0026)	0.0191 *** (0.0026)	0.0211 *** (0.0026)	0.0197 *** (0.0026)	0.0215 *** (0.0026)
Board	0.0401 *** (0.0098)	0.0380 *** (0.0098)	0.0371 *** (0.0098)	0.0377 *** (0.0098)	0.0369 *** (0.0098)
Duality	0.0831 *** (0.0260)	0.0857 *** (0.0260)	0.0884 *** (0.0259)	0.0869 *** (0.0260)	0.0894 *** (0.0259)
Independent	0.2849 (0.2573)	0.2540 (0.2572)	0.2694 (0.2569)	0.2501 (0.2572)	0.2663 (0.2569)
Age	0.2708 *** (0.0920)	0.2487 *** (0.0920)	0.2369 ** (0.0925)	0.2442 *** (0.0921)	0.2348 ** (0.0925)
Firm	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	21,117	21,117	21,117	21,117	21,117
adj. R ²	0.700	0.701	0.702	0.701	0.702

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.3.3. Negative Binomial Panel Model with Random Effects

Using the number of net forward citations received by firms' invention patent applications as the dependent variable, this study conducts a robustness test based on a negative binomial panel model. Sierra-Morán et al. [83] argue that random-effects estimation is more efficient than fixed-effects estimation in negative binomial panel models when the sample size is large. Accordingly, a negative binomial panel model with random-effects is adopted to account for the count nature of the dependent variable and potential over-dispersion. As shown in Table 7, the main findings remain consistent, providing additional support for the robustness of the results.

Table 7. Robustness test using a negative binomial panel model with random effects.

	Model 1	Model 2	Model 3	Model 4	Model 5
Bdegree		0.0113 *** (0.0018)	0.0109 *** (0.0018)	0.0107 *** (0.0019)	0.0105 *** (0.0019)
Sdegree			0.0001 *** (0.0000)		0.0001 *** (0.0000)
Bdegree × Sdegree			−0.0557 *** (0.0101)		−0.0545 *** (0.0101)
Cdegree				0.0005 (0.0004)	0.0004 (0.0004)
Bdegree × Cdegree				−0.0261 ** (0.0117)	−0.0225 * (0.0118)
Lev	0.4063 *** (0.0583)	0.3883 *** (0.0584)	0.3775 *** (0.0583)	0.3891 *** (0.0584)	0.3781 *** (0.0583)
ROA	2.3999 *** (0.1725)	2.3987 *** (0.1721)	2.3866 *** (0.1717)	2.4056 *** (0.1723)	2.3910 *** (0.1719)
RDI	5.6947 *** (0.3363)	5.6944 *** (0.3372)	5.7005 *** (0.3383)	5.7258 *** (0.3374)	5.7266 *** (0.3385)
SOE	0.2515 *** (0.0281)	0.2488 *** (0.0280)	0.2345 *** (0.0283)	0.2495 *** (0.0280)	0.2351 *** (0.0283)
Size	0.0255 *** (0.0010)	0.0248 *** (0.0010)	0.0249 *** (0.0011)	0.0248 *** (0.0011)	0.0249 *** (0.0011)
Board	0.0438 *** (0.0065)	0.0397 *** (0.0065)	0.0392 *** (0.0065)	0.0397 *** (0.0065)	0.0393 *** (0.0065)
Duality	0.0414 ** (0.0211)	0.0447 ** (0.0210)	0.0471 ** (0.0210)	0.0437 ** (0.0210)	0.0463 ** (0.0210)
Independent	0.2249 (0.1902)	0.1959 (0.1900)	0.1761 (0.1899)	0.1882 (0.1901)	0.1703 (0.1900)
Age	−0.0138 (0.0338)	−0.0220 (0.0338)	−0.0325 (0.0338)	−0.0217 (0.0338)	−0.0321 (0.0338)
_cons	−2.2553 *** (0.1900)	−2.2082 *** (0.1896)	−2.1604 *** (0.1896)	−2.2016 *** (0.1897)	−2.1557 *** (0.1897)
Firm	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	21,401	21,401	21,401	21,401	21,401

Note: Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5. Discussion

Drawing on absorptive capacity theory and employing social network analysis, this study investigates how board networks influence firms' technological innovation output, with an emphasis on the moderating roles of shareholder networks and CEO networks. Utilizing longitudinal data on Chinese A-share listed companies from 2005 to 2023 and applying fixed-effects panel models, our findings are as follows: First, firms' degree centrality within board networks (Bdegree) exerts a significant positive influence on technological innovation output (Cite). Holding other variables constant, a one-unit increase in Bdegree is associated with a 0.0120 increase in Cite. Second, this positive influence is weakened by firms' degree centrality within both shareholder networks (Sdegree) and CEO networks (Cdegree). Specifically, when Sdegree is low (at the mean level), a one-unit increase in Bdegree corresponds to a 0.0117 increase in Cite, controlling for other variables. By contrast, when Sdegree is high (one standard deviation above the mean), the corresponding increase in Cite declines to 0.0015. Similarly, when Cdegree is low (at the mean level), a one-unit increase in Bdegree leads to a 0.0116 increase in Cite, whereas at high levels of Cdegree

(one standard deviation above the mean), this increment decreases to 0.0106, controlling for other variables.

5.1. Theoretical Implications

As previously emphasized, information plays a crucial role in facilitating firms' technological innovation output. However, the mechanisms by which extensively studied board networks exert their roles in information absorption and drive firms' technological innovation output remain unclear. Drawing on absorptive capacity theory and social network analysis, we argue that the roles of board networks should be examined from a process perspective that distinguishes between different processes of information absorption [25]. As revealed by Hypothesis 1, consistent with our expectations, board network centrality positively impacts firms' technological innovation output through their roles in both the potential and realized processes of absorptive capacity. Our findings contribute to the growing literature on board networks and technological innovation [1,4,20,21] by emphasizing how board networks facilitate the acquisition and exploitation of information that supports technological innovation.

Our findings on the moderated hypotheses indicate that both shareholder networks and CEO networks shape the information absorption processes facilitated by board networks. A growing body of research has examined the role of interorganizational networks in facilitating information absorption [9,84,85]. Building on stakeholder network theory [24], this study focused on the integration of board networks, shareholder networks, and CEO networks. We theoretically and empirically elucidate the mechanisms underlying the moderating effects of shareholder networks and CEO networks. The findings suggest that shareholder networks and CEO networks exert substitution effects in the process of information acquisition. More importantly, consistent with the stakeholder network theory, our research highlights that central network positions of shareholder networks and CEO networks may generate conflicting motivations, thereby weakening the exploitation of information acquired from board networks. These findings align with Xu and Tian's [9] study, which demonstrated that different interorganizational networks interactively influence the development of organizational absorptive capacity.

Consistent with Hypothesis 2 and our theoretical predictions, the centrality of shareholder networks negatively moderates the positive relationship between board network centrality and firms' technological innovation output. Previous research indicates that board networks and shareholder networks are often intertwined, and phenomena initially attributed to board networks may, in fact, reflect the influence of shareholder networks [47]. Against this backdrop, Liu et al. [7] examined the interplay between board networks and shareholder networks, highlighting the synergistic effects of their interaction. By contrast, our study investigates how the substitutive effects and collusive motivations associated with shareholder networks operate within the mechanisms of potential and realized absorptive capacity processes. These findings align with prior research emphasizing the role of shareholder networks in providing heterogeneous information through weak ties and in maximizing portfolio value through principal shareholder collusion [5,27,30,36,70].

In line with Hypothesis 3 and our theoretical expectations, CEO network centrality negatively moderates the positive relationship between board network centrality and firms' technological innovation output. As key strategic leaders, directors and CEOs play a pivotal role in shaping organizational resource allocation, strategic decision making, and their execution [23,86]. In the context of technological innovation, many studies have explored how CEO tenure and age impact their risk preferences and capacity to process information, ultimately affecting firms' technological innovation output [87,88]. Our findings align with this perspective, revealing that CEO network centrality influences

CEOs' level of overconfidence, which may lead to neglecting the exploitation of information acquired from board networks. Furthermore, the information acquisition facilitated by CEO networks supports prior arguments that CEOs' external individual connections promote interorganizational information exchange [89].

In summary, building on the suggestion of Schiehl et al. [45] and Shui et al. [26], who emphasized that the roles of directors, shareholders, and CEOs in firms' technological innovation should be regarded as an integrated governance mechanism, our study advances this line of inquiry by disentangling and decoupling the respective networks of these three critical stakeholders. This approach not only responds to the call to "bring the owners back in" when examining director interlocks [7,47] but also offers a comprehensive framework for understanding the full spectrum of interorganizational information acquisition and exploitation dynamics.

5.2. Practical Implications

Our findings offer two valuable managerial implications for how firms can configure their board networks and leverage absorptive capacity to enhance technological innovation output. First, since interlocking directors serve as crucial "pipes" for information transfer and practice diffusion [90], we suggest that firms appoint interlocking directors who hold positions in multiple firms, particularly those with specialized expertise in relevant technological fields [17]. However, when firms occupy central positions in shareholder networks or CEO networks, they should carefully account for shareholders' and CEOs' potentially adverse motivation affecting information exploitation acquired from board networks. To mitigate shareholders' potential collusion motivation, firms could implement stronger external monitoring mechanisms, such as increasing the proportion of independent directors or attracting greater analyst coverage [69]. Given that overconfident CEOs may discount valuable information acquired from board networks, firms can enhance the board's power relative to the CEO by strengthening board expertise, thereby improving both monitoring effectiveness and advisory quality [91].

Second, building on prior research, we distinguish absorptive capacity into two processes: potential absorptive capacity and realized absorptive capacity [25]. On one hand, to enhance potential absorptive capacity, firms should acquire information from diverse external sources while cultivating organizational learning capabilities. For example, firms can engage in passive learning by obtaining explicit technological and managerial information from technical forums and management consulting firms. Alternatively, firms can adopt more proactive learning approaches such as benchmarking, competitive intelligence analysis, and academic collaboration, which offer forward-looking and differentiated information [92]. However, high potential absorptive capacity does not necessarily translate into improved technological innovation output. On the other hand, firms also need to enhance their realized absorptive capacity by integrating externally acquired information into their operations. Effective information exploitation requires both information sharing and mutual understanding among internal organizational members. To achieve this, firms could implement both formal and informal social integration mechanisms within the organization [93]. Formal mechanisms may include appointing coordinators across departments, while informal mechanisms may involve constructing social networks through communities of practice and collaborative workspaces that encourage spontaneous interactions.

5.3. Limitations and Future Research Agenda

Our study is not without limitations, which also present opportunities for future research. First, although we use patent data as a proxy for technological innovation output, some firms may opt not to patent their innovations due to strategic secrecy, cost

concerns, or other reasons [75]. Consequently, their technological innovation output may be underestimated under the current measurement approach. Future research could address this issue by incorporating textual analysis of innovation-related disclosures. As information disclosure practices continue to improve, firms increasingly report detailed descriptions of their innovation activities in annual reports, announcements, and other documents. By employing textual analysis techniques, researchers can extract information on innovation strategies, project progress, and application outcomes, thereby developing a more comprehensive and accurate measurement of firms' technological innovation output.

Second, while this study primarily examines the moderating effects of shareholder networks and CEO networks on how board networks leverage absorptive capacity to influence firms' technological innovation, future research could explore additional stakeholder networks. Investigating diverse information sources and the motivations of stakeholders embedded in different networks may shed light on how other interorganizational networks shape firms' technological innovation processes.

Third, as Volberda et al. [94] argue, absorptive capacity is a multi-level construct that can be studied at the individual, unit, organization, and interorganizational levels. Accordingly, future studies could examine the influence of multilayer network positions—such as those of R&D personnel or alliance partners—on firms' technological innovation output. In addition, given that networks are inherently dynamic [8,95], future research could also examine how changes in various stakeholder networks—such as directors' turnover—affect firms' technological innovation.

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