Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 21, No. 3, 2025

Cooperation Network and Enterprise Key Core Tech-Nology Breakthrough

-- Based on random forest model

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Abstract: The impact of cooperative network on enterprise innovation performance has been paid attention by the academic community. The importance evaluation of cooperative network on enterprise key core technology breakthroughs is the focus of this paper. This paper takes China's high-tech manufacturing industry from 2010 to 2020 as a research sample to build a cooperative network, uses a random forest-based machine learning model to measure the im-portance of cooperative network to the key core technology breakthroughs of enterprises, and further analyzes the relative importance of cooperative network features to fit the key core technology breakthroughs of enterprises. The findings are as follows: (1) Overall, the lack of cooperative network features will reduce the fitting performance of key core technology breakthroughs. (2) Rank the features in the cooperative network according to the degree of im-portance, and further use the partial dependence diagram to visualize the marginal impact of the three most important features, individual network size, number of intermediaries and proximity centrality, on the breakthrough of key core technologies of enterprises.

Keywords: Cooperation network; Enterprise key core technology breakthrough; Random forest; Influencing factor.

1. Introduction

Key core technologies are of great significance for promoting high-quality economic development and ensuring national security in China. In the face of the volatile international situation and the increasingly fierce global science and technology competition, the "choke point" problem of key core technologies has become increasingly prominent in its hindrance to the deepening of technological innovation and high-quality development of the industrial chain. If key core technologies cannot be firmly grasped, it will surely pose a major threat to issues such as the security of the national industrial chain and high-quality development, making how to achieve breakthroughs in key core technologies one of the major problems that China urgently needs to solve at present.

Enterprises are important entities for breakthroughs in key core technologies. Allocating innovation resources with enterprises at the core is a key measure to aggregate innovation elements, stimulate market vitality and build an innovation ecosystem. However, key core technologies have attributes such as strategic, high investment, embedding, knowledge complexity, and externality, and internal resources will be difficult to support the breakthrough of key core technologies of enterprises. Through inter-organizational cooperation, high-quality resources such as information, talent, knowledge, and technology can be obtained from the outside, and these valuable resources flow and transfer [1] through partnerships. It will provide new opportunities for enterprises to break through resource constraints and technological predicaments. The breakthrough of key core technologies is different from general technological innovation. Only by actively cooperating with multiple entities and enhancing technological research and development capabilities through information exchange and resource sharing can enterprises facilitate the systematic breakthrough of key core technologies.

The positional and structural differences in the cooperative network have an impact on the breakthrough of key core technologies of enterprises through various channels such as the cost of resource acquisition, the advantage of information combination and the ability to cope with uncertainty risks of the innovation subjects. The dynamics of the cooperative network are the externalization of the search activities of enterprises, and the characteristics of the cooperative network give enterprises the initiative [3] to adjust the external network by influencing the search behavior of enterprises. However, due to factors such as individual resource constraints and the uncertainty of external cooperation, whether a single entity can utilize the external cooperative network to achieve breakthroughs in key core technologies is affected by many aspects [2] such as scientific and technological talent resources, R&D investment and innovation capabilities. Therefore, How to promote breakthroughs in key core technologies of enterprises through the construction of cooperative networks has become one of the focuses of attention in the academic and industrial circles. An in-depth analysis of the relationship between the embedding of cooperative networks and breakthroughs in key core technologies of enterprises is of great theoretical and practical significance for organizations to break through resource bottlenecks and gain and maintain a competitive advantage position in the industry.

Research on the key core technology breakthrough through inter-organizational cooperation has received attention from the academic community, but related research is still in its infancy. Existing research mainly focuses on the construction effects of cooperative networks, such as proposing to strengthen the national science and technology innovation system starting from the role of government assistance, enhance independent innovation capabilities through the new national system, and establish a good innovation ecosystem to achieve breakthroughs in key core technologies. However, few studies have analyzed the impact of the characteristics of enterprise cooperative networks on breakthroughs in key core technologies from a micro perspective. The reason for this might be that the closed-loop and integrity required when building cooperative networks make the calculation of network features difficult and the calculation process complex. This leads to the question: How significant is the role of cooperative network features in the breakthrough of key core technologies in enterprises, and is it appropriate to deliberately ignore such features because of their difficulty and complexity? How do cooperative network features such as network size, centrality, and structural holes affect breakthroughs in key core technologies of enterprises? The research on the above issues is of great significance for the correct understanding of the importance of cooperative network characteristics and for enhancing the ability of enterprises to break through key core technologies.

This paper uses a predictive model based on machine learning and takes China's high-tech manufacturing industry from 2010 to 2020 as the research sample to evaluate the importance of cooperative network features in the predictive model based on the fitting effect; And use the feature importance assessment method to examine the degree of importance formation of major features in complex networks and social networks in cooperative network measurement; Finally, a partial dependency graph is used to visualize the marginal impact of the three most important features - individual network size, number of middlemen, and proximity centrality - on breakthroughs in key core technologies of enterprises.

2. Theoretical Analysis

2.1. The Theoretical Basis and Influencing Factors of Breakthroughs in Key Core Technologies

Social network embedding theory suggests that enterprises can overcome their own bottlenecks by building trust with other organizations to deepen connections and embed themselves in the social networks of other organizations, thereby obtaining the resources brought by the embedded networks. Individuals who have a dominant position in the network can bring more abundant information and resources to the enterprise, which is conducive to the enterprise increasing its own resource stock; Individuals on the periphery of the network are unable to access key information and resources due to their disadvantageous position on the network, which is not conducive to the accumulation of knowledge of the enterprise itself. The stronger the stickiness between individuals, the more extensive and deep the information and resources they exchange (more essential information exchange); Conversely, the less sticky the individuals are, the more limited the information and resources they exchange. Structural embeddings focus more on positional metrics such as individual centrality and the number of structural holes; Relational embeddings focus more on the closeness of connections between individuals, namely strong and weak relationships. Structural embeddings and relational embeddings can be evaluated by individual network feature metrics.

Resource dependency theory is one of the important theories in organizational theory, whose core proposition is that all organizations must obtain the resources in the environment they are in to survive. As an economic organization, it is impossible for an enterprise to be self-sufficient in all its resources. It must rely on supply in the economic environment and exchange with other organizations to survive and develop. The breakthrough of key core technologies of enterprises requires a large input of resources such as capital, infrastructure, scientific and technological personnel, etc. Therefore, many factors have an impact on the breakthrough of key core technologies of enterprises based on the resource dependence theory, and the accumulated resources within enterprises are also the main source of innovation projects, which can be evaluated by financial indicators including total assets, R&D investment, etc.

Dynamic competition theory suggests that when an enterprise perceives a competitive attack launched by another enterprise, it will take action to counterattack out of motives such as maintaining or enhancing its competitive position. This competitive activity is carried out on a large scale and will eventually change the allocation of enterprise resources and also bring about changes in the structure of the entire industry. The breakthrough of key core technologies of enterprises is an important means of market competition. Enterprises carry out competitive attacks through the breakthrough of key core technologies and also counterattack through the breakthrough of key core technologies to protect the patent income of enterprises and promote the adjustment of industrial structure and the continuous development of the industry. The influencing factors selected based on the dynamic competition theory include market concentration (HHI).

The stakeholder theory holds that enterprises should take into account the interests of other internal and external stakeholders other than shareholders. Based on this theory, when enterprises carry out key core technology breakthrough activities, they also need to take into account the interests of all stakeholders, including creditors, suppliers, customers, institutional investors, employees, etc. In terms of internal governance, it mainly includes equity structure governance, as well as management-related factors. These factors can represent the extent to which the enterprise fulfills its responsibilities to various stakeholders, thereby representing the enterprise's innovation level and development potential, sending favorable signals to the market, optimizing the enterprise's image, and further promoting the development of the enterprise.

2.2. Characteristics of Cooperative Networks and Breakthroughs in Key Core Technologies of Enterprises

The underlying logic of key core technology breakthroughs is the acquisition, integration, and allocation of resources that flow through the cooperative network between organizations, and the degree of enterprise embedding in the cooperative network determines the quantity and quality [4] of key strategic resources that are aggregated, coordinated, and allocated within the cooperative network, and ultimately affects key core technology breakthroughs. Therefore, based on the network embeddedness theory and the resource-based theory, this study conducts a detailed analysis of how enterprises can utilize the dual embedding effect of cooperative networks to achieve breakthroughs in key core technologies, starting from relationship embedding and structural embedding.

Cooperative network relationship embeddings are used to describe the richness of cooperative relationships within an organization's cooperative network. Enterprises with close cooperative network relationships will effectively overcome the high technical barriers and monopolistic problems required for breakthroughs in key core technologies, which is conducive to breakthroughs in key core technologies of enterprises. First, a high level of cooperative network relationship is characterized by more corporate connections through which value co-creation among organizations can be achieved and more complementary resources can be obtained, thereby reducing the monopolistic nature of critical resources. Second, the increase in the degree of embedding of enterprise cooperative network relationships helps to enhance the timeliness of information transmission and reduce information asymmetry, and also helps to evaluate and search resources such as knowledge and technology in the cooperative network based on their own R&D needs, reducing the sunk cost of resource search and facilitating the improvement of the efficiency of breakthroughs in key core technologies. Third, the increase in the degree of relationship embedding in the cooperative network shortens the communication distance between enterprises and other organizations, which is conducive to the establishment of trust and collaboration mechanisms among R&D entities and reduces the risks in the process of breaking through key core technologies. Fourth, the embedding of cooperative network relationships helps to widely detect the latest R&D dynamics and market orientation, enabling enterprises to formulate and adjust the direction of technology research and development and product development in a timely manner, thereby crossing the "valley of death" and breaking through the barriers to large-scale commercialization of key core technologies.

Cooperative network structure embedding is used to describe the unique position and "bridging role" of the enterprise within the cooperative network. Enterprises with a high degree of cooperative network structure embedding help address the uniqueness and systematicness of key core technology breakthroughs, thereby achieving key core technology breakthroughs. First, existing research suggests that breakthroughs in key core technologies require strengthened multi-subject cooperation, which essentially demands cross-collaboration of knowledge in different fields, and the embedding of cooperative network structures helps alleviate the problem of homogenization of enterprise resources, promotes cross-learning in technology fields, provides diversified and heterogeneous technical and knowledge conditions for breakthroughs in key core technologies of enterprises, and stimulates the R&D vitality of enterprises To achieve breakthroughs in key core technologies. Second, the higher the degree of embedding of the enterprise cooperation network structure, the more likely it is to become a hub where heterogeneous knowledge converges, and the greater the sensitivity to key core technology breakthrough issues helps overcome cognitive lock-in barriers and promotes enterprises to explore and integrate core technologies and knowledge within different technology tracks, thereby leaping over the original technology tracks to achieve key core technology breakthroughs. Third, in the cooperative network, enterprises with a deeper degree of structural embedding generally have a higher position of resource control, which helps to communicate the research entities of industry, academia and research, coordinate the upstream and downstream of the industrial chain and the innovation chain, and achieve coordinated and systematic breakthroughs in key core technologies.

3. Research Design

3.1. Sample Selection and Data Sources

This study takes A-share listed companies in China's high-tech manufacturing industry from 2010 to 2020 as the research samples. The basic information and financial data of the listed companies used are from the CSMAR database, the patent information is from the PatSnap patent database, and the annual report text information is from the Juchao Information Network. The initial sample was processed as follows: ① ST company samples were excluded; ② Excluding patent samples with missing key indicators; ③ Exclude companies with severely missing data indicators during the observation period; ④ To mitigate the impact of extreme values, tail down continuous variables at the 1% and 99% levels. After collation, 594,287 invention patent applications and 372,942 utility model patents, as well as 7,493 company-annual sample observations, were obtained.

3.2. Feature Description

3.2.1. Build a Network of Partnerships and Related Features

Referring to existing research, this study builds a cooperative network based on joint patent applications between organizations, that is, when two organizations jointly apply for patents, they are considered to have a cooperative relationship. Taking into account the maintenance cycle of corporate cooperation behavior and the long-term nature of breakthroughs in key core technologies, this study constructs corporate cooperation networks based on a 5-year rolling window (t-4 years to t years). 11 metrics of cooperative network characteristics were calculated through Python's built-in NetworkX library, including centrality metrics such as mediating centrality, proximity centrality, and eigenvector centrality; Structural hole metrics include network constraint coefficient (limiting system), equivalence index, network effective size, efficiency, and clustering coefficient; Individual network size; Individual net density; Number of middlemen.

3.2.2. Benchmark Features

In addition to cooperative network characteristics, this article also lists other internal company characteristics that may affect breakthroughs in key core technologies. The benchmark model includes seven types of characteristics, namely financial strength, growth ability, debt-paying ability, operational ability, research and development ability, corporate governance, and corporate nature. The first category of financial strength includes the size of the enterprise. The second type of growth capacity includes return on assets and corporate performance. The third type of debt-paying ability includes the debt-to-asset ratio and financial leverage. The fourth operational capacity includes product concentration. The fifth type of R&D capability includes R&D investment and the number of technical personnel. In the sixth category of corporate governance, it includes equity concentration and the integration of the two rights. The seventh type of corporate nature includes ownership nature and the age of the enterprise. The specific measures of the characteristic variables are shown in Table 1.

Table 1. Definition of Characteristic Variables

Type	Name	Symbols	Measurement methods
Cooperative network characteristics	Individual network size	Size	The number of other enterprises directly connected to the focus enterprise
	Individual network density	Densit	$D = \frac{2L}{n(n-1)}$
	Number of middlemen	Broker	If Business A needs to go through Business B to connect with Business C, then Business B is called the middleman
	Mediating centrality	Betweenness	$B_i = \sum_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}}$
	Approach centrality	inCloseness	$C_i = \frac{1}{n-1} \sum_{j=1}^{n} d_{ij}$
	Eigenvector centrality	Eigenvec	$EC_i = c \sum_{j=1}^{n} a_{ij} x_j$
	Network constraint coefficients	Constra	$CT_i = \sum_j \left(P_{ij} + \sum_q P_{iq} P_{qj} \right)$
	Equivalence index	Hierarc	$HI_j = \frac{\sum_j \left(C_{ij}/\frac{C}{n}\right) ln\left(C_{ij}/\frac{C}{n}\right)}{nln(n)}$
	Network Effective Scale	EffSize	$ES_i = n - \frac{1}{n} \sum_j \sum_q P_{jq}$
	Efficiency	Efficie	$EF_i = \frac{ES_i}{n}$
	Clustering coefficients	Clus Coef	$CC_i = \frac{2E(i)}{n(n-1)}$
Financial strength	Business size	Asset	The natural logarithm of total assets
Growth capacity	Return on assets	ROA	Net profit/total assets
	Corporate performance	TobinQ	Enterprise Tobin Q value
Solvency	Asset-liability ratio	DA	Total liabilities/total assets
	Financial leverage	Lev	Total liabilities/owner's equity
Operational capacity	Product concentration	HHI	Herfindal-hershman Index
Research and development capabilities	R&d input	RD	The natural logarithm of total R&D investment
	The number of technical personnel	TECH	The natural logarithm of the number of technical personnel
Corporate governance	Equity concentration	Top1	Number of shares held by the largest shareholder/total number of shares
	Two positions combined	Duality	1 if the chairman and the general manager are the same person, 0 if not
Nature of the company	Ownership nature	SOE	1 for state-owned enterprises and 0 for the rest
	Enterprise age	Age	The number of years since the establishment of the enterprise plus 1 takes the natural logarithm

3.3. Key Core Technology Breakthrough (BT)

Drawing on previous research, this study measures the situation of enterprises winning high-level scientific and technological innovation awards such as national or provincial-level science and technology progress awards, national industry association science and technology awards, and China Patent Awards. The reasons are as follows: ① High-level science and technology innovation awards are a concentrated reflection and important indicator of an enterprise's ability to break through key core technologies. They are granted at the national level to organizations that have made creative contributions in basic research, major scientific and technological innovation, and breakthroughs in key core technologies, and are typical, authoritative and comprehensive. ② Winning a high-level science and technology innovation award is not only an acknowledgement of past efforts for leading enterprises, but also a boost for future development, indicating that the enterprise has a certain ability to break through key core technologies and has been officially recognized by government departments and the industry; ③ The award-winning data is transparent, accurate, objective, easy to obtain and highly reliable.

Winning different levels of awards reflects the ability to break through key core technologies. For example, winning the Special Prize of National Science and Technology Progress represents the strongest breakthrough ability of the enterprise. The more awards a company receives and the higher the level, the stronger its breakthrough ability is to some extent. Based on this, the study values the breakthrough capabilities reflected by each award from high to low (see Table 2), and the annual breakthrough capability of the enterprise is the sum of the scores of all high-level science and technology innovation awards received in that year. Further, this study uses the natural logarithm of the combined value of the current year and the following two years (year t, t+1, t+2) plus 1 as the current breakthrough capability of the enterprise.

Table 2. Points Table for Various Awards

Award Names	Assignment
National Science and Technology Progress Special Prize/First Prize/Second Prize	9/8/7
National Industry Association Science and Technology First Prize/Second Prize/Third Prize	6/5/4
Gold/Silver/Excellence Awards for Chinese patents	6/5/4
Provincial and ministerial science and technology Progress (Special Prize)/First Prize/Second Prize/Third Prize	3/2/1

4. Empirical Results and Analysis

In this paper, benchmark features and cooperative network features are used as input variables for the model, and breakthroughs in key core technologies of enterprises are used as labels for the model output values. To eliminate the randomness of results from a single experiment, this paper randomly selects 80% of the training set data for modeling and the remaining 20% for testing the fitting effect, repeats the experiment 50 times, and finally takes the average of the results.

4.1. Descriptive Statistical Analysis

Table 3. Descriptive statistics of feature variables

Variable	Mean	Std. Dev.	Min	Max
BT	4.031	1.489	1	9
Size	25.354	14.346	0	79
Densit	51.344	13.112	0	68.32
Broker	239.897	271.474	0	1574
Betweenness	48.235	89.876	0	684.159
inCloseness	6.482	4.37	1.324	46.983
EffiSize	7.382	2.894	0	17.409
Effcie	.134	.038	0	.337
Constra	.068	.042	0	.725
Hierac	.007	.006	0	.028
Clus Coef	.532	.049	0	.605
Asset	21.840	1.542	10.842	31.310
Roa	.338	86.539	-146.161	509.77
TobinQ	2.356	61.846	.387168	14810.31
DA	.495	3.494	-.194	877.255
Lev	1.569	16.893	-106.260	2708.793
HHI	.205	.187	.0307	1
RD	17.483	1.575	.815	25.025
TECH	5.337	1.279	0	15.177
Top1	35.641	15.952	.29	100
Duality	.275	.446	0	1
SOE	.397	.489	0	1
Age	1.977	.90	0	3.526

Table 3 lists the breakthroughs of key core technologies of the enterprise and the descriptive statistics of each characteristic variable, including the mean, standard deviation, minimum value and maximum value. The minimum for breakthroughs in key core technologies of enterprises was 1, the maximum was 9, and the average was 4.031, indicating that the overall breakthrough capabilities of key core technologies of the sample enterprises were at a relatively low level and there were significant differences among enterprises. Among the cooperative network characteristics, the most notable is that the standard deviation of the number of middlemen brokers is the largest, with a minimum of 0 and a maximum of 1574, indicating that some companies in the industry are marginalized while others are at the convergence center of cooperation.

Figure 1 shows the heat map of symmetrical correlations among the characteristic variables, with each small square having a bluer color indicating a stronger correlation between the two variables. A good feature variable should be strongly correlated with the output label, but not correlated or weakly correlated with other feature variables, that is, the variable is not a redundant feature. If two variables are totally correlated, they are redundant features for each other. As a whole in Figure 1, most of the feature variables do not have a strong correlation. Therefore, it can be seen from the correlation analysis that there are no redundant features among the 22 variables.

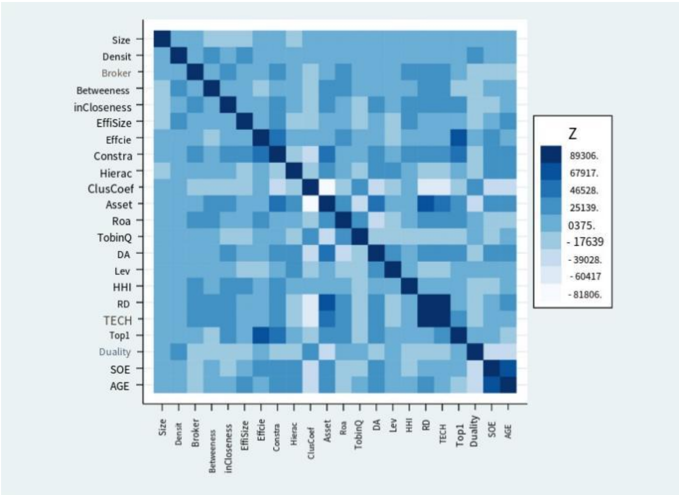

Figure 1. Correlation heat map

4.2. Analysis of Model Evaluation Results

This paper empirically examines whether and to what extent cooperative network characteristics improve the fitting effect of the enterprise key core technology breakthrough model using the random forest regression model, and uses three common indicators to evaluate the performance of the enterprise key core technology breakthrough model Including Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and CorrelationCoefficient (R2). Among them, MAE and RMSE both describe the difference between the regression values and the true values of the key core technology breakthroughs of the enterprise. The smaller the difference, the better the model fitting effect. R2 describes the correlation between the regression of key core technology breakthroughs of enterprises and the real values. The greater the correlation, the better the model fitting effect.

In Table 4, Group1 adds all 22 features as model inputs for fitting, Group2 selects features with an interpretation of over 98% for the model based on the random forest algorithm, Group3 adds cooperative network features to the baseline model, and Group4 adds only the baseline features. Table 3 reports the fitting effect of the random forest method, determining the contribution of cooperative network features to the predicted value of the enterprise's key core technology breakthrough.

First, the Group2 fitting in Table 4 is an improvement over Group1. In the random forest model, feature selection has significantly improved the fitting performance of the model, indicating that feature selection helps to enhance the model's fitting effect. Second, on the basis of Group2, the fitting effect shows a significant downward trend after removing the cooperative network feature (Group3). The interpretation R2 of Group3 in the random forest model was 2.33% lower than that of Group2 (0.9045-0.8812), and the interpretation R2 fitted by Group4 in the random forest model was more than 8% lower than that of Group2, without considering the cooperative network features. This further highlights the importance of cooperative network features.

Table 4. Fitting results of the Random Forest method

Model: BT	Group1	Group2	Group3	Group4
MAE	0.4821	0.2862	0.5941	0.8783
RMSE	3.3970	2.056	3.5842	3.7164
R2_Score	0.8738	0.9045	0.8812	0.8044

4.3. Feature Importance Results Analysis

To delve deeper into the importance of cooperative network features compared to other features and which features occupy a more significant position, this paper will use random forest feature importance to assess the impact of each feature variable, and the results are shown in Table 5. Overall, apart from the size of the enterprise, the cooperative network features have the highest level of importance. Among the characteristics of cooperative networks, individual network size, number of middlemen, and proximity centrality play very important roles, accounting for 11.3570%, 8.5704%, and 7.4085% respectively.

Table 5. Ranking of feature importance Based on Random Forest

Category	Feature variables	Importance %
Financial strength	Asset	50.4933
Cooperative Network Features	Size	11.3570
	Broker	8.5704
	inCloseness	7.4085
	Constra	2.5553
	EffSize	1.0448
	Densit	0.7868
	Efficie	0.1778
	Hierarc	0.1495
	Clus Coef	0.0617
	Betweenness	0.0031
Growth ability	ROA	1.5071
	TobinQ	1.2261
Solvency	DA	1.2999
	Lev	0.6522
Operational capability	HHI	4.5855
Research and development capabilities	RD	5.4389
	TECH	4.9837
Corporate governance	Top1	0.6917
	Duality	0.2654
Company Nature	SOE	0.2106
	Age	0.2047

4.4. Important Feature Partial Dependency Graph Results Analysis

To further answer the marginal effect between three important features in cooperative networks and breakthroughs in key core technologies of enterprises, this paper uses partial dependency graph analysis in Python, and the results are shown in Figure 2.

The horizontal axis in Figure 2 represents the standardized values of the cooperative network features, and the vertical axis represents the breakthroughs in the key core technologies of the enterprise. It can be seen from the graph that the functional relationship of the characteristics of the cooperative network to the breakthroughs of key core technologies of enterprises follows a power-law distribution. This result indicates that the three important characteristics of the cooperative network can reveal the degree of cooperation among enterprises from different perspectives. Among them, the individual network size reflects the number of enterprises that directly cooperate with the focus enterprise. The individual network size not only reduces the demand for enterprises to update the cooperative network, but also increases the opportunity for the cooperative network to update. Through inter-organizational cooperation, high-quality resources such as information, talents, knowledge, and technology can be obtained from the outside world. These valuable resources flow and transfer through cooperative relationships. It will provide new opportunities for enterprises to break through resource limitations and technological predicaments. The number of middlemen reflects the extent to which enterprises are affected by their partners. The larger the value, the stronger the stickiness between enterprises, the more extensive and deep the information and resources they exchange, and the more likely they are to cooperate based on trust, reducing transaction risks between enterprises, providing a strong guarantee for the exchange of information and resources in the cooperative network, and facilitating systematic breakthroughs in key core technologies. Proximity centrality reflects the shortest distance between enterprises and their partners. The greater the proximity centrality, the smaller the distance, and the more advantageous the position in the cooperative network. Different individuals have different access to information and resources due to their different positions in the network. Individuals who have a dominant position in the network can bring more abundant information and resources to the enterprise, which is conducive to the enterprise's ability to break through key core technologies.

The results verify the relevant conclusions of theories such as social network embedding and resource dependence, that in cooperative networks, enterprises can build trust with other organizations to deepen connections and embed into the social networks where other organizations are located, thereby obtaining the resources brought by the embedded networks and thus overcoming their own bottlenecks; Enterprises occupying the middleman position are often in the middle of other different enterprises, thus grasping the information and resources transmitted by other enterprises, and thus being able to control the flow of more information. This information control advantage can prompt enterprises occupying the middleman position to connect with enterprises with more diverse attribute characteristics, and often achieve breakthroughs in key core technologies. When in close proximity to the partner in the cooperative network, as the degree of cooperation deepens, the cooperative behavior among enterprises becomes more frequent, and the ability to break through key core technologies also increases.

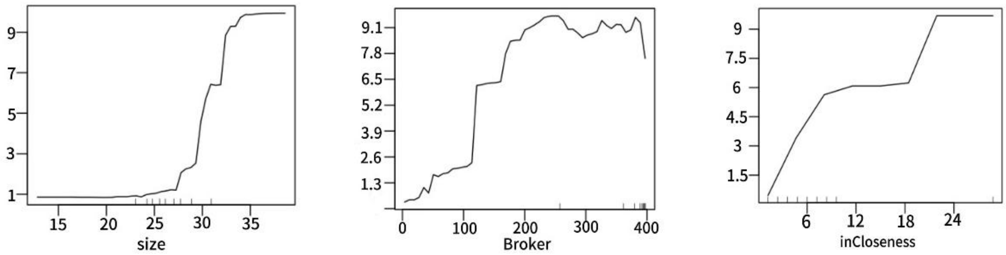

Figure 2. Partial dependency graph of cooperative network features

5. Robustness Test

To further illustrate the robustness of the results, this section analyzes different partitioning methods of the sample set and other commonly used machine learning regression models, etc. Overall, the results of the validation in this paper are robust, with the random forest fitting being the best.

5.1. A Rolling Time Window Is Used

To validate the robustness of the results, this paper will change the way the training and test sets are divided, using a 4-year rolling window, that is, 2010-2013 as the training set, 2014 as the test set, 2015-2018 as the training set, 2013 as the test set, and so on. Each training session is 50 times, and the average of the annual fitting results is taken as the final result, as shown in Table 6. After removing the features of the cooperative network, the error between the true value and the fitted value keeps increasing, and the correlation also decreases to some extent, indicating that our results are robust.

Table 6. fitting results using the rolling time window

Model: BT	Group1	Group2	Group3	Group4
MAE	0.5382	0.3049	0.5929	0.8939
RMSE	5.3221	4.7214	5.9219	7.3047
R^2_Score	0.8655	0.8709	0.8725	0.7646

5.2. Extreme Gradient Promote Regression Tree (ExtremeGradientBoosting XGBoost)

As an ensemble learning method, gradient Boosting regression trees draw on the idea of boosting ensembles, which essentially integrates multiple weak learners to construct stronger learners with better performance. When training each weak learner, the algorithm iterates along the direction of the negative gradient of the loss function against the predicted values of the previously trained strong learners, thereby constructing the label values of the training samples to guide the training of the weak learners, as shown in Table 7. In the model, after removing the cooperative network features, both MAE and RMSE are significantly improved, while R2_Score is decreasing, indicating the robustness of the results.

Table 7. Method Fitting Results of XGBoost

Model: BT	Group1	Group2	Group3	Group4
MAE	0.4297	0.3446	0.581	0.6199
RMSE	3.0925	2.9767	3.3792	3.5464
R^2_Score	0.9257	0.9481	0.94	0.8886

This paper also selects machine learning methods such as decision tree regression, gradient boosting regression tree, and support vector machine regression. The results also show that after removing the features of the cooperative network, the model's error keeps increasing and the R2_Score keeps decreasing, thereby demonstrating the robustness of the results.

5.3. Randomly Delete Some of The Data

From a data perspective, a more common robustness test is to exclude samples that may influence the conclusion. Therefore, this paper randomly deletes 100 data points from the study sample for reprocessing to eliminate the randomness brought by the sample. After randomly deleting 100 study samples, the size of individual networks, the number of middlemen, and proximity centrality in the competitive network still play a relatively important role, which once again demonstrates the robustness of the results presented in this paper.

Table 8. Ranking of feature Importance after random deletion of data (Based on Random Forest Method)

Categories	Characteristic variable	Importance %
Financial strength	Asset	60.453
Cooperative Network Features	Size	6.3970
	Broker	3.1404
	inCloseness	2.9085
	Densit	0.5553
	Constra	0.2948
	Hierarc	0.2368
	Clus Coef	0.1741
	Hierarc	0.1495
	EffSize	0.1217
	Betweenness	0.1031
The ability to grow	ROA	0.7071
	TobinQ	1.9291
Solvency	DA	0.6949
	Lev	0.6312
Operational capability	HHI	0.3855
Research and development capabilities	RD	4.2974
	TECH	3.4271
Corporate governance	Top1	0.5715
	Duality	0.2417
Company Nature	SOE	0.1307
	Age	0.0946

6. Conclusions and Implications

6.1. Conclusions

This paper takes China's high-tech manufacturing industry from 2010 to 2020 as the research sample to construct cooperative relationship networks and related characteristics, and empirically examines the importance of cooperative network characteristics to the breakthrough of key core technologies of enterprises through machine learning models based on random forests, and draws the following conclusions:

(1) This paper uses the machine learning method based on random forest to establish a regression model for the breakthrough of key core technologies of enterprises by listing the features that may affect the breakthrough of key core technologies of enterprises and the cooperative network. The results show that removing the features of the cooperative network significantly reduces the fitting performance of the model, verifying the importance of the features of the cooperative network to the breakthrough of key core technologies of enterprises. At the same time, machine learning methods such as extreme gradient boosting regression tree, decision tree regression, gradient boosting regression tree, and support vector machine regression prove the robustness of the results.

(2) To further verify the importance of the cooperative network and the degree of importance of each variable in the cooperative network features, this paper uses the feature importance assessment method based on the random forest model to calculate the relative importance of each feature variable. From the results, it can be seen that the cooperative network features have an impact of about 30% on the breakthrough of key core technologies of enterprises, which is much higher than the impact of the benchmark features. Among them, the features that account for the importance are the size of the individual network, the number of middlemen, and the proximity centrality.

(3) This paper uses the SHAP interpretation model to analyze the intrinsic mechanism of the impact of cooperative network features on the breakthrough of key core technologies of enterprises. The results validate the relevant conclusions of theories such as social network embedding and resource dependence, that in cooperative networks, enterprises can build trust with other enterprises to deepen connections and embed into the social networks where other enterprises are located, thereby obtaining the resources brought by the embedded networks and thus overcoming their own bottlenecks.

6.2. Implications

In order to better leverage the role of cooperation networks in enhancing enterprises' ability to break through key core technologies, specific practical insights are as follows: From the perspective of the government, first, build an industrial innovation and technology cooperation ecosystem, improve and strengthen the intellectual property management system, actively build diversified cooperation networks through multiple channels, encourage knowledge sharing and cross-border exchanges and cooperation, and enhance the embedding degree of enterprise cooperation networks. Second, cultivate innovative talents with innovative consciousness, comprehensive ability and international frontier vision, strengthen the reserve support force of cooperation network embedding, and enhance the efficiency of enterprises' breakthroughs in key core technologies. Third, improve the software and hardware facilities needed for breakthroughs in key core technologies, enhance the efficiency of resource orchestration, strengthen the advantages of embedded cooperation networks, and achieve breakthroughs in key core technologies with high efficiency. From the perspective of enterprises, first, actively build cooperative relationships with other innovation entities, focus on the construction and development of multilateral relationships, and occupy and utilize network bridging positions in order to provide resource acquisition, integration and control advantages for breakthroughs in key core technologies. Secondly, firmly adhere to the technology diversification strategy, enhance the embeddedness of the cooperative network, continuously break through its own technology boundaries through cooperation, expand the level of technology diversification, delve into the application scenarios of technology diversification, and explore the breakthrough strategies of key core technologies from different technology perspectives. Finally, actively enhance absorption capacity, continuously attract high-level talents to enrich the enterprise talent pool, and strive to digest and absorb the dual embedding degree of the network to empower the efficient breakthrough of key core technologies.

The findings of this paper offer some implications for research in related fields: (1) The important role of cooperative network characteristics in the breakthrough of key core technologies of enterprises cannot be ignored. With the continuous advancement of data science, data augmentation techniques such as generative adversarial networks and transfer learning help us infer the structure of the unknown network based on known network structures and some samples of the unknown network, in order to expand the application of cooperative network features in various industries in the breakthrough of key core technologies of enterprises. (2) In the process of enhancing the ability of enterprises to break through key core technologies, attention should be paid to the important features in cooperative networks, such as the size of individual networks, the number of man-in-the-middle, and proximity centrality. (3) According to the partial dependency graph analysis of the SHAP model, there is a power-rising characteristic between the important features of the cooperative network and the breakthroughs in key core technologies of enterprises, which supports the viewpoints of the social network embedding theory and the resource dependency theory.

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