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Board Interlock Networks and Corporate Low-Carbon Innovation in China: Does Position Matter?

Li Xia, Shuo Gao, Qianwen Shao, Jiuchang Wei, and Zhi Li

***Abstract*—Through combining the resource dependence theory and social network theory, this study sheds light on how two major kinds of interlocking network positions—central network position and structural holes position—drive corporate low-carbon innovation. We consider the mediating effect of information asymmetry and knowledge absorptive capacity to reap benefits from occupying the two advantageous network positions. We have empirically investigated a sample of 3365 listed firms over the period of 2009–2018 drawn from China, the largest emerging market economy as well as the biggest carbon dioxide emitter. Our main results show that either holding a central network position or spanning a structural holes position plays a significant role in stimulating low-carbon technologies, and the promotion effect can be partially channeled through downward information asymmetry and upward knowledge absorptive capacity. Our findings differ from earlier work because of our emphasis on network position, and our specific focus on corporate low-carbon innovation and China's unique setting, rather than network size, greenhouse gas emissions, and developed economies. This study also provides significant implications for executives striving to improve firms' low-carbon innovation performance, and for policymakers seeking ways to fulfill the mission of carbon dioxide abatement.**

***Index Terms*—Centrality, corporate environmental performance, low-carbon innovation, network position, structure hole.**

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Nomenclature

Abbreviations and Acronyms

LCI	Low-carbon innovation.
ASY	Information asymmetry.
KAC	Knowledge absorptive capacity.
R&D	Research and development.

I. Introduction

Since the mid-20th century, climate change has been widely recognized as a growing threat to society and the economy, owing largely to the surging greenhouse gases from human activities. As an effective response to climate challenges under ever-increasing environmental pressures, LCI has been in the spotlight for decades, primarily for its great potential to achieve carbon abatement and gain competitive advantages for firms. In comparison with conventional innovation, LCI is featured by a so-called double externality issue, that is, technological spillover at the R&D stage and ecological spillover at the implementation and diffusion stage [1]; thus, economic subjects (e.g., firms) will find it almost impossible to fully internalize the additional cost of developing LCI, thereby hurting the incentives for their adoption of LCI [2]. Besides, innovating low-carbon technologies necessitates higher capacities for acquiring and recombining external resources, particularly for information and knowledge [1], which further restrains firms from investing in LCI. However, it can be easily observed in the marketplace that a fraction of firms are with outstanding patenting records of LCI, leading a question to arise as to why and how these firms outperform others in the area of low-carbon technologies.

As for this question, previous studies in the field of environmental innovation management have investigated a series of antecedents of environmentally friendly innovation from the perspective of corporate boards, such as the educational diversity of board members [3], given the advisory and monitoring role of boards of directors. While recent subsequent studies turn to shift their attention to the resource-managing role, which considerably manifests in the aspect of board interlock networks, that board social capital plays in managing dependencies of external information and knowledge resources [4], [5]. A board interlock network emerges when more than one board member of a firm holds the membership of the other firms' boards at the same time [6], which reveals an interfirm relationship between focal firms and partnering firms. Despite some previous studies that have explored the association between board interlocks and general innovation behaviors, such as investment efficiency [7], conventional innovation [8], and general R&D expenditure [9], it still remains unclear about the influence of board interlock networks on environmental innovation behaviors like LCI. To bridge the knowledge gap, several prior studies have explored the effect of the network size of board interlocks on corporate environmental behaviors [5], [10], however, to a large extent, another important property of board interlock networks—network position—has been neglected. Indeed, there are several studies that have stressed the value of network positions to new product introduction [11], organization innovative capabilities [12], and new product development [13], whereas there is little empirical evidence on if and how specific positions embedded within board interlock networks affect LCI.

Besides, there is an apparent paucity of empirical investigations on the association between board interlocks and firm-level LCI within the context of emerging market settings, given that most of the closely relevant studies situated their investigations in the context of firms from such developed economies as the United States [5]. However, firms operating in emerging economies are more in demand of external knowledge resources and complete information to support their survival and sustainable growth [14], [15]. It has been pointed out that China's unique setting might hinder firms without board social capital from identifying and accessing symmetric information and absorbing knowledge for at least two reasons. First, China is famous for its strong *guanxi* society [15], [16], and there is an old saying that reflects the great value of *guanxi* networks rooted in the Chinese mindset, "it is not what you know, but who you know that matters." It thus triggers the formation and prevalence of interlocking directorship in China's marketplace and stresses the necessity of cultivating board social capital through sharing board membership. Second, China is featured by the incomplete capital market, unstable market regulations, and constantly shifting political landscape [7], [16], particularly for those close to environmental-friendly development, suggesting the need for firms to inherently search for additional information and knowledge advantages to offset their additional cost of developing low-carbon technologies. In this sense, innovation failure for low-carbon technologies can be less tolerated by most Chinese firms and largely attributed to the incomplete information environment, referred to as ASY, and the insufficient capacity to absorb external knowledge, that is, KAC. In fact, as a quintessential emerging economy, China is faced with the dilemma between pursuing economic growth and the urgency of environmental problems [17], [18], [19], given the truth that China became the world's largest carbon dioxide emitter in 2004 and the world's second-largest economy in 2011.

As noted earlier, board social capital embedded within board interlock networks is responsible for managing information and knowledge constraints. Specifically, alliance network position is likely to determine information diversity and knowledge acquisition [20], and cultivating board interlock network has been adopted as a useful tool to ensure and enrich firms' knowledge resources [4]. In fact, it can be noticed that firms devoted to LCI suffer from two major managerial issues, that is, the asymmetric information environment [21] and the incompetence to absorb acquired knowledge [1], [14]. Notably, external knowledge acquisition is insufficient *per se* to ensure the success of LCI, meaning that there is a must for external knowledge to be smoothly integrated into the trial-and-error learning so as to facilitate the development process of LCI [14]. Considering specific network positions that mirror the discrepancies of established board social capital [22] as well as China's institutional setting, it seems intuitive to take into account ASY and KAC as potential mediators in the relationship between board network positions and LCI to further examine latent mechanisms by which occupying such focal network positions drive firm-level LCI. Surprisingly, in the extant literature, the effect of board interlock networks on LCI has mostly been directly explored while the factor of KAC has only been studied occasionally. The few studies that cover such a factor normally treated KAC as a boundary condition while ignored the role of ASY.

To fill in these lacunas in the literature, this study begins with theorizing and hypothesizing the relationship between interlocking network positions and LCI by drawing on the combination of resource dependence theory and social network theory. Next, we empirically identify the relationship using a sample of 3365 firms for the years 2009 to 2018 drawn from China, the largest emerging economy as well as the biggest carbon dioxide emitter. We find that firms either occupying central network positions or bridging structural holes positions tend to innovate more low-carbon technologies. Furthermore, we study ASY and KAC as two potential latent mechanisms by which both advantageous network positions could potentially affect a firm's output of LCI. We examine if the effect of both types of network position on LCI could be channeled or explained by added information and knowledge advantages, that is, by the decrease in the degree of information asymmetry and by the increase in the capacity for absorbing external knowledge. Our results imply that these are indeed the mechanisms.

In the literature, there are in fact several studies closest to our research including papers, [5], [10], [21], [23]. Table I provides the comparisons between our study and theirs. Specifically, these prior studies predominantly cast light on how the network size of board interlocks (i.e., the number of interlocking ties with other firms) impacts corporate environmental performance, for example, firm-level greenhouse gases [5], [23]. Instead of calculating the quantity of sharing board members, we extend their works by taking one step forward in investigating the causal effect of interlocking network positions on the firm-level output of low-carbon technologies. Besides, in contrast to introducing absorptive capacity as a moderator [10], we turn to conceptualize that it has the potential to play a mediational role and this is the case as mentioned before. Lastly, unlike those drawn on the sample from developed countries like the U.S. [10], [23], the current study is situated in the research context of China with the aim to provide more fruitful evidence on the consequences of cultivating board social capital and meanwhile the drivers of adoption of corporate environmental actions such as innovating low-carbon technologies.

This study is of great significance in several ways. First, by fusing insights from resource dependence theory and social network theory, we contribute to a growing body of general literature on board social capital and corporate environmental behaviors by demonstrating the top-down effect of board interlock networks on LCI, an issue that has been so far neglected in the literature. By doing so, we contribute to the ongoing discussion on the question of why some firms have the superior performance of LCI to others from a relatively novel perspective

TABLE I
COMPARISONS BETWEEN OUR STUDY AND OTHER CLOSELY RELATED STUDIES

Studies	Network position	Network size	Emerging economy	Information asymmetry	Knowledge absorptive capability	Dependent variable
[23]	×	√	×	×	×	Greenhouse gas emissions
[5]	×	√	×	×	×	Greenhouse gas emissions
[10]	×	√	×	×	√	Environmental performance scores
[21]	×	√	√	×	√	Environmental performance scores
Our study	√	×	√	√	√	Corporate low-carbon innovation

Note: × refers to "not considered", √ refers to "considered".

of network position. Second, to our knowledge, we are the first to introduce ASY and KAC as two potential mediators in the relationship between interlocking network positions and LCI. Our findings imply that advantageous network positions can turn into improved LCI performance through downward ASY and upward KAC, which helps to further explain why some firms are of competitiveness in the field of low-carbon technologies and others are not. Third, this study contributes to the area of LCI by addressing recent calls for more attention to both the antecedents of LCI [24] and the influence of board interlocks on multifaceted aspects of firm performance [25]. Finally, this study investigates the association between board interlocks and LCI in the research setting of China, a quintessential emerging economy that is striving for sustainable industrial development [26], [27], [28], for studying. In this sense, although this study is situated in the context of board interlock networks and low-carbon technologies in China, our key insights are likely to still hold in other settings. It has been evidenced that firms worldwide are embracing the value of sharing members of boards under ever-increasing pressure of fulfilling low-carbon targets [23], [25], indicating that our main findings have the potential to be extrapolated from China to other regions.

The rest of this article is organized as follows. Section II reviews the literature related to board interlock networks and low-carbon innovation, then proposes several key research hypotheses. Section III describes the methods, data, and measurements. Section IV illustrates our main results. Section V reports the results of a series of robustness checks. Section VI discusses the findings, Section VII states our contributions to the literature, and Section VIII shows the managerial implications. Finally, Section IX concludes this article.

II. LITERATURE REVIEW AND HYPOTHESES

A. Board Interlock and Corporate Low-Carbon Innovation

LCI is sometimes synonymous with green innovation, eco-innovation, and environmental innovation. It is integral to low-carbon energy transformation for mitigating climate change [29]. The typical distinctions between low-carbon innovation and conventional innovation are that the former could exert a more significant effect of knowledge spillover (i.e., positive externality) on society [1], and that businesses individually cannot fully internalize the cost in terms of information and knowledge resources when developing eco-friendly innovation (i.e., negative externality), thereby impeding firms' engagement in LCI [30]. The double externality puts forward higher requirements for firms in pursuit of LCI. For instance, compared with conventional innovation, promoting LCI requires firms to have a higher capacity for seeking and recombining resources and knowledge [1]. In addition, the development of LCI also entails multistage and long-term complex processes [21], meaning that it will be much more time-consuming to transfer LCI into visible profitability. More importantly, it has been documented that those activities associated with environmental innovation necessitate more knowledge and information from outside sources [10], [31].

As indicated by the resource dependency theory, firms are not self-sufficient in developing critical resources; they have to be reliant on other external actors which can provide critical resources for their survival and to sustain their long-term investment [32], [33]. In this light, it is reasonable that the interfirm relationship embedded within board interlock networks can facilitate the sharing of these key resources for developing LCI. Although it is argued that interlocking directorates may not have a sufficient technical understanding of firms' activities regarding LCI, most of them are expected to play a resource-managing role in addition to the advisory and monitoring role [9], such as providing forums for discussion on LCI [34] and suggesting firms attach more importance to developing low-carbon technologies. Thus, these interlocking directorates could probably influence the focal firm's decisions on LCI investment. In addition, it is also expected that they should perceive the strategic implications regarding low-carbon technologies investment and its real effect on the firms' performance [4]. When it comes to innovation activities, firms typically learn from failures and engage in trial-and-error learning [34]. Within the interlock networks, exterior directorates can exchange failure experiences and potential strategic pitfalls with partnering firms [35], thereby helping focal firms to understand the determinants of low-carbon innovation performance [36].

Based on these discussions, we continue to demonstrate how specific network positions in board interlock networks, namely central network position and structural holes positions, influence LCI in the following two sections.

B. Central Network Position and Corporate Low-Carbon Innovation

According to the social network theory, an actor's network position indicates his prominence or power within the network [37], and this type of position reflects the quo status of previously established social capital [22]. In this logic, firms holding central positions in board interlock networks can possess more prominence and power (e.g., bargaining power). Previous studies have found that firms with a prominent role in board interlock networks are more likely to achieve scale economies [8] and enhance incremental innovation capability [38], enabling these firms to absorb and utilize the knowledge generated from large LCI programs more effectively and efficiently. In addition, the firm in a prominent position in the interlock networks will be closer to broader financing channels [7], which alleviates their financing constraints on developing low-carbon technologies. For most firms, good investment programs and sufficient financial support are the basis for innovating low-carbon technologies. If a firm has a prominent (or central) position in the board networks, its accessibility to innovation investment programs, such as LCI programs, will see an upward trend due to its greater bargaining power.

The literature has recognized that firms' innovation outputs could benefit from holding a central network position in board interlocks. First, firms centrally located in a board interlock network can acquire enormous updated and superior information that allows them to be aware of market trends and external environmental changes in advance [4], [39], which may influence the output of LCI. For example, domestic new energy vehicles firms have experienced dynamic environmental policies since 2009 [3], and information flow brought by interlocking directorates can provide useful references for the focal firm to make optimal investment decisions on low-carbon programs. Additionally, firms can take advantage of board interlocks to effectively manage environmental uncertainty concerning LCI. Second, there is no denying that knowledge resources play a fundamental role in most innovation processes [40]. Given that the board interlock network has been recognized as a useful means of managing firms' knowledge dependence [4], firms occupying central positions are likelier to acquire and maintain access to valuable knowledge resources related to low-carbon technologies. In this regard, one can be reasoned that such firms may have a heightened capacity to recombine knowledge and resources [34], which is key to developing LCI [1]. Accordingly, a more central position not only facilitates firms' accumulation of knowledge but enhances their capacities to further convert this knowledge into low-carbon technologies [8], [36]. Besides, as underlined by Howard et al. [4], it can be inferred that being more centrally located means a lower cost of searching for information and knowledge resources related to the improvement of LCI.

Moreover, it has been evidenced that board interlocks can serve as a catalyst for forming strategic R&D alliances between firms [4], [41]. Baum et al. [42] even found that startups can enhance early innovation performance by allying with their potential rivals to secure more learning opportunities. The alliance increases firms' social and environmental legitimacy [33], and allows firms to share exclusive knowledge resources [36] that can take effect in improving collaborative LCI. Meanwhile, it can help focal firms to find new ideas triggering LCI. Furthermore, alliance firms will reduce or avoid conflicts like patent infringement whilst developing low-carbon technologies. For instance, Bernini et al. [43] empirically documented that interlocked firms tend to cite each other when applying for related innovation patents. In addition, the partnering firms may provide external channels for the focal firms to approach suppliers who can supply desirable energies and materials [44], and may help them address customer needs through reaching potential customers who are in demand of low-carbon technologies. Considering the double externalities and high R&D risk featured by LCI, a firm's development process of low-carbon technologies can considerably benefit from holding a central position in board interlock networks. Taken together, we conjecture that:

H1. Firms occupying central network positions in board interlock networks tend to innovate more low-carbon technologies.

C. Structural Holes Position and Corporate Low-Carbon Innovation

Social network theorists stress that some structural positions are superior to others, for example, the structural holes position [45]. In addition to the central network position, structural holes position in the network also plays a part in affecting firms' strategic decision-making and therefore their LCI performance. Structural holes refer to a gap in the flow of information between two unconnected firms [20], [36]. In a similar vein, structural holes emerge when any two independent partnering firms are interlocked to the same focal firm. As such, the focal firm is regarded as spanning a structural holes position in its interlocking network. It is tenable that these firms serving as a bridge between unconnected firms are likely to have access to diverse, nonredundant, and novel information, which will positively impact firms' innovation outputs [36], [46]. The rationale is that their innovation performance can benefit from brokering the linkage between disconnected groups, the so-called brokerage advantage [46], [47]. Specifically, they could probably access superior and diversified knowledge and information partly because of new and diverse contact with partnering firms that differ in their characteristics [48], [49]. And possessing this heterogeneous information and knowledge content will be conducive to generating good ideas as well as reassembling existing ideas [45], thereby prompting LCI outputs. Meanwhile, the brokerage advantage can be translated into a greater ability to address complex R&D problems, facilitating the development of innovative products [8], [45], [46], [50], for example, low-carbon technologies.

As mentioned above, focal firms tend to ally with their partnering firms and potential rivals within the board interlock network. The alliance network will arguably provide firms spanning structural holes position with greater opportunities to recombine resources and knowledge into innovation outcomes [20]. Specifically, it is more likely for such firms to develop new understanding and create new combinations of existing ideas. Notably, the recombination mechanism is more crucial to LCI than conventional innovation, given that developing low-carbon technologies necessitates a higher capacity for recombining knowledge and resource [1]. Besides, spanning structural holes position allows these firms to have more discretion regarding the speed and rate of innovation in the alliance network by controlling resource and knowledge flow and diffusion. In so doing, their competitive advantages in the area of LCI can be guaranteed. Moreover, firms' success rate of innovating low-carbon technologies and entering new market elements can benefit from spanning structural holes positions by means of efficiently operating external search in collaboration networks and learning industrial threats and opportunities from technological imitation [51], [52]. Collectively, we conjecture that:

H2. Firms spanning structural holes positions in board interlock networks tend to innovate more low-carbon technologies.

D. Information Asymmetry (ASY) as the Mediator

As stated earlier, board interlocks play a key role in disseminating diverse and useful information between firms, and in a similar vein, serve as information conduits among organizations [4], [22]. Specifically, interlocking directorates within the same networks (in the sense of alliance) tend to exchange updated information that may be unavailable or costly for firms without interlocking experience to access [20], [23], so that the network members have more accurate and symmetrical information regarding the emerging market demand, supply chain partners, financing channels, and innovation policies, in particular for those firms located in advantageous network positions [51]. This enables them to mitigate financial constraints and make optimal decisions on developing LCI programs. Based on previous discussions pertaining to the function of network position, this study argues that ASY may be less concerned for firms occupying central network positions or spanning structural holes positions in the interlocking network, given that both advantageous positions allow such firms to serve as important information hubs through which high volume of valuable, updated and non-redundant information can inflow and outflow.

Effectively, in China, where the capital market is imperfect, ASY is the major reason for firms' inefficient investment in innovation [53]. Notwithstanding, it has been noticed that network positions have the potential to influence innovation by alleviating the adverse effect of ASY on investment efficiency. For example, Zhao [7] has pointed out that firms in central or structural holes positions are more likely to enjoy an appropriate level of investment as a result of less asymmetrical information. In this light, advantageous network positions can provide such firms with more opportunities to mitigate and even reverse the underinvestment or overinvestment induced by ASY on low-carbon technologies, thereby leading to an improvement of LCI. Thus, we conjecture that:

> *H3(a). Information asymmetry (ASY) negatively mediates the relationship between central network position and low-carbon innovation (LCI).*

> *H3(b). Information asymmetry (ASY) negatively mediates the relationship between structural holes position and low-carbon innovation (LCI).*

E. Knowledge Absorptive Capacity (KAC) as the Mediator

KAC generally refers to a firm's ability to recognize the value of newly acquired external knowledge resources, assimilate them, and apply them for innovation outputs and other commercial purposes [54]. As noted earlier, cultivating a board interlock network is an effective tool for firms to manage knowledge dependence through obtaining access to external knowledge resources [4]. In addition, the interfirm relationships embedded within interlock networks also play an important role in enhancing firms' capacity for absorbing these external knowledge resources. For example, Ebers and Maurer [55] empirically found that the improvement of KAC results from the formation of firms' network embeddedness. Also, KAC for employees, especially for R&D staff, can significantly benefit from interlocking networks, because network relations enable them to learn, process and transfer complex knowledge better [56], which helps them increase their innovative capacities. Furthermore, director interlocks contribute to more interactions between firms whether they have similar or diversified knowledge backgrounds. These interlocking directorates could exchange expertise and learning experiences, accelerating firms' capacities to learn, assimilate, combine, and recombine external knowledge resources [51]. In fact, occupying advantageous network positions regardless of central network position or structural holes position will help such firms enhance their abilities to understand the cause–effect of innovation activities and assimilate tacit knowledge, thereby strengthening a firm's capacity to absorb knowledge acquired from network memberships [51].

An array of studies has highlighted the importance of KAC to innovation. For instance, successful innovation heavily relies on the organizational absorptive capacity of external knowledge sources [57], particularly for LCI featuring double externalities [1]. Besides, a higher level of KAC can be translated into superior innovation outputs by getting rid of the competency trap and avoiding technological lockout [58]. Hence, it appears that KAC can help firms better respond to changes in the external LCI environment, by continually assessing and meeting the market demand for LCI. As Tsai [59] suggested, KAC can serve as a conduit that can transfer valuable ideas and knowledge from the partnering firms to the focal firm for developing LCI, thereby facilitating cross-firm LCI activities. Thus, it is possible that firms with high levels of KAC are inclined to conduct more LCI. Notably, firms are not identically capable of accessing, learning, and assimilating these external knowledge resources [59]. The acquisition and utilization of knowledge are more facilitative for those who work in firms situated in advantageous network positions (in the sense of a high level of board social capital) [60]. Given these knowledge-based competitive advantages embedded within advantageous network positions, it can be referred that firms occupying central positions or spanning structural holes positions will see an upward level of KAC which in turn has a significant influence on their LCI performance. We, therefore, conjecture that:

> *H4(a). Knowledge absorptive capacity (KAC) positively mediates the relationship between central network position and low-carbon innovation (LCI).*

> *H4(b). Knowledge absorptive capacity (KAC) positively mediates the relationship between structural holes position and low-carbon innovation (LCI).*

III. Methods

A. Sample and Data

Our research sample consists of China's A-share listed firms from 2009 to 2018. We delete firm-year observations labeled as "ST (Special Treatment)" as it indicates that the firm may be soon delisted from China's stock market. In line with an array of studies (e.g., [10]), given that financing firms are less likely to innovate low-carbon technologies directly, these sample firms listed in the financial industry without patenting records are excluded. Our final research sample comprises 22 410 firm-year observations, including 3365 listed firms. Table II describes the sample distribution across industries and years.

We collect director information from multiple sources such as corporate annual reports, public media, and the China Stock Market and Accounting Research Database for the years 2009–2018. Then, we scrutinize related information on board members

TABLE II
SAMPLE DISTRIBUTION ACROSS INDUSTRIES AND YEARS

Panel A: Sample distribution across industries		
SIC code	Industry	Freq
A	Agriculture, forestry, animal husbandry, and fishery	321
B	Mining	555
C	Manufacturing	14342
D	Electricity, heat, gas, and water production and supply	775
E	Construction industry	595
F	Wholesale and retail	1262
G	Transportation, warehousing, and postal services	727
H	Hospitality and catering	89
I	Information and software technology services	1354
K	Real estate	1104
L	Leasing and business services	263
M	Scientific research and technical services	186
N	Environment and public facilities management	227
O	Residential services and other services	27
P	Education	12
Q	Sanitation and social work	45
R	Culture, sports and entertainment	284
S	Comprehensive industry	242

Panel B: Sample distribution across years	
Year	Freq.
2009	1239
2010	1535
2011	1830
2012	2029
2013	2111
2014	2278
2015	2479
2016	2670
2017	3098
2018	3141

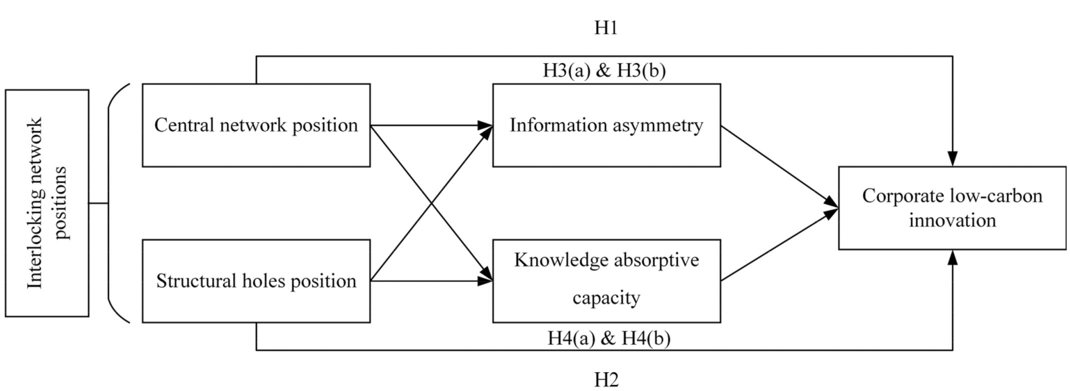

Fig. 1. Conceptual framework and hypotheses.

of each listed firm in each fiscal year, which allows us to identify whether any given two firms are connected through the directors who serve on the board of both firms in the same year. If so, we define this pair of firms are *interlocked*. Then, following Mazzola et al. [36], we create an annual matrix of board interlock networks by assigning one if any two firms are interlocked and 0 otherwise. With reference to the well-established method proposed by Freeman et al. [61], we create a Python script to compute the degree to which a firm occupies the central network position or spans the structural holes position in each fiscal year. For clear illustration, we extract the largest connected component of board interlock networks in each year from 2009 to 2018. The situation in 2009 and in 2018 are shown in Figs. 1 and 3, respectively. The situations in other years are provided

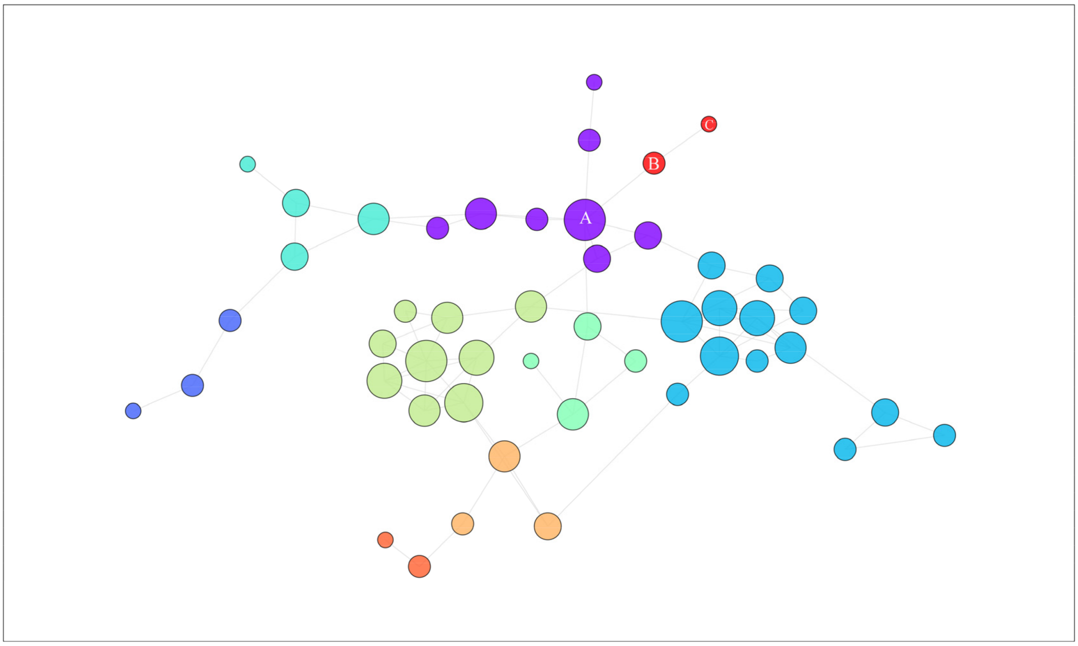

Fig. 2. Largest connected component of the board interlock network in 2009. Note: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.669. Nodes (i.e., firms) belonging to the same cluster are painted with the same color. Thus, Firm A is occupying a network position with the highest centrality within its own cluster. While Firm A and C have no direct connections, it is Firm B that bridges these two firms. So, Firm B is spanning a structural holes position.

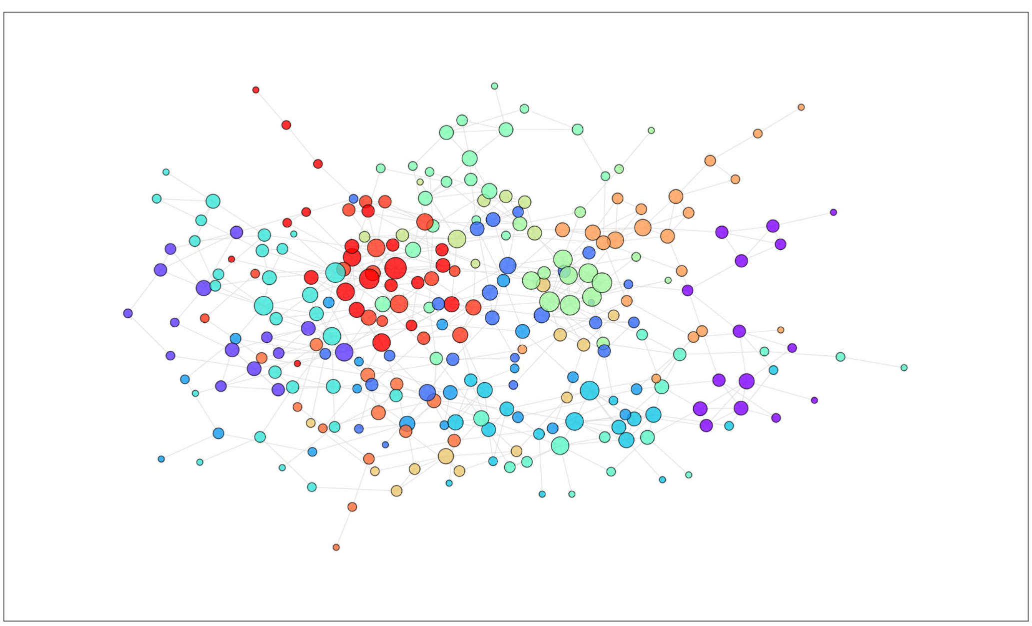

Fig. 3. Largest connected component of the board interlock network in 2018. Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.737. Nodes (i.e., firms) belonging to the same cluster are painted with the same color.

in Supplementary Material Figs. S1–S8. The node denotes an individual firm, and a solid line connects two interlocked firms by sharing the same directors. The size of a node is proportional to the number of its direct connections with others. The color of nodes denotes the detected communities or clusters (in the sense of alliances) by using the community detection algorithm [62]. Modularity scores for these clusterings are 0.669 in 2009 and 0.737 in 2018, indicating a significant network detection [63].[1] It can be evidently seen from Figs. 2 and 3 and Figs. S1–S8 (See Supplementary Material) that the underlying community structure of interlocking directorship has become increasingly complex in China during our research period.

[1] According to Newman and Girvan [63], the indicator of modularity is used for assessing the results of network partitioning. Networks with higher modularity are featured by denser connections between nodes within clusters.

In line with Zhu et al. [64], detailed patent information, including patent types and International Patent Classification (IPC) code, was attained from the State Intellectual Property Office (SIPO). Each patent application is assigned one or more IPC codes by the committee of experts in SIPO to mirror its unique technological property. Thus, the IPC code accompanied by each patent enables us to distinguish low-carbon innovation patents from conventional innovation patents. In detail, these low-carbon patents were associated with the broad area of climate change mitigation in the IPC Green Inventory,[2] including energy generation, transportation, energy conservation and recycling, carbon dioxide capture and storage, waste management, etc. All continuous variables have been winsorized at the 1st and 99th percentiles to eliminate the effect of outliers.

B. Dependent Variable

Following a large body of related studies [3], [64], [65], we use low-carbon patent applications as a proxy for LCI at the firm level. To mitigate the overdispersion of patent data, we take the natural logarithm of the number of low-carbon innovation patents plus one.

C. Independent Variables

1) Central Network Position: Degree centrality is the most straightforward measure to capture the number of direct links a firm has in the network [7], which has been widely employed as a leading indicator to gauge network centrality [8], [9], [52]. Following these previous studies, we choose degree centrality to be the proxy of central network position which *Central* denotes. The value of *Central* for firm *j* in each board interlock network can be calculated using the following equation:

$$\text{Central}\ (j) = \frac{1}{N-1}\sum_{i(\neq j)} x_{ij} \tag{1}$$

where x_{ij} denotes a network connection between firm i and firm j; and N is the total number of firms in the network.

2) Structural Holes Position: Consistent with mainstream literature [13], [20], [38], we measure the extent to which a firm spans a structural holes position as one minus the firm's constraint score (in cases where the constraint score was nonzero) and zero for all other cases, which *Holes* denotes. Specifically, *Holes* norms the effective size of a focal firm's ego-network by its actual size, thereby representing the proportion of its interlock ties to its neighborhood are nonredundant.

D. Mediator Variables

1) Knowledge Absorptive Capacity (KAC): As Cohen and Levinthal [54] suggested, KAC generally seems to be a byproduct of R&D investment, and R&D expenditure is arguably a reliable and accessible proxy for diverse capabilities involving knowledge acquisition, assimilation, and utilization. Thus, R&D expenditures have been widely used by mainstream researchers to measure KAC [59], [66], [67]. Following these studies, we employ the log transformation of R&D expenditures as a key proxy for KAC.

2) Information Asymmetry (ASY): This study followed methods suggested by Amihud et al. [68], Amihud [69], and Pástor and Stambaugh [70] to gauge the degree of ASY in China's stock market, which is based on daily frequency transaction data. Specifically, Amihud et al. [68] and [69] proposed the indicator LR and ILL to respectively identify the liquidity and illiquidity of a given stock over some periods, as shown in the following equations:

$$LR_{it} = -\frac{1}{D_{it}}\sum_{k=1}^{D_{it}}\sqrt{\frac{V_{it}(k)}{|r_{it}(k)|}} \tag{2}$$

$$ILL_{it} = \frac{1}{D_{it}}\sum_{k=1}^{D_{it}}\sqrt{\frac{|r_{it}(k)|}{V_{it}(k)}} \tag{3}$$

where $r_{it}(k)$ and $V_{it}(k)$ respectively denote the stock return and daily trading volume of firm *i* on trading day *k* of fiscal year *t*, and D_{it} is the total number of trading days for the firm *i* in a given year *t*.

Furthermore, Pastor and Stambaugh [70] constructed a measurement of market liquidity (GAM) for firm *i* on the basis of weighted daily data within a given year *t*, which is estimated through the ordinary least squares regressions, as shown in the following equations:

$$r^e_{i,t}\ (k) = r_{i,t}\ (k) - r_{m,t}(k) \tag{4}$$

$$r^e_{i,t}\ (k) = \theta_{i,t} + \phi_{i,t} r_{i,t}(k-1) + \gamma_{i,t} V_{i,t}(k-1)\,\text{sign}\left[r^e_{i,t}(k-1)\right] + \varepsilon_{i,t}(k) \tag{5}$$

where $r^e_{i,t}(k)$ is the abnormal return of firm *i* on trading day *k* of fiscal year *t*, and $r_{m,t}(k)$ is the value-weighted market return of firm *i* in year *t*. As a result, GAM equals the absolute value of $\gamma_{i,t}$.

The rationale behind these is that the market liquidity of a stock is negatively related to ASY, which means that, ceteris paribus, the greater the value of LR, ILL, and GAM is, the higher the degree of ASY is. Notwithstanding, it is noteworthy that these three indicators contain components that are irrelevant to ASY [71], and are therefore unable to gauge ASY accurately. With reference to Bharath et al. [72], we calculate ASY based on the principal component of LR, ILL, and GAM so as to exclude noninformational components of ASY and extract the common feature concerning ASY across these indicators. In so doing, we obtained a combinative and more accurate measurement of ASY.

E. Control Variables

This study controls a wide array of variables that may influence firms' LCI. First, we control firm size (FirmSize), which is measured by taking the natural logarithm of total assets. Firm age (FirmAge) is measured by calculating the number of years since the firm was established and we take the natural logarithm of this variable. Return on Equity (ROE) is key to measuring firms' profitability and is approved to be a determinant of LCI. Besides, firm leverage (FirmLev) controls firms' financial risk since higher financial leverage may discourage them from engaging in LCI [73]. Thus, this study measures FirmLev by proportionating

[2]IPC Green Inventory is developed by the World Intellectual Property Office (WIPO) under the guidance of the United Nations Framework Convention on Climate Change (UNFCCC). Interested readers can refer to https://www.wipo.int/classifications/ipc/green-inventory/home.

TABLE III
INFORMATION SUMMARY OF VARIABLES USED IN THIS STUDY

Variables	Description
LCI	The low-carbon innovation patent application (Log transformed)
Central	The central network position held by a firm in board interlock networks
Holes	The structural holes position spanned by a firm in board interlock networks
ASY	The degree of information asymmetry based on daily frequency transaction data
KAC	R&D expenditure of a firm (Log transformed)
FirmSize	Total assets of a firm (Log transformed)
FirmAge	The time period since the firm was established (Log transformed)
FirmLev	The proportion of total debt to total assets
ROE	Return on Equity
Dual	A dummy variable that equals one if the CEO plays a dual role in the firm and, otherwise, zero.
SOE	A dummy variable that equals one if the firm is controlled by the government and, otherwise, zero.
Top1	The most shareholding proportion among stakeholders
BoardSize	Board size at the end of a fiscal year

TABLE IV
DESCRIPTIVE STATISTICS AND CORRELATIONS

	Mean	S.D.	1	2	3	4	5	6
1. LCI	0.306	0.755	1.000					
2. *Central*	0.001	0.001	0.049^{***}	1.000				
3. *Holes*	0.578	0.258	0.046^{***}	0.778^{***}	1.000			
4. ASY	-0.009	0.545	-0.128^{***}	-0.099^{***}	-0.098^{***}	1.000		
5. KAC	13.816	7.326	0.229^{***}	0.009	0.023^{***}	-0.048^{***}	1.000	
6. ROE	0.074	0.113	0.061^{***}	0.021^{***}	0.005	-0.054^{***}	0.016^{**}	1.000
7. FirmLev	0.427	0.210	0.064^{***}	0.117^{***}	0.110^{***}	-0.112^{***}	-0.206^{***}	-0.171^{***}
8. FirmSize	22.164	3.042	0.001	-0.005	-0.006	0.037^{***}	0.010	0.029^{***}
9. Dual	0.266	0.442	0.004	-0.060^{***}	-0.064^{***}	0.071^{***}	0.118^{***}	0.024^{***}
10. SOE	0.378	0.485	0.019^{***}	0.096^{***}	0.096^{***}	-0.107^{***}	-0.224^{***}	-0.054^{***}
11. FirmAge	2.771	0.380	-0.026^{***}	0.108^{***}	0.105^{***}	-0.072^{***}	-0.119^{***}	-0.076^{***}
12. Top1	0.354	0.151	0.011	0.013^{*}	0.008	0.011^{*}	-0.057^{***}	0.135^{***}
13. BoardSize	8.723	1.743	0.074^{***}	0.165^{***}	0.148^{***}	-0.081^{***}	-0.051^{***}	0.037^{***}

	7	8	9	10	11	12
7. FirmLev	1.000					
8. FirmSize	-0.032^{***}	1.000				
9. Dual	-0.167^{***}	-0.003	1.000			
10. SOE	0.320^{***}	0.001	-0.298^{***}	1.000		
11. FirmAge	0.205^{***}	0.004	-0.102^{***}	0.168^{***}	1.000	
12. Top1	0.066^{***}	0.031^{***}	-0.048^{***}	0.233^{***}	-0.120^{***}	1.000
13. BoardSize	0.170^{***}	-0.003	-0.182^{***}	0.267^{***}	0.022^{***}	0.023^{***}

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent applications. ASY represents the degree of information asymmetry. KAC represents the capacity for absorbing knowledge.

a firm's year-end asset-liability. We control CEO duality (Dual), a dummy variable whose value is one if the CEO plays a dual role in the firm and zero otherwise. In most cases, dual CEO will dominate the corporate agenda, including making decisions to develop LCI. State-owned enterprise (SOE) is measured as a dummy variable that equals 1 if the firm is controlled by the government and, otherwise, zero. The stakeholder who holds the most shares (Top1) is likelier to influence corporate strategic decisions on LCI, so this study measures it by computing the shareholding proportion of major stakeholders. In line with Helmers et al. [9], we control the firm's board size (BoardSize) which is measured by the total number of the board of directors. In sum, we provide the information summary of each variable and its description in Table III.

F. Econometric Models

To test the mediating effect of KAC and ASY on the relationship between interlocking network positions and LCI, we established three econometric models with reference to Baron and Kenny [74]. We first tested the relationship between the central network position and structural holes position and LCI (i.e., baseline model), as depicted in (6). Second, we respectively examined the effect of both network positions on two mediators (i.e., KAC and ASY), as shown in (7).[3] Finally, we added mediators into the baseline model, and then respectively investigated the mediating effect of KAC and ASY, as demonstrated in (8). Therein, the coefficients of KAC and ASY are expected to be significant, and the effect of the central network position and structural holes position should either decline in magnitude (partially mediating) or be with no statistical significance (fully mediating)

[3]The coefficients of Central and Holes in (7) should arguably achieve significance in statistics. Otherwise, the Sobel test and Bootstrap analysis are recommended by Hayes [75] in order to ensure the existence of mediating (indirect) effects. In this regard, (7) is useful but not a must for identifying the mediational effect.

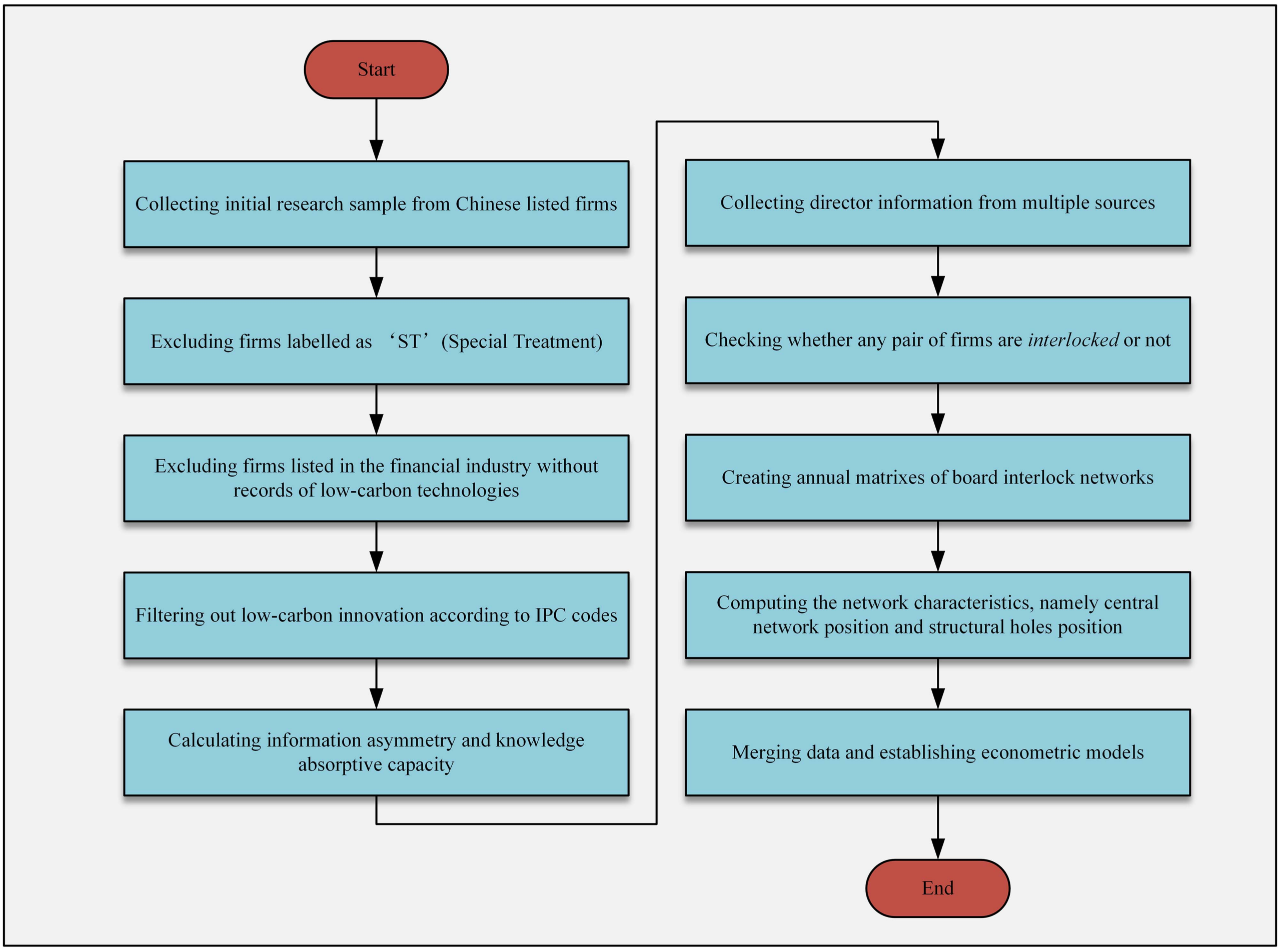

Fig. 4. Research method flowchart.

$$\mathrm{LCI}_{i,t} = \partial_0 + \partial_1 \mathrm{Central}_{i,t-1} \text{ or } \mathrm{Holes}_{i,t-1} + \partial_2 X_{i,t-1} + \text{Fixed Effects} + \varepsilon \quad (6)$$

$$\mathrm{KAC}_{i,t} \text{ or } \mathrm{ASY}_{i,t} = \partial_0 + \partial_1 \mathrm{Central}_{i,t-1} \text{ or } \mathrm{Holes}_{i,t-1} + \partial_2 X_{i,t-1} + \text{Fixed Effects} + \varepsilon \quad (7)$$

$$\mathrm{LCI}_{i,t} = \partial_0 + \partial_1 \mathrm{Central}_{i,t-1} \text{ or } \mathrm{Holes}_{i,t-1} + \partial_2 \mathrm{KAC}_{i,t-1} \text{ or } \mathrm{ASY}_{i,t-1} + \partial_3 X_{i,t-1} + \text{Fixed Effects} + \varepsilon \quad (8)$$

where *i* denotes the firm and *t* refers to the observed time point; Central denotes the central network position; Holes denotes the structural holes position; Fixed effects include industry fixed effect and year fixed effect; *X* is the set of control variables; and ε is the random error term. Considering the potential endogenous issues caused by reverse causality, independent and control variables are lagged for one year.

Following Chen et al. [76], we report heteroskedasticity-robust standard error clustered at the firm level to deal with panel heteroskedasticity and potential contemporaneous error correlation. Additionally, we illustrate a flowchart to help improve the readability of the section of the research method, as shown in Fig. 4.

IV. Results

Table IV shows the descriptive statistics and correlations among independent variables, mediating variables, dependent variables, and control variables. As can be seen, all correlation coefficients are under 0.8, and the highest variance inflation factors value is 4.62, suggesting that there is no serious issue of multicollinearity [77]. It appears that the correlations among variables of interest (i.e., Central and Holes), and the dependent variable - LCI are positive and highly significant, thereby providing preliminary evidence to support H1 and H2.

To further verify our hypotheses, we report detailed regression results for H1 and H2 as shown in Table V. Thereinto, Model (1) examines the direct effect of central network position on LCI. Specifically, the coefficients of Central ($\beta = 24.427$, $p < 0.05$) are positive and statistically significant when predicting LCI, supporting H1. Furthermore, Model (2) in Table V provides empirical evidence to support H2, given that the coefficients of Holes ($\beta = 0.074$, $p < 0.05$) are positive and highly significant.

Subsequently, we estimated the correlations between two types of network positions and two mediators. Model (1) in Table VI reports the regression results of central network position when predicting ASY, and these results indicate that firms occupying interlocking network positions with higher centrality

TABLE V
EFFECT OF INTERLOCKING NETWORK POSITIONS (CENTRAL NETWORK POSITION AND STRUCTURAL HOLES POSITION) ON LOW-CARBON INNOVATION

	(1) LCI	(2) LCI
Central	24.427**	
	(11.930)	
Holes		0.074**
		(0.033)
ROE	0.888***	0.894***
	(0.122)	(0.123)
FirmLev	0.425***	0.427***
	(0.064)	(0.064)
FirmSize	0.002	0.002
	(0.003)	(0.003)
Dual	0.022	0.022
	(0.026)	(0.026)
SOE	0.078**	0.078**
	(0.031)	(0.031)
FirmAge	-0.095***	-0.095***
	(0.034)	(0.034)
Top1	0.016	0.017
	(0.099)	(0.099)
BoardSize	0.035***	0.036***
	(0.010)	(0.010)
_cons	-0.111	-0.124
	(0.152)	(0.151)
Industry FE	Yes	Yes
Year FE	Yes	Yes
Within R^2	0.118	0.117
F	11.301	11.353
Obs.	18587	18587

Note: Robust standard errors clustered at the firm level are in parentheses. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent applications. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

TABLE VI
EFFECT OF CENTRAL NETWORK POSITIONS ON LOW-CARBON INNOVATION (ASY AS THE MEDIATOR)

	(1) ASY	(2) LCI	(3) ASY	(4) LCI
Central	-18.523***	20.091*		
	(3.957)	(11.781)		
Holes			-0.069***	0.057*
			(0.011)	(0.033)
ASY		-0.125***		-0.125***
		(0.026)		(0.026)
ROE	-0.771***	0.839***	-0.775***	0.844***
	(0.047)	(0.117)	(0.047)	(0.118)
FirmLev	-0.225***	0.393***	-0.226***	0.395***
	(0.022)	(0.062)	(0.022)	(0.063)
FirmSize	0.000	0.003	0.000	0.003
	(0.001)	(0.003)	(0.001)	(0.003)
Dual	0.008	0.027	0.008	0.028
	(0.008)	(0.026)	(0.008)	(0.026)
SOE	-0.074***	0.067**	-0.073***	0.067**
	(0.011)	(0.030)	(0.011)	(0.030)
FirmAge	0.015	-0.096***	0.015	-0.096***
	(0.012)	(0.034)	(0.012)	(0.034)
Top1	0.144***	0.036	0.144***	0.037
	(0.030)	(0.098)	(0.030)	(0.098)
BoardSize	-0.013***	0.034***	-0.014***	0.034***
	(0.003)	(0.010)	(0.003)	(0.010)
_cons	0.177***	-0.095	0.192***	-0.105
	(0.050)	(0.150)	(0.050)	(0.150)
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Within R^2	0.365	0.125	0.365	0.125
F	49.834	10.566	50.835	10.599
Obs.	18587	18587	18587	18587

Note: Robust standard errors clustered at the firm level are in parentheses. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent applications. ASY represents the degree of information asymmetry. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

tend to have a lower degree of ASY ($\beta = -18.523$, $p < 0.01$). In addition, Model (1) in Table VII presents the regression results of central network position when predicting KAC. It is evident that the central network position is a significant contributor to KAC, and specifically, firms located at network positions with a higher value of Central are more likely to exhibit greater absorptive capacities of knowledge ($\beta = 158.482$, $p < 0.05$).

When it comes to structural holes position, Model (3) in Table VI reports the result of regressing ASY on structural holes position, and it appears that those firms spanning structural holes position are likely to have less symmetrical information ($\beta = -0.069$, $p < 0.01$). Moreover, as shown in Model (3) in Table VII, we found a positive and significant association between *Holes* and KAC ($\beta = 0.773$, $p < 0.01$).

Finally, we estimate a full model by simultaneously taking into account both the effect of network positions (i.e., central network position and structural holes position) and two mediators (i.e., ASY and KAC) on LCI. As can be seen from Model (2) in Table VI, we found that when controlling for ASY, the effect of Central deceased in magnitude ($\beta = 20.091$, $p < 0.1$), suggesting that ASY partially mediates the relationship between central network position and LCI. The same thing happened when we tested the mediating role of KAC in Table VII, within Model (2) suggested that KAC serves as a partial mediator in the relationship between central network position and LCI ($\beta = 22.288$, $p < 0.1$). Therefore, H3(a) and H4(a) are supported.

What is more, Model (4) in Table VI indicates that ASY partially mediates the relationship between Holes and LCI ($\beta = 0.057$, $p < 0.1$). Also, Model (4) in Table VII suggested that KAC exerts a partial mediating effect on the Holes–LCI relationship ($\beta = 0.062$, $p < 0.1$). Taken together, H3(b) and H4(b) are supported. Notably, consistent with our earlier arguments and predictions, ASY and KAC show an opposite pattern when predicting LCI. That is, ASY is negatively and significantly related to LCI (see Models (2) and (4) in Table VI)

TABLE VII
EFFECT OF CENTRAL NETWORK POSITIONS ON LOW-CARBON INNOVATION (KAC AS THE MEDIATOR)

	(1) KAC	(2) LCI	(3) KAC	(4) LCI
Central	158.482**	22.288*		
	(70.670)	(11.766)		
Holes			0.773***	0.062*
			(0.229)	(0.032)
KAC		0.016***		0.016***
		(0.002)		(0.002)
ROE	4.348***	0.830***	4.365***	0.836***
	(0.663)	(0.125)	(0.663)	(0.125)
FirmLev	0.566	0.425***	0.554	0.428***
	(0.425)	(0.064)	(0.424)	(0.064)
FirmSize	-0.004	0.002	-0.004	0.002
	(0.021)	(0.003)	(0.021)	(0.003)
Dual	0.185	0.019	0.190	0.019
	(0.144)	(0.026)	(0.144)	(0.026)
SOE	-0.130	0.081***	-0.139	0.081***
	(0.210)	(0.030)	(0.210)	(0.030)
FirmAge	-1.858***	-0.061*	-1.857***	-0.061*
	(0.232)	(0.034)	(0.232)	(0.034)
Top1	1.369**	-0.001	1.373**	-0.000
	(0.551)	(0.098)	(0.551)	(0.098)
BoardSize	0.263***	0.031***	0.260***	0.032***
	(0.046)	(0.010)	(0.046)	(0.010)
_cons	15.720***	-0.365**	15.529***	-0.374**
	(0.863)	(0.159)	(0.868)	(0.159)
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Within R^2	0.502	0.129	0.502	0.129
F	19.113	16.120	19.684	16.087
Obs.	18587	18587	18587	18587

Note: Robust standard errors clustered at the firm level are in parentheses. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent applications. KAC represents the capacity for absorbing knowledge. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

while KAC is positively and significantly correlated with LCI (see Models (2) and (4) in Table VII).

V. Robustness Checks

A. Alternating Dependent Variable

In addition to using low-carbon patent applications as a measure of LCI, we also consider low-carbon patent authorizations as an alternative proxy for LCI, which was in line with related literature [3]. Given that it will take at least 2 to 3 years for most patents to be granted since applications start,[4] we lagged two years for low-carbon patent authorizations. The regression results of alternative LCI suggested that our baseline hypotheses (i.e., H1 and H2) were supported again (see Table VIII in the Appendix). As shown in Tables IX and X in the Appendix, the mediating effects of ASY and KAC are also still significant when alternating the indicator of LCI.

B. Rechecking the Mediation Using Sobel Test

Although the approach proposed by Baron and Kenny [74] has been widely used to test for mediation, researchers argued that it is not quantitative enough but just suggests the mediating effect through logical inference from three conditions [75]. Thus, to make sure the indirect (mediating) effect of interlocking network positions on LCI via ASY and KAC, we repeated previous estimates by using the test of Sobel [78] as well as the bootstrap analysis to complement our results. The Sobel test enables us to test the significance of the indirect effect by producing a statistic. We provide the corresponding results of the Sobel test for the direct and indirect effect in Table XI (Appendix), and these results show that ASY and KAC indeed significantly carry the influence of interlocking network positions to LCI, thereby further supporting H3(a)–(b) and H4 (a)–(b).

C. Rechecking the Mediation Using Bootstrap Analysis

Nonetheless, Hayes [75] pointed out that the Sobel test relies on the normality assumption for testing the indirect effect. Hence, we take a step forward to use Bootstrap analysis to generate one thousand estimates of the indirect effect based on resampling procedures, which then generates a confidence interval of the indirect effect. As reported in Table XII in the Appendix, the results of Bootstrap analysis corroborate the mediating role of ASY and KAC again.

D. Reverse Causality

Finally, we examined whether the firm's network positions could be affected by their LCI performance or the degree of ASY and KAC. No significant direct and mediating effect was found. In effect, innovation management literature has suggested the board interlock network as a predictor of firms' innovation performance, rather than the reverse relationship. Thus, the possibility of reverse causality is arguably minimal.

VI. Discussion

This study casts light on whether and how superior network positions bring firms advantages in terms of external ASY and internal KAC, and how firms translate these advantages into their LCI performance. Taking into consideration the potential conduits served by KAC and ASY, we add to the current understanding of the relationship between board

[4] According to the investigation from IP-Coster (https://www.ip-coster.com/), the average processing time for the patent registration procedure in China is 3 years.

interlock networks and LCI by examining two major types of network positions: central network position and structural holes position.

First of all, this study supports ASY as a significant mediator between firms' network positions and LCI. Our results show that occupying advantageous network positions can enhance a firm's output of low-carbon technologies by enhancing its ability to gather more external symmetric information. Specifically, we found that the issue of information asymmetry should be less concerned for firms occupying central network positions or spanning structural holes positions. It enables firms to symmetrically discern the changes of emerging market demand for low-carbon technologies, to timely learn the trend of LCI policies, and to broadly access financial support for LCI. This result is in part consistent with what Zhao [7] reported.

Second, given that ASY is mainly responsible for inappropriate R&D investment in China [53], the mitigation of ASY enables these firms to avoid overinvestment and reverse underinvestment in low-carbon technologies, thereby contributing more LCI outputs. The finding is in line with prior research implying that board interlocks are likely to influence the volume and diversity of information acquired by focal firms [4], [20], [22]. Also, it is consistent with extant studies [7], [53], revealing that the reduction of ASY is conducive to R&D investment and therefore the innovation outcomes.

Finally, information-based advantage aside, our mediation analysis shows that occupying superior positions in board interlock networks can accelerate a focal firm's internal capacities to learn, assimilate, and recombine knowledge resources [51], which particularly fosters the development of low-carbon technologies [1]. In other words, we found that the relationship between network positions and LCI is partially and positively mediated by KAC. This finding is in line with a body of previous studies which noted that interfirm network embeddedness would influence a firm's capacity to learn, process, and absorb complex knowledge, such as Cohen and Levinthal [54] and Howard et al. [4].

In general, our findings are consistent with the resource dependence theory and social network theory that firms aiming to improve environmental performance (e.g., LCI) are not self-sufficient but have to rely on and take advantage of network relationships with others [5], [33].

VII. Theoretical Contributions

This study adds value to the literature in several ways. First, by shedding light on the relationship between board interlock networks and corporate low-carbon innovation from a relatively novel perspective of network position, it contributes to a growing body of literature on the role of social capital investment in corporate environmental actions. Most relevant studies on the antecedents of corporate environmentalism have focused on mere changes of interlocking networks in size [10], [23], whereas less attention has been paid to another valuable property of the network in nature, that is, interlocking network position. This study echoes the recent calls from the literature on environmental innovation management for a more in-depth investigation into the drivers of eco-innovation [24] and provides empirical evidence that occupying a central network position or structural holes position does have a positive effect on the output of low-carbon technologies. By exploring the possible benefits of advantageous network positions featuring board social capital (e.g., power, status, prominence) [51], our study offers a complementary to a strand of literature predominately centered on the effect of network size on corporate environmental performance [5], [23]. We, therefore, contribute fresh insights to an ongoing discussion about why some firms are with excellent records of low-carbon technologies while some are not.

Second, to our knowledge, despite that social capital researchers have mentioned potential information-based and knowledge-based superiorities brought by advantageous network positions [20], we are the first to introduce ASY and KAC as two latent mechanisms by which firms can reap benefits from interlocking network positions, which is of importance for firms to make proper investment decisions on LCI [53]. Specifically, the central network position or structural holes position is related to downward information asymmetry and upward knowledge absorptive capacity, which in turn transfers the inherent advantages of both types of network positions into the adoption of low-carbon technologies. Thus, our findings further contribute to the literature by clarifying how these firms outperform others in the area of low-carbon technologies. While prior studies highlighted that board interlock networks serve as a vehicle for firms to maintain access to external knowledge resources [4], [52], access to knowledge *per se* could not guarantee which could be well absorbed [10]. We extend these works by revealing the positive effect of advantageous network positions on firms' internal capacities for absorbing external knowledge.

Overall, our investigation into the relationship between interlocking network positions and LCI and further identification of two latent mechanisms contributes to the progress of the field of environmental innovation management. Also, our findings lend empirical and theoretical support to the argument that social capital appears to be the bedrock of innovation capabilities [12].

VIII. Managerial Implications

This study has several important managerial implications. First, most previous literature has highlighted the benefits of expanding board network size for improving environmental performance, while our results provide executives with an alternative approach to reap sustainable value from board social capital, that is, concentrating on improving network positions. Executives are thus offered another choice to promote LCI performance, given the fact that not all firms can afford to network expanding. As such, it is encouraged for executives to place more emphasis on developing strategic networks and evaluating the status quo of their network positions. Specifically, firms may want to occupy central network positions or span structural holes positions in board interlock networks, because our results revealed that in this way executives can make the most of their social capital investment in the field of low-carbon innovation.

Second, in the real world, it can be easily observed that industrial practitioners aiming to improve low-carbon innovation performance will increasingly confront the need to address asymmetrical information environment and manage their knowledge resources efficiently. Our findings, therefore, give them a solid reason for corroborating with other firms through sharing board memberships rather than acting as outliers whilst innovating low-carbon technologies, because it implies that occupying advantageous network positions likely helps to alleviate external information asymmetry and enhance internal capacities for absorbing knowledge, both of which are the bedrock of developing low-carbon technologies [1], [12]. In this sense, managers should keep in mind the value of developing board interlock networks in terms of specific positions.

Third, our results implied that firms are likely to translate those competitive advantages arising from higher network centrality or bridging structural holes to technology generation associated with carbon abatement. Hence, policymakers who are seeking ways to reduce carbon dioxide emissions may need to encourage firms on the periphery of board interlock networks to proactively initiate and/or actively engage in environmental innovation network. Specifically, governments are advisable to, when necessary, compensate their cost for searching for complete market information and promoting knowledge assimilation due to their current inferior network positions. As a result, policymakers might will see the greater potential to fulfill the mission of carbon reduction in a timely manner.

IX. Conclusion, Limitations, and Future Research

While current literature has recognized that social capital is responsible for catalyzing innovative capabilities [12], far less attention has been devoted to exploring whether and how advantageous network positions in the sense of embedded board social capital drive corporate low-carbon innovation. To this end, we take a first step toward identifying the latent mechanisms by which occupying advantageous network positions can bring about the improvement of LCI outputs, which is based on 3365 China's A-listed firms over the research period from 2009 to 2018. Specifically, our results imply that either holding a central network position or spanning a structural holes position serves as a significant contributor to firm-level LCI in the sense that board social capital and corporate low-carbon technologies go hand in hand. And we identify ASY and KAC as two mediators that channel the effect of central network position and structural holes position on LCI. These findings add substantially to our current understanding of how firms' output of low-carbon technologies benefits from interlocking network positions in terms of information-based and knowledge-based competitive advantages.

Our study still has several limitations. First, there are in fact many other forms of interfirm networks in the marketplace, such as the supply chain partnership, while this study is just based on board interlock networks. Future research may find it worthwhile to examine whether advantageous positions in other network types also take effect in facilitating low-carbon technologies.

Second, this study is situated in China—the largest emerging market economy and the biggest carbon dioxide emitter in the world. Although we argue that our insights have the potential to be appropriately extrapolated to other economies sharing common characteristics with China, it is encouraged for future research to further verify the degree to which our results could be generalizable in other contexts.

Finally, we must acknowledge the limitations of utilizing patent data to measure corporate low-carbon innovation. There is no denying that not all low-carbon innovation activities can be measurable through patenting [51], and thus we may underestimate a firm's LCI efforts by solely using patent data. Besides, in line with mainstream literature, we excluded sample firms that are listed in the financial sector without patenting records, while it does not mean that these firms completely exclude themselves from innovative activities concerning low-carbon technologies. Hence, future studies may want to explore other techniques to identify LCI more accurately and broadly, such as text-based machine learning.

Appendix

TABLE VIII
Regression Results of Alternative Proxy for Low-Carbon Innovation

	(1) LCI	(2) LCI
Central	20.970**	
	(9.283)	
Holes		0.053**
		(0.023)
ROE	0.404***	0.409***
	(0.082)	(0.083)
FirmLev	0.236***	0.239***
	(0.043)	(0.043)
FirmSize	0.002	0.002
	(0.002)	(0.002)
Dual	0.023	0.023
	(0.019)	(0.019)
SOE	0.025	0.026
	(0.020)	(0.020)
FirmAge	-0.039*	-0.039*
	(0.023)	(0.023)
Top1	0.081	0.082
	(0.074)	(0.073)
BoardSize	0.027***	0.028***
	(0.008)	(0.008)
_cons	-0.231**	-0.238**
	(0.109)	(0.109)
Industry FE	Yes	Yes
Year FE	Yes	Yes
Within R^2	0.080	0.079
F	6.807	6.841
Obs.	15102	15102

Note: Robust standard errors clustered at the firm level are in parentheses. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent authorizations. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

TABLE IX
REGRESSION RESULTS OF ALTERNATIVE PROXY FOR LOW-CARBON INNOVATION (ASY AS THE MEDIATOR)

	(1) LCI	(2) LCI
Central	18.459^{**}	
	(9.205)	
Holes		0.044^{*}
		(0.023)
ASY	-0.077^{***}	-0.077^{***}
	(0.019)	(0.019)
ROE	0.378^{***}	0.383^{***}
	(0.079)	(0.080)
FirmLev	0.220^{***}	0.223^{***}
	(0.041)	(0.042)
FirmSize	0.002	0.002
	(0.002)	(0.002)
Dual	0.025	0.024
	(0.019)	(0.019)
SOE	0.019	0.019
	(0.020)	(0.020)
FirmAge	-0.039^{*}	-0.039^{*}
	(0.023)	(0.023)
Top1	0.091	0.092
	(0.073)	(0.073)
BoardSize	0.026^{***}	0.027^{***}
	(0.008)	(0.008)
_cons	-0.221^{**}	-0.225^{**}
	(0.108)	(0.107)
Industry FE	Yes	Yes
Year FE	Yes	Yes
Within R^2	0.087	0.087
F	6.469	6.479
Obs.	15102	15102

Note: Robust standard errors clustered at the firm level are in parentheses. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent authorizations. ASY represents the degree of information asymmetry. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

TABLE X
REGRESSION RESULTS OF ALTERNATIVE PROXY FOR LOW-CARBON INNOVATION (KAC AS THE MEDIATOR)

	(1) LCI	(2) LCI
Central	19.998^{**}	
	(9.194)	
Holes		0.048^{**}
		(0.023)
KAC	0.008^{***}	0.008^{***}
	(0.001)	(0.001)
ROE	0.382^{***}	0.387^{***}
	(0.083)	(0.084)
FirmLev	0.239^{***}	0.242^{***}
	(0.042)	(0.043)
FirmSize	0.002	0.002
	(0.002)	(0.002)
Dual	0.022	0.022
	(0.019)	(0.019)
SOE	0.027	0.028
	(0.020)	(0.020)
FirmAge	-0.018	-0.018
	(0.023)	(0.023)
Top1	0.073	0.073
	(0.073)	(0.073)
BoardSize	0.025^{***}	0.026^{***}
	(0.008)	(0.008)
_cons	-0.373^{***}	-0.379^{***}
	(0.118)	(0.118)
Industry FE	Yes	Yes
Year FE	Yes	Yes
Within R^2	0.088	0.087
F	7.993	7.885
Obs.	15102	15102

Note: Robust standard errors clustered at the firm level are in parentheses. *Central* denotes central network position. *Holes* denotes structural holes position. LCI stands for low-carbon patent authorizations. KAC represents the capacity for absorbing knowledge. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

TABLE XI
INDIRECT EFFECTS OF ASY AND KAC (SOBEL TEST)

Indep.Var	Mediator	Dep.Var	Direct effect	Indirect effect	The ratio of indirect effect to total effect	Sobel test
Central	ASY	LCI	20.091^{***}	4.335^{***}	17.75%	4.335^{***}
Holes	ASY	LCI	0.057^{***}	0.016^{***}	22.57%	0.016^{***}
Central	KAC	LCI	22.287^{***}	2.139^{***}	8.75%	2.139^{***}
Holes	KAC	LCI	0.061^{***}	0.012^{***}	16.45%	0.012^{***}

TABLE XII
INDIRECT EFFECTS OF ASY AND KAC (BOOTSTRAP ANALYSIS)

Indep.Var	Mediator	Dep.Var	Observed Coefficient	Bootstrap S.E.	*Z* value	*p* value	Confidence interval	
Central	ASY	LCI	4.335	0.713	6.08	0.000	2.938	5.733
Holes	ASY	LCI	0.016	0.002	5.41	0.000	0.011	0.022
Central	KAC	LCI	2.139	0.642	3.33	0.001	0.881	3.398
Holes	KAC	LCI	0.012	0.002	4.56	0.000	0.006	0.017

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Online Appendix (for online publication only)

Board Interlock Networks and Corporate Low-Carbon Innovation in China: Does Position Matter?

Online Appendix S. Supplemental Figures.

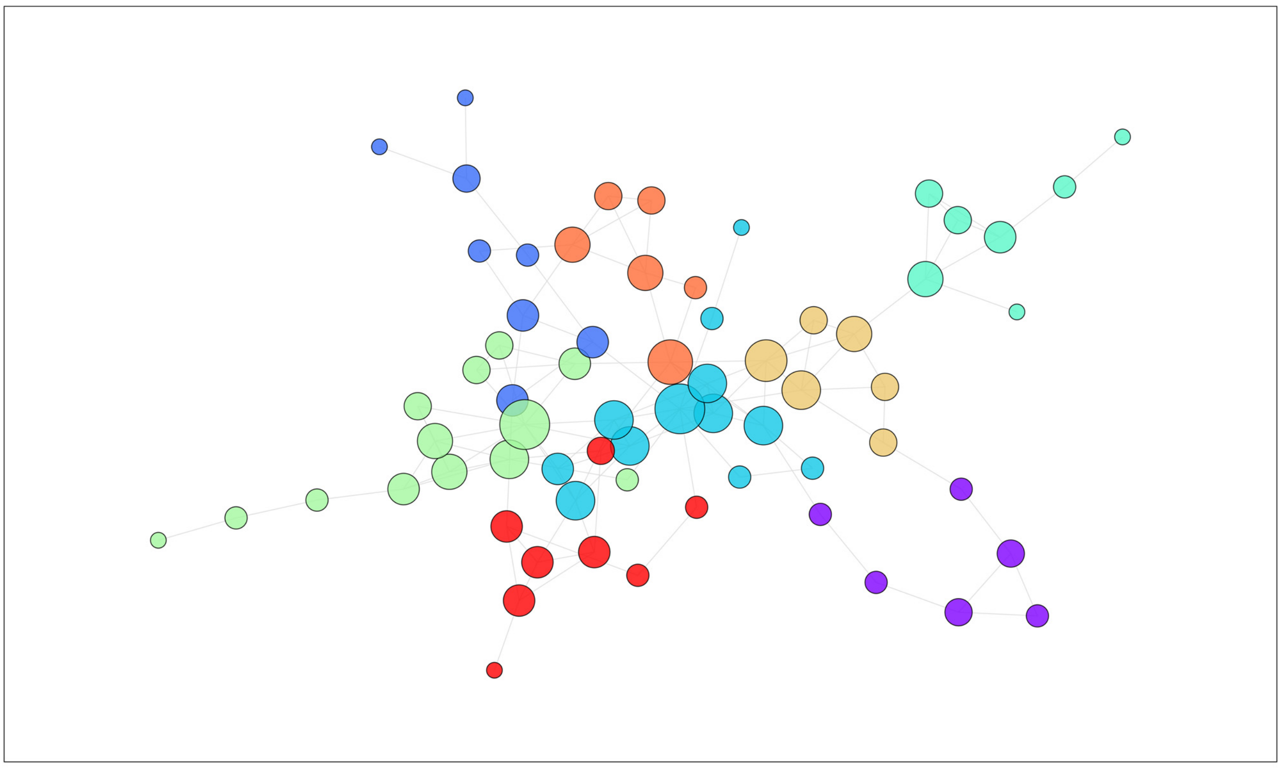

Fig. S1. The largest connected component of board interlock networks in 2010.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.634. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

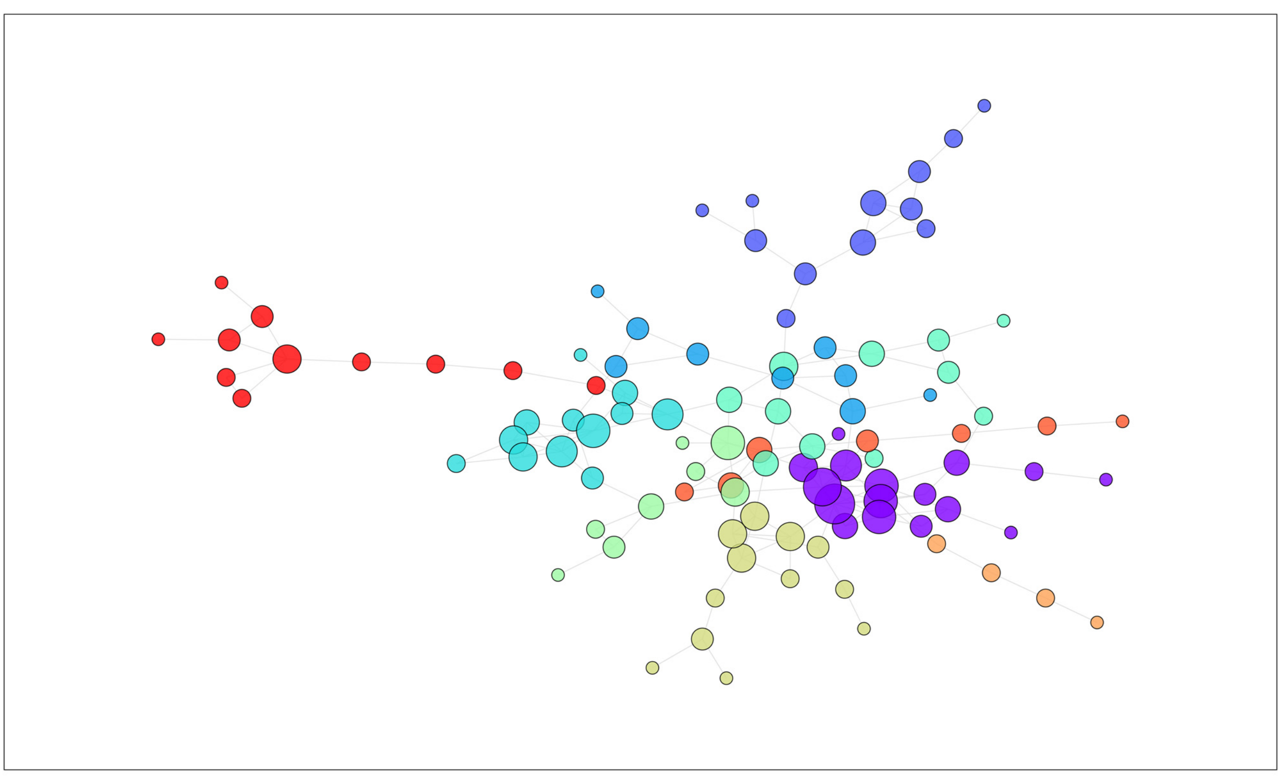

Fig. S2. The largest connected component of board interlock networks in 2011.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.721. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

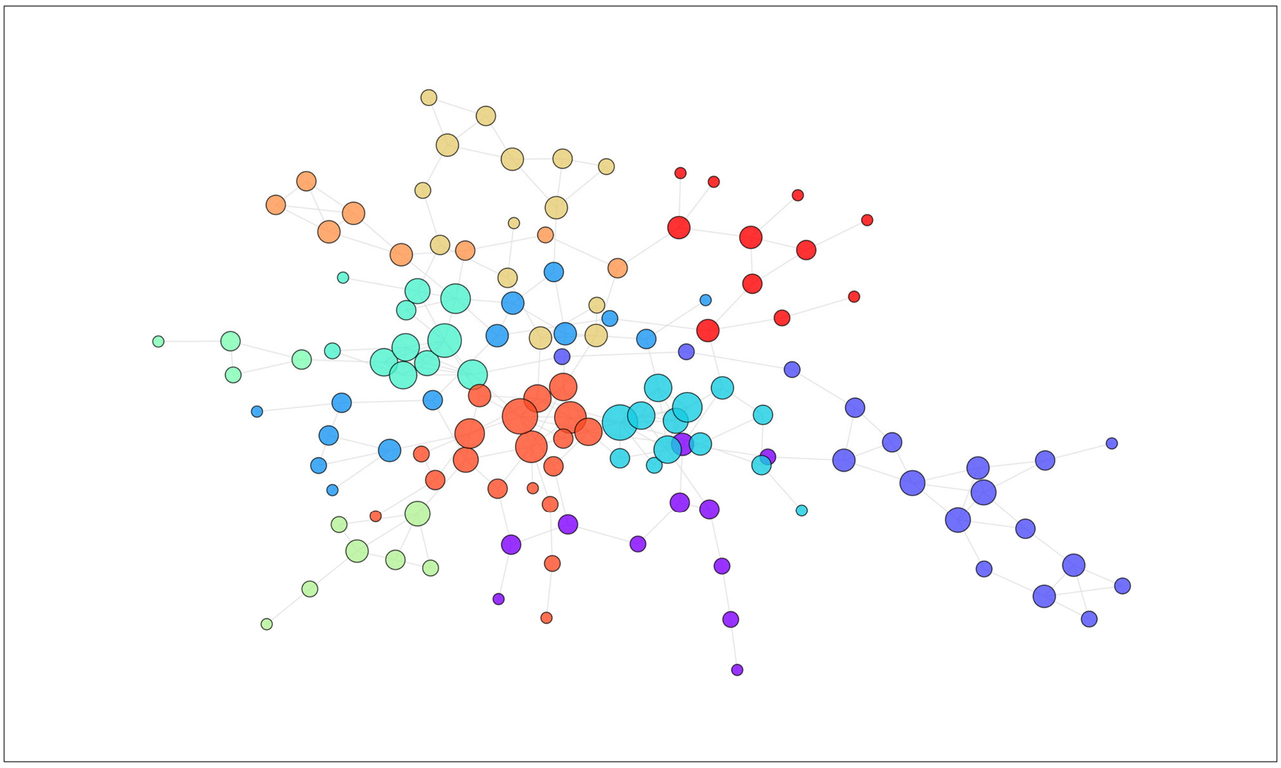

Fig. S3. The largest connected component of board interlock networks in 2012.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.743. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

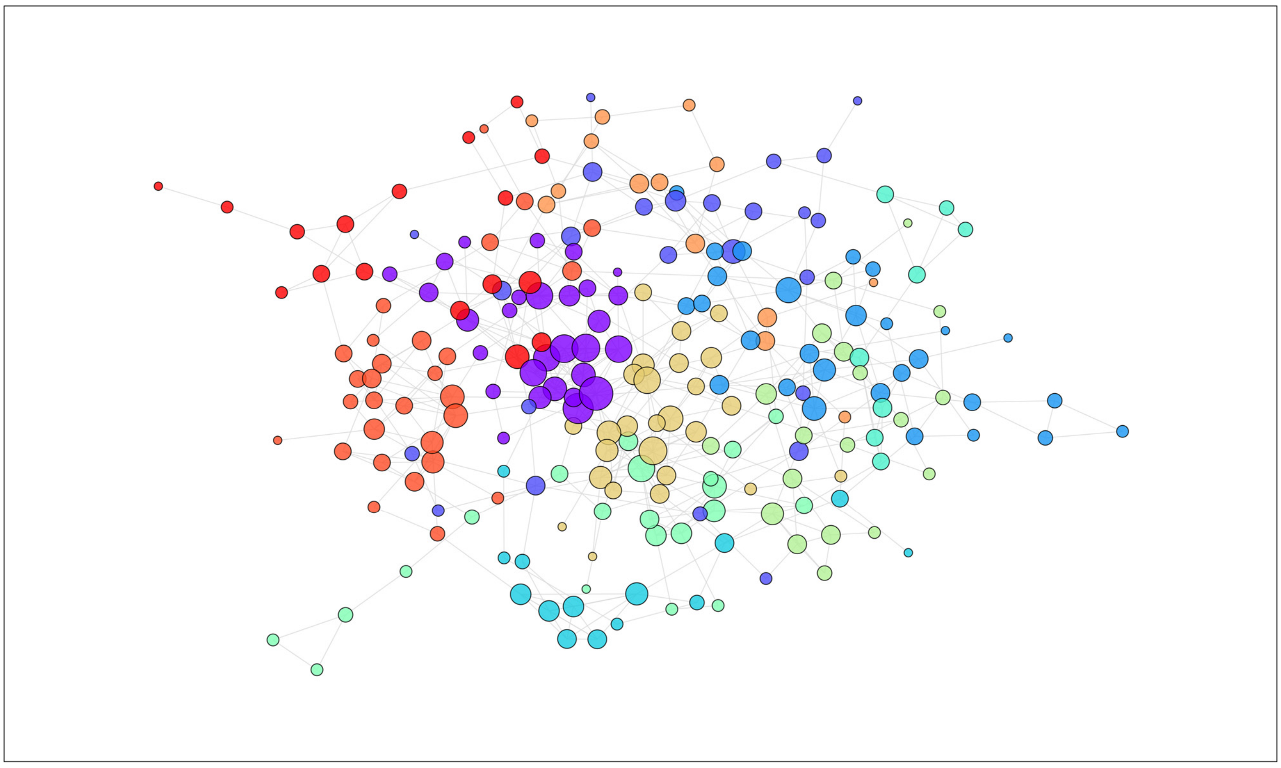

Fig. S4. The largest connected component of board interlock networks in 2013.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.732. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

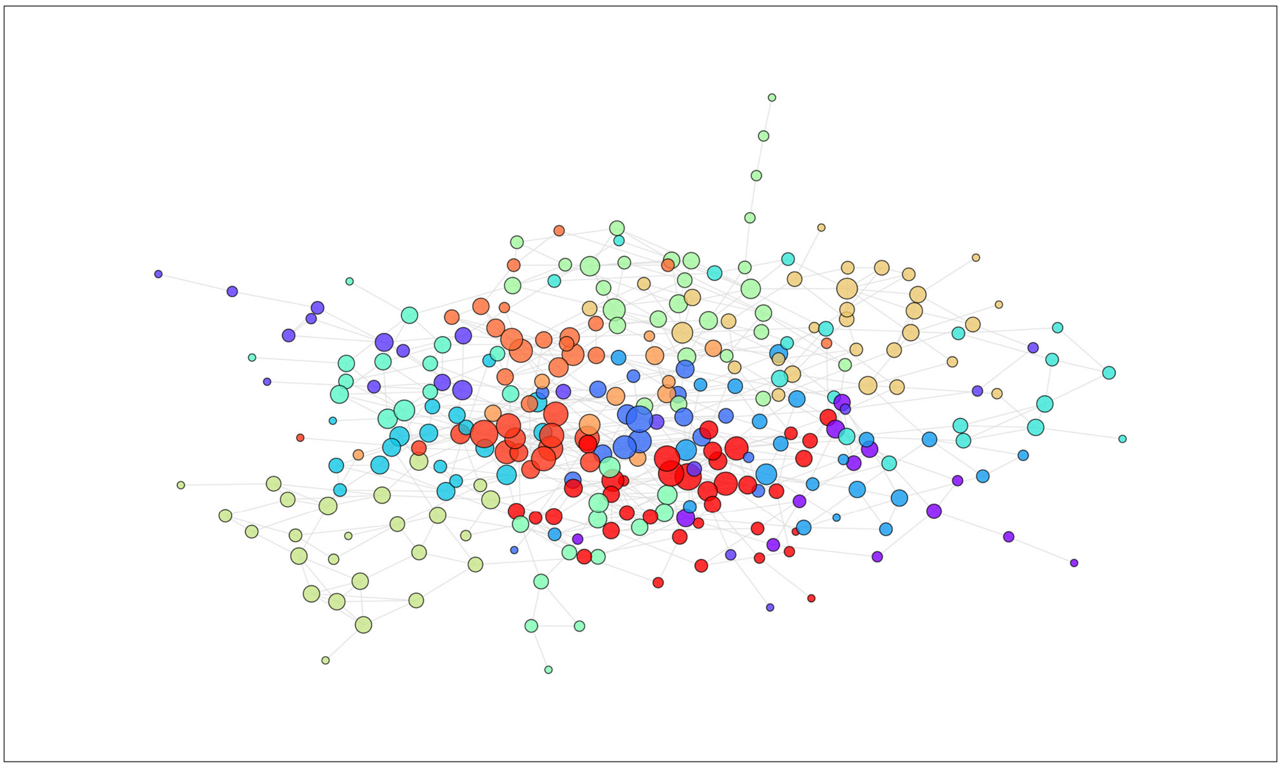

Fig. S5. The largest connected component of board interlock networks in 2014.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.712. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

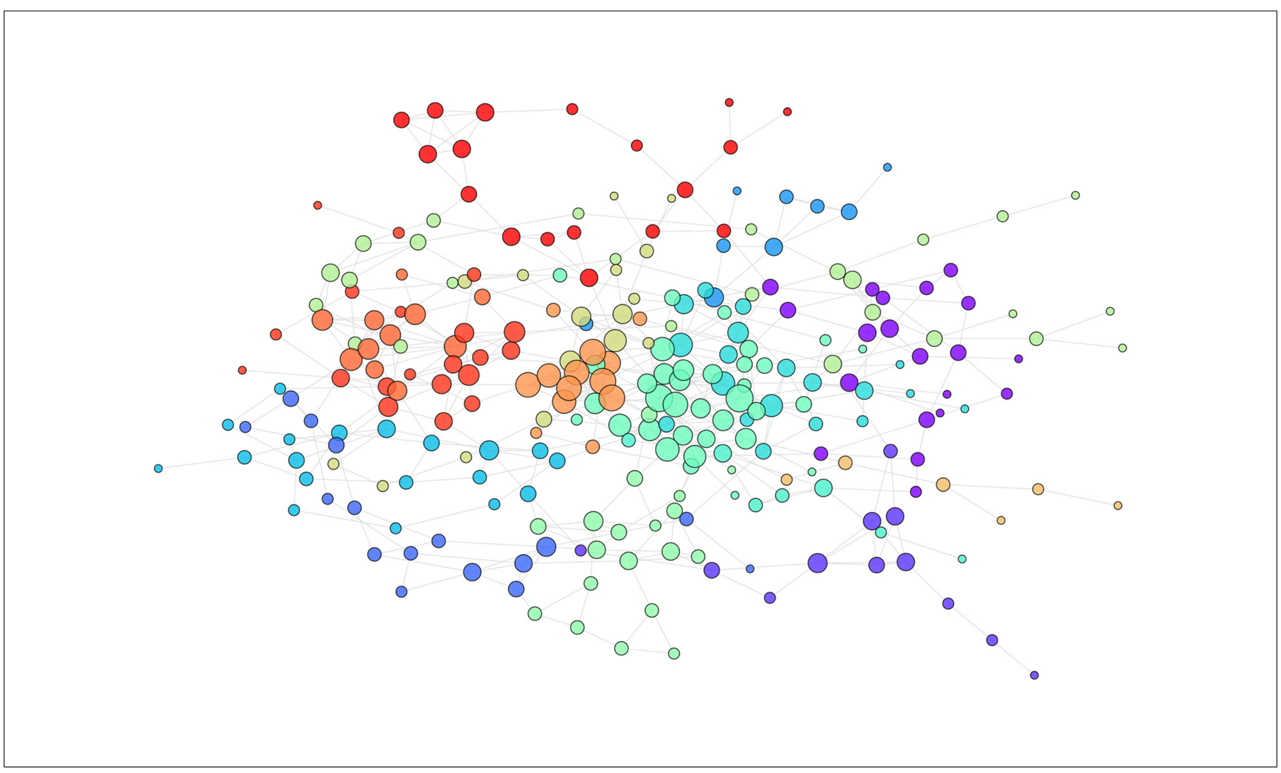

Fig. S6. The largest connected component of board interlock networks in 2015.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.751. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

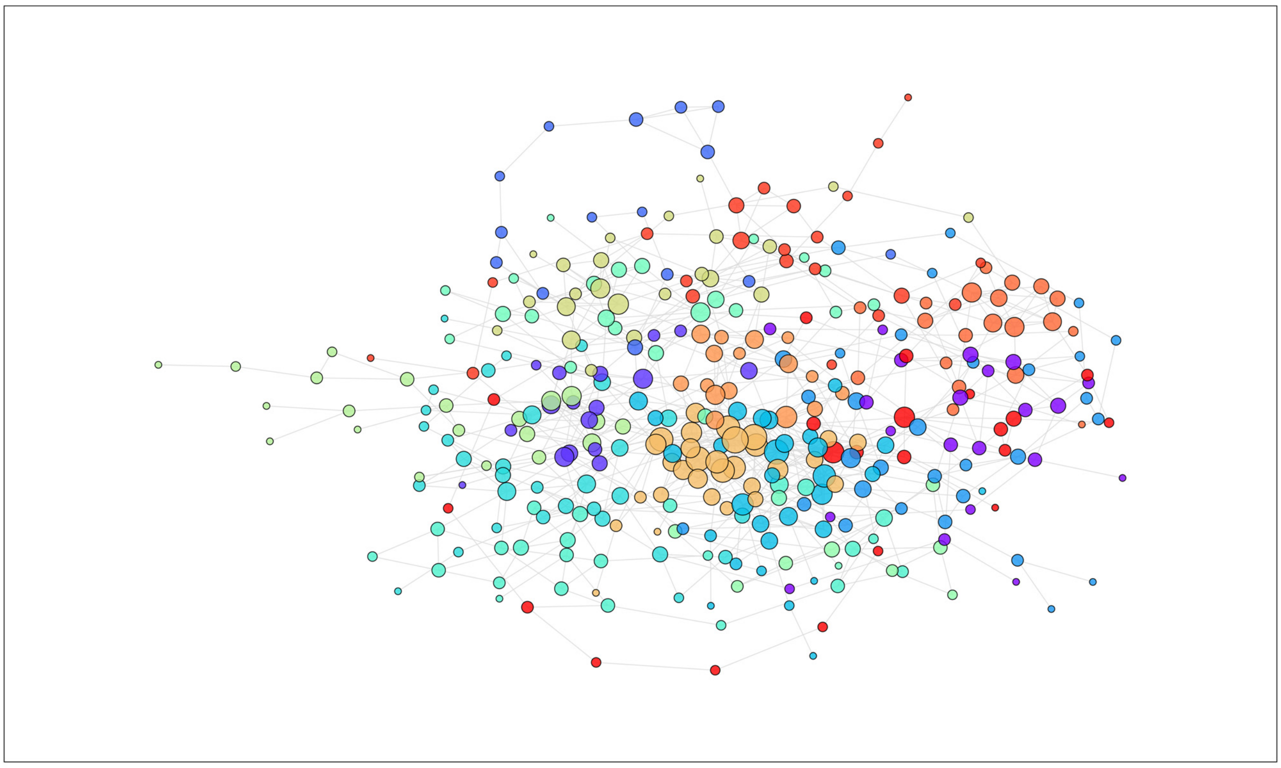

Fig. S7. The largest connected component of board interlock networks in 2016.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.714. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.

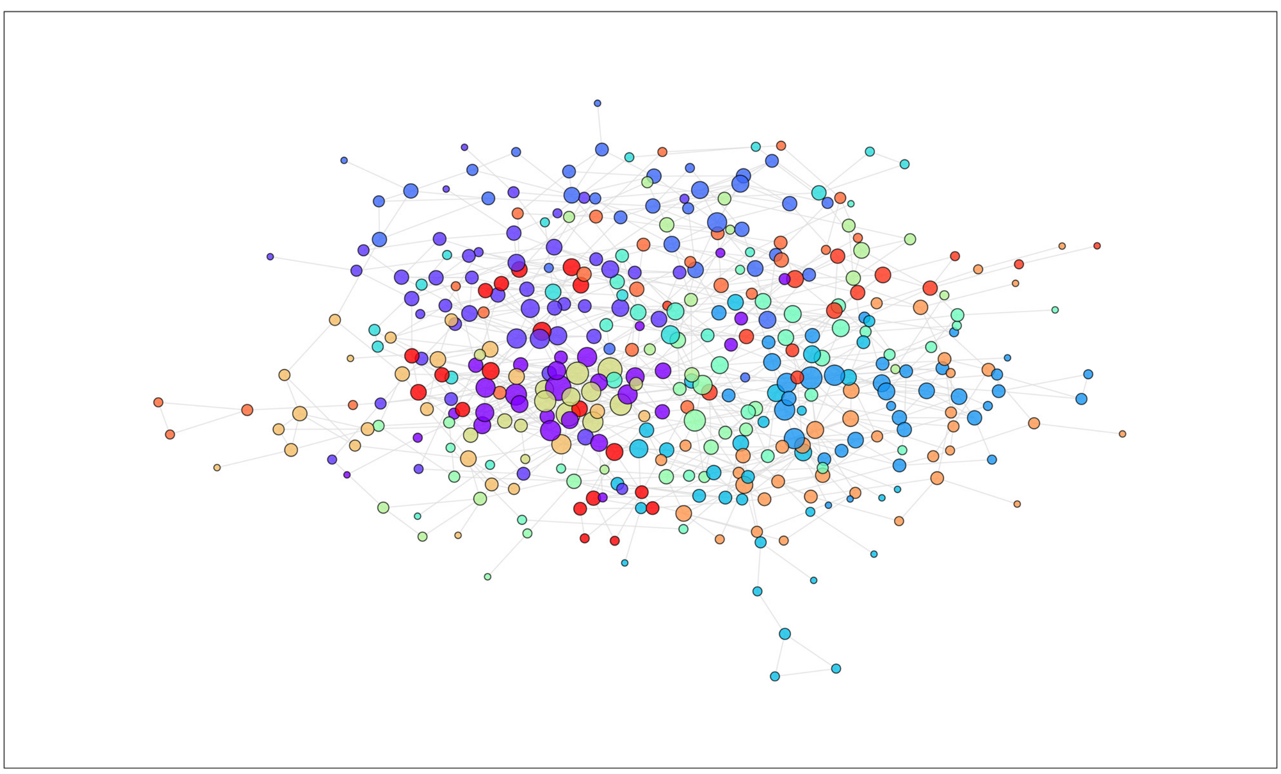

Fig. S8. The largest connected component of board interlock networks in 2017.

Notes: Each node denotes an individual firm. The size of a node is proportional to the number of its connections with other nodes. The color of nodes refers to the clustering results based on the community detection algorithm, and the corresponding weighted modularity score is 0.719. Nodes (i.e. firms) belonging to the same cluster are painted with the same color.