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Evolution of New Energy Vehicle Collaborative Innovation Networks in China

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Abstract

Technological innovation is a driving force of the continuously developing new energy vehicle (NEV) industry, in which establishing good collaborative networks plays an important role. However, studies on collaborative networks are rare. In this study, the overall structural laws and specific location of NEV collaborative innovation networks were identified by evaluating the NEV patent database obtained by China's State Intellectual Property Office for 2005–2021. The structural evolution laws and spatial development characteristics of these networks were analyzed from the perspectives of network topology, node centrality, and cohesive subgroups. Results show that the rapid development of China's NEV collaborative innovation networks is able to facilitate continuous breakthroughs in technological innovation, and innovative subjects become increasingly extensive and diversified. However, the influences of innovative subjects on technological innovation resources vary. For instance, the State Grid Corporation of China controls the flow of technological innovation resources of a certain network. Further analysis of space cohesive subgroups shows that the collaborative innovation space among subjects has non-significant adjacent characteristics. The collaboration and communication among subjects shall be strengthened, the collaborative innovation system must be perfected, and an integrated platform of the automobile industry during technological innovation shall be built. In this manner, the continuous and rapid development of the NEV industry can be ensured. The obtained conclusions provide references for the optimization of NEV collaborative innovation network structures and the enhancement of cross-regional collaboration.

Keywords: New energy vehicle, Technological innovation, Collaborative network

1. Introduction

Faced with intensifying international energy crises and environmental problems, countries seeking to take a leading role in global energy resource advancements have engaged in the research and development (R&D) and use of new energy resources dominated by "green energy." In the aspect of energy transformation and upgrading of the automobile industry, the development of the new energy vehicle (NEV) industry has become an important strategic choice for China to strengthen its international competitive advantage. In recent years, China's NEV industry has developed rapidly in response to calls for policy support and achieved remarkable success. However, this industry is currently facing bottlenecks in key core technologies, such as power batteries and drive motors. In consideration of the high R&D cost, risk, and uncertainty of technological innovation, some studies [1-2] recommended that collaborative networks be built to integrate knowledge, strengthen the innovation ability of enterprises, and increase innovative outputs during technological innovation as a means of improving R&D performance. This approach not only offers an important pathway for breaking the current technological challenges but also directs the future development of the NEV industry in China.

Existing studies on the technological innovation of NEVs have simply focused on the importance or characteristics of collaborative innovation, whereas the study on the dynamic evolution of collaborative innovation networks is rare. Consequently, the aim of this study is to determine the influences of collaborative subjects based on NEV technological collaboration patents and explore the evolution of collaborative networks. This study mainly focuses on two problems: (1) What are evolution laws of NEV collaborative innovation networks, and do they facilitate NEV industrial development? How do the network structures evolve, and which subjects have more prominent effects? (2) On the basis of the explicit structures of collaborative networks, this study analyzed whether the subjects have helped to develop NEVs, and then the spatial development laws of the collaborative networks were explored. Solving the aforementioned problems is conducive in disclosing the role of collaborative networks in NEV industrial development and formulating specific development strategies.

2. State of the art

Existing studies on NEV technological collaboration have mainly focused on two aspects: NEV collaborative innovation and collaborative networks.

With respect to NEV collaborative innovation, the research interest has centered on factors affecting the innovation of collaborative subjects. Scholars have attempted to analyze the influences of the government and market, multidimensional proximities, and other factors

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pertaining to the collaborative innovation of different subjects. First, Cao et al. [3] and Li et al. [4] found that subsidy policies and appropriate market mechanisms facilitate the collaboration between upstream and downstream enterprises in the NEV industry or among industry–university–research innovation subjects. However, as new energy technologies are developed or perfected, the marginal benefits of the policy effect tend to decrease. In terms of increasing the proportion of collaboration and its effective facilitation, Sun et al. [5] and Han et al. [6] proposed the appropriate selection of subsidy policies or the implementation of the double-credit policy. Second, scholars have mainly analyzed the influences of multidimensional proximity, such as geographical proximity [7-8], organizational proximity [9], industrial proximity [8], and cognitive proximity [9-10], on collaborative innovation. Their findings showed that adjacent effects can positively influence trans-regional and trans-industrial enterprise collaboration. Furthermore, as knowledge information develops, technological updating attributable to knowledge exchange gradually increases the influence of cognitive proximity on collaborative innovation. Finally, other influencing factors were investigated from the internal and external perspectives of enterprises. Studies mainly included the technological innovation ability of enterprises [11], relationships with partners [12], and innovation environment [13]. Scholars found that enterprises with strong technological ability tend to engage in collaborative research, and collaborative innovation is influenced by profit sharing and liquidated damage adjustments.

With respect to collaborative networks, associated studies have helped to form a relatively complete framework, namely, network characteristics, relationships, and evolution, with the analyses focusing on collaborative subjects, regions, and technological patents. In terms of network characteristics, scholars have used different indexes, analysis perspectives and analytic contents. Overall network structural characteristics (e.g., network density) were mainly selected for the static analyses and characterization of knowledge networks [14] and collaborative networks [15] in different regions. In terms of network relationships, Xiu et al. [16] and Li et al. [17] explored the relationships among collaborative subjects and their influence on technological innovation from the perspective of technological patents. Meanwhile, Ba et al. [18] determined the positive effects of knowledge integration and interaction among knowledge networks on innovation. In terms of network evolution, the studies included specific fields of technological innovation. Pu et al. [19] analyzed the technological innovation evolution of Li-ion storage batteries. And Xu et al. [20] analyzed the global NEV patent collaboration from the perspective of the position and distribution of core innovative subjects.

In summary, scholars have successfully analyzed the technological collaboration conditions of the NEV industry from different perspectives, including collaborative innovation and social networks. However, the studies on the structural evolution laws and spatial development characteristics of China's NEV collaborative innovation networks are relatively few. In this study, the structural evolution and spatial development laws of China's NEV collaborative innovation networks are explored via the social network analytical method from perspectives of network and individual positions based on the application data of NEV industrial patent collaboration from 2005 to 2021.

The remainder of this study is organized as follows. Section 2 reviews the studies on NEV technological collaboration. Section 3 presents the methods for data collection and network structural analysis. Section 4 presents the analysis of results, including the overall network characteristic description, node centrality analysis, and cohesive subgroup analysis. Section 5 summarizes conclusions and proposes suggestions.

3. Methodology

3.1 Data collection

The "patent retrieval and analysis system" developed by the Intellectual Property Publishing House of the State Intellectual Property Office of China was used as the patent retrieval tool, and keywords were used in the searching. In relation to existing studies, the keyword searching formula was formulated as follows: "electric vehicle" or "battery electric vehicle" or "plug-in hybrid electric vehicle" or "fuel cell vehicle" or "hybrid electric vehicle." The published papers were simultaneously searched for "title," "abstract," and "claims" to decrease missing entries. The date of data retrieval was January 31, 2022. After a thorough cleaning process, statistical analysis was conducted in Microsoft Excel. A total of 3,182 patents related to NEVs of 1607 collaborative organizations from 2005 to 2021 were obtained.

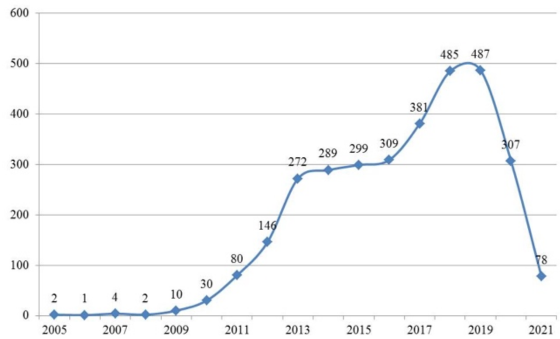


Fig. 1. Number of NEV patents granted per year, 2005–2021

The dynamic evolution of NEV patents granted yearly is shown in Fig. 1. The sample data were divided into four stages based on the annual growth. In Stage 1 (2005–2010), the annual patent quantity was less than 30, and it was in the low-growth stage. Stage 2 (2011–2013) was the fast-growth stage, and the annual increasing rate of patents was 112%. Stage 3 (2014–2019) was the stable increasing stage, and the patent quantity increased from 289 in 2014 to 487 in 2019. Stage 4 (2020–2021) was the stage of sharp reduction. Subsequently, the production was suspended due to unpredictable factors, such as COVID-19, and the patent studies decreased sharply. In general, China's NEV patent applications increased gradually from 2005 to 2021.

The application institutions of NEV patents are shown in Fig. 2. Since 2005, electric power and automobile enterprises, namely, the State Grid Corporation of China and Zhejiang Geely Holding Group Co., Ltd., have taken the leading role in patent application. Electric power and automobile enterprises are clearly fully mobilized in terms of the R&D of NEVs, hence their dominant role. This scenario implies that the potential of universities and research institutions have to be stimulated.

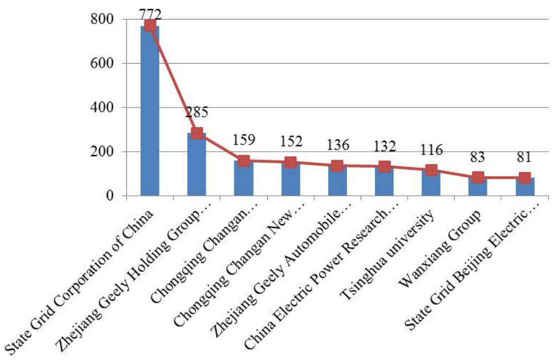


Fig. 2. Top ten applicants of patents in the NEV field, 2005–2021

3.2 Network structural analysis

In this study, the structural evolution of collaborative networks was analyzed using UCINET and GEPHI as the social network analysis software. UCINET is commonly used for network topological analysis and node centrality analysis [21]. Network topological analysis including the analysis of network density and the average clustering coefficient is useful in understanding the collaborative condition of the entire network. The importance and values of individual nodes were further analyzed by performing node centrality to examine the structural location of an individual node and assess its importance. Table 1 shows the measures, calculation formulas, and descriptions of the social network analysis conducted in this research.

Table 1. Definitions of the network topological analysis and node centrality analysis

Measures	Calculation formulas	Descriptions
Network density d	$d=\frac{2l}{n(n-1)}$	n refers to number of nodes, and l is the number of lines (hereinafter inclusive). The higher the network density, the tighter the network structure.
Connection number N	$N=\sum_{1}^{n} c_i$	c_i refers to the number of lines between adjacent points (hereinafter inclusive). It refers to the total connections among nodes in the network.
Network diameter L	$L=\max_{i,j} d_{ij}$	d_{ij} is the shortest path between any two nodes i and j in the network (hereinafter inclusive). The higher the value of L, the less information exchange and the stronger the resistance against information flow.
Average network distance AL	$AL=\frac{2}{n(n-1)}\sum_{i,j} d_{ij}$	AL is the average shortest distance of all nodes in the network. The higher the value of AL, the lower the sparsity of the network structure. Furthermore, the more difficult the information is transferred, the lower the efficiency.
Average degree ad	$ad=\frac{2l}{n}$	ad is the average number of collaboration nodes of each node. The average weighting degree is the mean of the weighting degree of the nodes.
Average clustering coefficient AC	$AC=\frac{1}{n}\sum_{i=1}^{n}\frac{2c_i}{C_{AD}(i)\left(C_{AD}(i)-1\right)}$	$C_{AD}(i)$ refers to degree of the node i (hereinafter inclusive). AC measures the clustering degree of the network and describes its overall cohesiveness.
Degree centrality C_{RD}	$C_{RD}=\frac{\sum_{i=1}^{n}\left(C'_{RD\max}-C'_{RDi}\right)}{n-2}$	C'_{RDi} is the relative degree centrality of node i. $C'_{RD\max}$ is the maximum value of the relative degree centrality of the node in the diagram, i.e., $C'_{RD}=\frac{C_{AD}(i)}{n-1}$. The node with a higher degree of centrality has more connected nodes and more partners, and it is more influential.
Betweenness centrality C_B	$C_B=\frac{\sum_{i=1}^{n}\left(C_{RB\max}-C_{RBi}\right)}{n-1}$	C_{RBi} is the relative betweenness centrality of node i. $C_{RB\max}$ is the maximum value in which node i may be accessed. It measures the resource control degree of nodes. The higher the value, the stronger the power and resource control force.
Relative betweenness centrality C_{RBi}	$C_{RBi}=\frac{2\sum_{j}^{n}\sum_{k}^{n}\frac{g_{jk}(i)}{g_{jk}}}{n^2-3n+2}$	$g_{jk}(i)$ is the number of shortcuts between nodes j and k that pass through node i. g_{jk} is the number of shortcuts between nodes j and k, where $j\neq k\neq i$ and $j<k$.
Closeness centrality C_C	$C_C=\frac{\sum_{i=1}^{n}(C'_{RC\max}-C'_{RCi})}{(n-2)(n-1)}(2n-3)$	C'_{RCi} is the relative closeness centrality of node i. $C'_{RC\max}$ is the maximum value that node i may be accessed, i.e., $C'_{RCi}=\frac{\sum_{j=1}^{n} d_{ij}}{n-1}$. It measures the ability of an actor that is beyond the control of other actors.

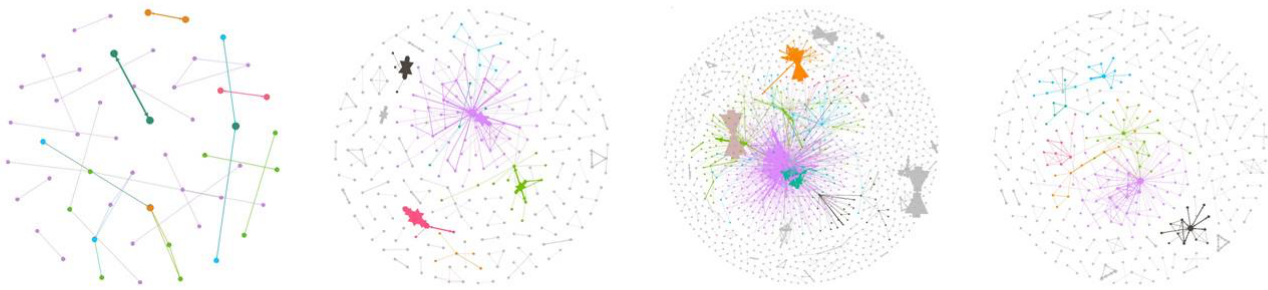
4. Results analysis and discussions

4.1 Network visualization and topological analysis

NEV patent collaborative networks were constructed using UCINET by referring to patent collaboration application data classified into four stages (2005–2010, 2011–2013, 2014–2019, and 2020–2021). The visual evolution diagram of the collaboration network in the stages was plotted using GEPHI.

Fig. 3 shows the preliminary visualization results. Each network has multiple connections at the center and discrete collaborative relationships with few connections in the peripheral regions. A node represents an innovative subject, in which the node size is set according to degrees (the number of participating entities in the patent collaboration). The higher degree of a node, the larger the node. The number of nodes in a network represents the network scale. The higher the number of nodes, the larger network scale. The thickness of connecting lines represents the number of patent collaborations among nodes. The thicker the connecting line, the higher the collaboration among nodes in the network.

Here, the nodes were classified according to the connected relations in the diagram, and the same type of nodes was marked with the same color. In this manner, a node set with close collaborative relations can be described intuitively. Then, the data of topological structural indexes were analyzed using UCINET.



(a) 2005–2010 (b) 2011-2013 (c) 2014-2019 (d) 2020-2021

Fig. 3. Evolution of the NEV patent collaborative networks

Table 2 shows the collaborative network scale, which has expanded by nearly 23 times from 52 to 1188 (i.e., from Stage 1 to Stage 3). The number of lines in the network increased from 72 to 4502. The increasing percentage across the different stages exceeded 300%, with the collaboration among nodes increasing gradually. In terms of new collaborative connections, they increased by 4132 in Stage 3, accounting for 91.78% of the total collaboration for the year. This scenario indicates an explosive growth among nodes in terms of collaboration and exchange in Stage 3. In Stage 4, the network scale decreased significantly, and the number of collaborations decreased sharply. However, the number of incumbents increased to 176, and continuous connections increased from 370 in Stage 3 to 472 in Stage 4. A continuous solid collaboration was established among certain nodes in the collaborative network.

Table 2. Collaborative network evolution analysis

	2005–2010	2011–2013	2014–2019	2020–2021
Persistent associations	—	18	180	246
Newly added associations	—	560	3208	578
Disappearing associations	—	48	398	3142
Incumbents	—	26	121	176
Newcomers	—	264	1070	220
Dropouts	—	26	169	1016
Network scale	52	290	1191	396
Lines	66	578	3388	824
Connection number	118	1616	9088	1456
Average degree	1.269	1.993	2.918	2.081
Average weighting degree	2.269	5.572	7.624	3.067
Network diameter	2	6	10	9
Network density	0.025	0.007	0.002	0.005
Average clustering coefficient	0.639	0.766	0.684	0.713
Average network distance	1.175	2.545	3.353	3.161

In general, the increasing rate of lines in the collaborative network is higher than the expansion rate of the network scale, and the trend of network density is decreasing. The collaborative network is relatively sparse. Meanwhile, the network diameter and average network distance increase continuously, while the network connectivity decreases gradually. Adding new nodes into the network increases the distance between two nodes, so there are many isolated nodes. This scenario suggests a relatively strong resistance against information exchange among nodes in collaborative networks. As for some fixed nodes, this configuration implies collaborative relationships, but a large collaborative space is still apparent among innovative subjects. The aforementioned patterns indicate the urgent need to build more extensive network collaborative relationships.

The average degree and average weighting degree of the nodes in this study both have rising trends. Some nodes are characterized by many collaborative relationships, indicating established collaboration. In the network, each node has at least one partner in Stage 1 and at least two partners in Stage 4, suggesting that the breadth of collaboration has only slightly increased. Nonetheless, from Stage 1 to Stage 3, the average weighting degree of the nodes is higher than the average degree, and the connection number of lines is higher than the number of lines. The differences increase gradually. This pattern indicates a significant increase in collaborative depth among nodes. The average clustering coefficient presents a gradual rising trend, and the interactions among nodes in the network are strengthened gradually. The findings imply that the collaborative depth among nodes in China’s NEV patent collaboration network has increased significantly.

4.2 Centrality analysis

The evolution of key nodes in the NEV patent collaboration network was analyzed using three centrality indexes (i.e., degree centrality, betweenness centrality, and closeness centrality, which can jointly reflect the importance of the nodes in the network structure). In this manner, the collaborative ability of a node with respect to other nodes, the ability of other nodes to control the collaboration in the network, and the ability of a node to be independent from other nodes in the information acquisition can be measured. The top three key nodes across the different stages were explored using UCINET.

As shown in Table 3, before 2010, universities and technology-based enterprises in Jiangsu Province and Zhejiang Province initiated the development of NEV technological innovation through their congenital advantages in scientific research and talent reserves. After 2011, the NEV industry was determined as a strategic emerging industry in the “12th Five-Year Plan.” Consequently, an increasing number of enterprises or research institutions engaged in electric power and automobile manufacturing participated in China’s NEV patent collaboration networks. According to the comparative analysis of the centrality data of the collaborative networks, the degree centrality of most nodes is positively related with betweenness centrality, but it is negatively related with closeness centrality. In other words, the core nodes of a network not only have a strong control force but also have a strong ability to be independent in acquiring information and influencing the knowledge flow in the network.

Table 3. Centrality analysis of collaborative networks

	Degree centrality	Closeness centrality	Betweenness centrality
2005 – 2010	Hangzhou Dayou Technology Development Co., Ltd.	Beijing Jiaotong University	Beijing Jiaotong University
	State Grid Zhejiang Electric Power Co., Ltd.	South China University of Technology	South China University of Technology
	Beijing Jiaotong University	Shanghai Jiulong Electric Power Technology Co., Ltd.	Chongqing Changan Automobile Company Limited
2011 – 2013	State Grid Corporation of China	State Grid Corporation of China	State Grid Corporation of China
	Zhejiang Geely Holding Group Co., Ltd.	Tsinghua University	Tsinghua University
	Zhejiang Geely Automobile Research Institute Co., Ltd.	China Electric Power Research Institute	China Electric Power Research Institute
2014 – 2019	State Grid Corporation of China	State Grid Corporation of China	State Grid Corporation of China
	Zhejiang Geely Holding Group Co., Ltd.	China Electric Power Research Institute	Tsinghua University
	China Electric Power Research Institute	Tsinghua University	Shanghai Jiao Tong University
2020 – 2021	State Grid Corporation of China	State Grid Corporation of China	State Grid Corporation of China
	Zhejiang Geely Holding Group Co., Ltd.	XJ Electric Co., Ltd	Tsinghua University
	State Grid Jiangsu Electric Power Co., Ltd.	Xuji Group Co., Ltd.	State Grid Shanghai Municipal Electric Power Company

The State Grid Corporation of China focuses on the new business of energy transformation and has been devoted to the development of clean and green energy resources as a means of meeting the power demands and positively influencing the development of electric power-related technologies. The firm has clearly dominantly controlled the collaborative network, superseding most partners in its network. Furthermore, it possesses more information resources and has the strongest ability to independently acquire information. It assumes the key hub position in information exchange and regulates information and resource flow among the nodes in the network. The State Grid Corporation of China also strongly controls the collaboration of other nodes in the network.

China's incentive policies pertaining to the technological development of NEVs have also motivated the other institutions in the collaborative innovation network. In terms of degree centrality, Zhejiang Geely Holding Group Co., Ltd., an automobile enterprise, is second to the State Grid Corporation of China, and its connections with other subjects have become prominently close over the years. Meanwhile, academic institutions led by Tsinghua University act as "bridge builders" of the collaborative network and connect different subjects, consequently enhancing the smooth resource sharing and information exchange. These two entities jointly greatly contribute to the innovation development of the NEV industry.

4.3 Space cohesive subgroup analysis

Cohesive subgroup analysis is a method of dividing node members with similar properties and close relations in a network. After dividing the internal correlations and groups of nodes in the network, the structural characteristics and interaction mechanisms of the different subgroups formed by nodes can be determined. In this study, the maximum depth of splits and convergence criteria were set to 2 and 0.2 via the iterative correlation convergence method using the CONCOR program. Then, cohesive subgroup analyses of the networks in the different regions were performed using UCINET. The different subgroups were marked on a map of China various in colors using ArcGIS. The results are shown in Table 4 and Fig. 4.

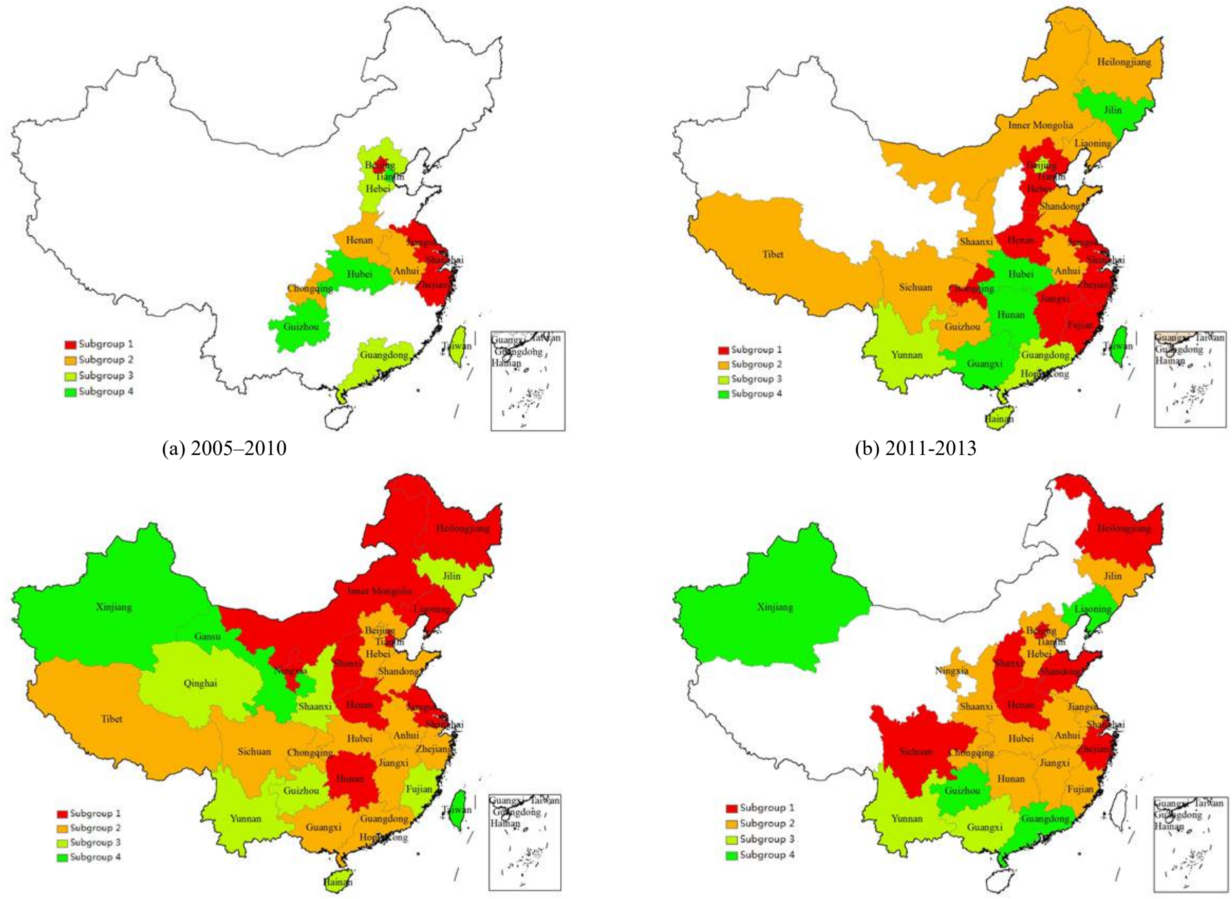
Table 4. Network density of condensed subgroups in different regions of China

	Subgroup 1	Subgroup 2	Subgroup 3	Subgroup 4
Subgroup 1	0.5/0.278/0.267/0.571	0/0.062/0.483/0.344	0.083/0.467/0.186/0	0/0.089/0.1/0.094
Subgroup 2	0/0.062/0.483/0.344	0/0.028/0.53/0.061	0/0.2/0.19/0	0/0.044/0.1/0.188
Subgroup 3	0.083/0.467/0.186/0	0/0.2/0.19/0	0/0.1/0.048/0	0.556/0.12/0.086/0
Subgroup 4	0/0.089/0.1/0.094	0/0.044/0.1/0.188	0.556/0.12/0.086/0	0.333/0.3/0.7/0.167

Fig. 4 shows the four major cohesive subgroups formed during the four stages of China's NEV innovation network building. As the internal and external environments for collaborative innovation shifted, the internal members of the different subgroups also changed. Meanwhile, as shown in Table 4, the internal densities of the four subgroups formed during the different stages changed continuously, but these changes were somewhat low. The internal members of the different subgroups have yet to form close interactions as they appear to operate independently from each other. A number of interactions and relatively stable collaborative relationships have been developed across certain regions, namely, Shanghai, Beijing, Zhejiang, and Jiangsu, in Subgroup 1. However, collaborations across adjacent regions appear to have changing patterns, and spatial adjacent characteristics among members in the subgroup are not yet prominent.

The density between subgroups is extremely low, indicating weak and sparse interactions across the four subgroups. The interaction is strong between Subgroups 3 and 4 in Stage 1. In Stage 2, the interaction and exchange across the four subgroups shifted to low. The geological distance across the NEV collaborative innovation network members, which are based in different provinces and regions in China, is not significant. The trends, combined with analysis of the collaboration network characteristics, indicate that the Zhejiang Geely Holding Group Co., Ltd., State Grid Jiangsu Electric Power Co., Ltd., and Shanghai Jiaotong University jointly function as the information control center. These enterprises and universities with strong R&D abilities are mainly located in developed regions. Their roles in the network suggest that technological information communication can solve the problem of geological restriction in R&D collaboration.

Regarding regional distribution, the enterprises participating in China's NEV industrial chains are mainly located in the coastal regions of Guangdong and Jiangsu. For instance, Tianci Material and Jiangsu Guotai supply electrolytes, anode and cathode materials, diaphragm, and other raw materials, while Ningde Contemporary Amperex Technology Limited supplies automobile battery parts. Regarding the distribution of representative NEV manufacturing enterprises, many of them are based in Guangdong and Shanghai, including BYD Auto and Guangzhou Automobile Group Co., Ltd. These firms are mainly concentrated in regions undergoing rapid economic development and have complete infrastructure facilities. They also benefit from the country's rapidly developing railway network construction, which breaks the existing spatial pattern, shortens the spatiotemporal distance, and facilitates the social resource exchange.



(a) 2005–2010 (b) 2011-2013

(c) 2014-2019 (d) 2020-2021

Fig. 4. Evolution of cohesive subgroups in China's regional collaborative network

5. Conclusions and suggestions

5.1 Conclusions

This study used social network analysis to identify the structural evolution and spatial development characteristics of collaborative networks in China by using NEV patent data from 2005 to 2021. The results of analysis showed that China's NEV collaborative networks underwent rapid development. The close and stable collaboration among subjects in the networks facilitated continuous breakthroughs and technological innovation. Nevertheless, the influences of subjects on the technological innovation resources significantly varied as the universality and diversity of innovative subjects increased, resulting in a sparse overall network. The State Grid Corporation of China occupied the core position in the evolution of the network and controlled the flow of technological innovation resources. Additionally, the spatial distribution of NEV innovative subjects was uneven during the network evolution, which can be attributed to the low sensitivity of the collaboration subjects to geological space. The spatial characteristics of adjacent regions in the regional collaboration were not significant.

5.2 Suggestions

The aforementioned conclusions not only are conducive to perfecting NEV collaborative innovation networks but also have important significance to regional innovation and integrated industrial development. Hence, some suggestions are proposed.

First, potential collaborative relationships among innovative subjects should be stimulated and strengthened to enhance the breadth of collaboration in the NEV industry. Collaborative networks can be combined with internal enterprise networks by building platforms for market demand information sharing and user feedback sharing, such as among automobile manufacturing enterprises led by Zhejiang Geely Holding Group Co., Ltd. This measure can shorten the information exchange and transfer path of the NEV industrial chain, improve the information transfer efficiency, stimulate the potential innovation ability of innovative subjects and increase their trans-industrial collaborative opportunities, and facilitate the innovation development of the NEV industry.

Second, the dominant role of key nodes in the NEV patent collaboration network should be fully considered. The collaborative relationships among innovative subjects have to be further solidified and deepened on the basis of existing collaboration. Furthermore, the collaborative innovation abilities of universities, research institutions, and automobile enterprises must be guided and stimulated with respect to the power resource advantages and information control of the State Grid Corporation of China. Universities are not only creators of new technologies but also the incubation base of innovative talents. They have a strong R&D ability and can build stable collaborative platforms, realize industry–university–research collaboration, and jointly facilitate the stable development of the NEV industry.

Finally, a regional collaborative innovation system for facilitating automobile industrial integration must be perfected. Government departments in the different regions should strengthen the overall planning, improve the infrastructures, and facilitate the establishment of policy mechanisms related to the NEV industry. Moreover, the leading role of Shanghai, Beijing, and Zhejiang in innovation must be mobilized, and the closed-loop collaboration and exchange among upstream, middle stream, and downstream of the industrial chain in the different regions must be completed.

5.3 Study limitations

This study investigated collaborative innovation in the NEV field. Key attention was paid to the structural evolution laws and spatial development characteristics of collaborative networks. However, the measures used in this study were subjectively selected. Industry–university–research collaborative performance can influence independent innovation improvement and the enthusiasm of enterprises to a large extent. Collaborative performance has not been explored deeply in this study. Further study is required to determine the knowledge transformation laws of enterprises, universities, and research institutions. Collaborative innovation performance can be tested by analyzing the knowledge flow during collaborative innovation.

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