On Innovation Performance of Low-Carbon Technology Breakthrough Innovation Network in Manufacturing Industry Under the Global Value Chain: A Case Study Based on Chinese Manufacturing Industries

CHAOQUN DONG1 AND KEXIN BI1,2

1School of Economics and Management, Harbin University of Science and Technology, Harbin 150080, China
2School of Management, Harbin Engineering University, Harbin 150001, China

Corresponding author: Chaoqun Dong (dcq@hrbust.edu.cn)

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ABSTRACT The strengthening scientific and reasonable quantitative evaluation of innovation performance of low-carbon technology breakthrough innovation network in manufacturing industry under the background of economic globalization is of important significance, which can enrich relevant theoretical system of low-carbon technology breakthrough and improve the core competitiveness of Chinese manufacturing industries. In this paper, the scientific and reasonable quantitative evaluation of the innovation performance of low-carbon technology breakthrough innovation network is firstly determined as a dynamic (time-varying) evaluation problem, which involves multi-source influencing factors. Note that many evaluation objects in the innovation performance of an innovation network are gray, ambiguous and dynamic variables, which are difficult to be quantified and the collected industrial data has certain discreteness and fluctuation. Hence, a fuzzy clustering analysis on influencing variables of innovation performance of low-carbon technology innovation network is carried out via the sampling data from 28 manufacturing industries during 2011–2016. Moreover, an innovation performance evaluation model for low-carbon technology innovation network is constructed through analytic hierarchy process (AHP), grey theory and fuzzy clustering analysis. Based on this model, the qualitative and quantitative evaluations of innovation performances of the innovation network before and after low-carbon technology breakthrough are realized. The results show that the low-carbon technology breakthrough innovation has a positive effect on improving the development level of manufacturing industry. In addition, the construction performance evaluation model not only decreases the influences of subjective factors by combining qualitative analysis with quantitative analysis, but also applies the grey theory innovatively to determine the membership matrix. It realizes accurate, systematic and scientific evaluation of the innovation performance of the low-carbon technology breakthrough innovation network in the manufacturing industries. Finally, the research conclusions provide the theoretical and practical references to the strategic arrangement of the low-carbon technology breakthrough innovation in Chinese manufacturing industries.

INDEX TERMS Low-carbon technology breakthrough innovation, innovation network, innovation performance, Chinese manufacturing industries, AHP.

I. INTRODUCTION

With the continuous transition of global technological innovative ability, the innovation-driven development has become a core strategy of China’s economic development.

The innovation-driven development not only is the key factor to improve the overall innovation level of China, but also is an effective guarantee to improve the innovative efficiency. On May, 2016, the State Council of China issued the Outline of Innovation-driven Development Strategy of China. It stated that establishing a national innovative system is to construct an ecosystem of collaborative interaction of
various innovation subjects as well as smooth flow and high-efficiency configuration of innovation elements, form practice carriers, institutional arrangement as well as environmental guarantee for innovation-driven development, and set up an open and high-efficiency innovative system with explicit functional orientations of various innovation subjects, including enterprises, scientific research institutions, universities, social organizations, etc. In addition, the breakthrough innovation is a strong weapon for Chinese manufacturing industries to participate in international competition and the low-carbon technology breakthrough innovative achievements are core technology of industries [1]–[4].

Recently, the climatic changes have become the primary global environmental problem at present. The climatic changes are widely accepted as the consequence that human uses a great deal of fossil fuels which can increase CO₂ concentration in atmosphere in order to pursue the rapid development of material lives. In order to relieve the environmental pressure, realize sustainable development and maintain economic-environment harmony, how to control and constrain energy consumption and carbon emission becomes the primary task of countries in the world. This is the sign that human society enters into an era of low-carbon economy. The low-carbon economy was proposed officially by the British government in the Energy White Paper in 2003. The low-carbon economy establishes an economic development mode which incurs less greenhouse gas emissions compared to existing economic mode through energy reform based on technological innovation and government policies, aiming to realize the goal of relieve climatic changes. The technological progresses which are needed to develop the low-carbon economy refer to the low-carbon technologies that can decrease the carbon emission level in the production process rather than ordinary technological progresses which can only increase the production efficiency only. Therefore, the innovation and applications of low-carbon technology as important indispensable support to the low-carbon economic development are core impetus needed to develop the low-carbon economy [9]. As one of important routes to realize the goal of greenhouse gas emission reduction, accelerating low-carbon technological innovation has been widely accepted in the world [10].

Motivated by the above discussions, in this paper, the influencing mechanism and influencing factors of innovation performance of the low-carbon technology breakthrough innovation network in manufacturing industries are investigated by combining studies concerning updating of manufacturing industries and low-carbon technology breakthrough innovation. An evaluation model of innovation performance of low-carbon technology breakthrough innovation network for manufacturing industries is constructed to quantify the performance of Chinese manufacturing industries under the
global value chain. The research conclusions provide theoretical references for development and progresses of low-carbon technology breakthrough innovation for Chinese manufacturing industries, enrich and perfect relevant theoretical systems. This study is conducive to increase the low-carbon technology breakthrough innovation activities and strengthen the core competitiveness of Chinese manufacturing industries.

II. THEORETICAL BACKGROUND
A. TECHNOLOGICAL INNOVATION AND LOW-CARBON TECHNOLOGICAL INNOVATION
Nature is the transformed object of the technological innovation. The technological innovation activity indeed is the transformation among materials, energy and information that participate in the whole ecosystem. Influenced by traditional values, human views nature as a plundered object only, but they don’t aware that human is a part of the natural environment. Accordingly, random emissions of various waste gases and wastes from indulged production by using materials and energy sources from nature cause serious threats to survival of other species. Now, this “edge” has hung over human beings. Moreover, the traditional technological innovation develops the energy reserves on earth without restraint for the purpose of rapid economic development and pursuing more economic benefits, which has caused significant tremendous barriers against continuous development of human.

The low-carbon economy is an economic system that follows the overall principle of nature and conforms to ecological law, which reduces the energy problem to the nature. By using the knowledge in ecology and system engineering, the low-carbon economy tries to use the energy sources reasonably and effectively in each stage of development, production, manufacturing, transportation and consumption, reduce the wastes of energy sources and waste emission, and set up a virtuous circle between human and environment. Moreover, the low-carbon economy overcomes the disadvantages of traditional technological innovation and establishes a new innovation system and evaluation system. Moreover, the carbon emission will be used as a measurement standard to value the low-carbon technology and it is applied to guide the practices of the low-carbon technology innovation [11], [12].

B. INNOVATION NETWORK AND LOW-CARBON TECHNOLOGY INNOVATION NETWORK
The scholars generally express the innovation network by either innovation network or university-industry network. In fact, the concept of innovation network is proposed for the first time in 1991, which mentioned that, different from ordinary cooperation network, the innovation network is a kind of basic institutional arrangement and serves for systematic innovation of subject. The main coupling mechanism of the innovation network structure lies in the innovative cooperation relations among different enterprises. Subsequently, some scholars found that as presenters and testers of innovative opinions, universities and scientific research institutions are vital to promoting the technological progresses of enterprises. Therefore, enterprises, universities and scientific research institutions constitute the subject of the innovation network together. However, “rule breakers” who consider the maximum of individual benefits may disturb formation and development of the innovation network since the innovation subjects pursue cooperation for different purposes. Therefore, the government which serves as the releaser of rights and policies plays an important coordination in maintaining stable operation of the innovation network. Besides, the financing institution and scientific and technological intermediary organization which are the financing parties of technologies and capitals serve as “a remover” in the innovation network and inject resources for continuous innovation of the innovation network. The innovation network is a product when technological innovation develops to a certain stage. Production and development of innovation network play an important role in innovation stimulation and operation of R&D subjects. In a word, this study defines the innovation network as a kind of network organization form which is built up by organizations at different levels based on a common innovative goal. The innovation network is to solve uncertainty of innovations, scarcity of resources and limitation of innovation capability, and help innovation subjects to realize the innovation goal by using external resources better. As a result, all subjects can benefit from the innovation network.

The low-carbon technology innovation has the characteristics of originality and key technological changes. Therefore, the breakthrough innovation network development strategy is generally a common state, while the breakthrough innovation competitive strategy is an abnormal state. However, the breakthrough innovation competitive strategy is inevitable to make breakthrough innovation to projects with explicit competitive bid. Moreover, it is common to have coexistence of breakthrough innovation network development strategy and breakthrough innovation competitive strategy. For the low-carbon breakthrough innovation in manufacturing industry, the low-carbon breakthrough innovation competitive strategy is an inevitable choice with considerations to the global situation of low-carbon problem, future development prospects of low-carbon economy and attentions and investment of countries to low-carbon innovation [13], [14]. Therefore, the low-carbon technology breakthrough innovation strategy of manufacturing industry adopts synchronous promotion of both the low-carbon breakthrough innovation development strategy and the low-carbon breakthrough innovation competitive strategy of manufacturing industries. Additionally, implementing the low-carbon breakthrough innovation network development strategy of manufacturing industries is to cope with the low-carbon breakthrough innovation competitive strategy of manufacturing industries better.
C. UPGRADEING OF AN INDUSTRIAL STRUCTURE AND LOW-CARBON TECHNOLOGY INNOVATION NETWORK BREAKTHROUGH INNOVATION

Upgrading of an industrial structure is a process of changes in industrial structural form. It is a process or trend of transformation from low-level form to high-level form and from quantitative changes to qualitative changes, finally achieving transformation in economic ways. Rationalization and supererogation of industrial structure are main relevant manifestations in upgrading of an industrial structure. The industrial structural changes can be realized through industrial structure supererogation, industrial structural rationalization and industrial structure efficiency. The industrial structural supererogation effect refers to flow of resources from a low-efficiency department to a high-efficiency department, thus realizing industrial structure supererogation. The industrial structural rationalization effect is to improve the overall balance of economic structure through free resource flows. In addition, the industrial structure efficiency is to increase use efficiency of resources in different departments.

There’s a positive interaction between the breakthrough innovation of low-carbon technology innovation network and industrial updating: the breakthrough innovation of low-carbon technology innovation network is conducive to production of various industrial sectors and can promote adjustment as well as optimization of industrial structure, thus facilitating upgrading of industries. The low-carbon technology breakthrough innovation can change the traditional industrial mode from the source to trigger great reforms in industrial structure and promote updating of manufacturing industries. On contrary, the breakthrough innovation of low-carbon innovation network occurs as a response to upgrading of industrial structure and some characteristics of upgrading of industrial structure bring new opportunities for low-carbon technology breakthrough innovation. The integration effect of upgrading of industrial structure also can promote the low-carbon technology breakthrough innovation effect and promote a new turn of technological innovation [15], [16].

D. UPGRADEING OF MANUFACTURING INDUSTRIES AND BREAKTHROUGH INNOVATION OF LOW-CARBON TECHNOLOGY INNOVATION NETWORK

The low-carbon breakthrough innovation of manufacturing industries promotes the upgrading of manufacturing industries by changing market demand structure and demand preference. In fact, the market demand is the root cause for the low-carbon breakthrough innovation in manufacturing industries, the potential business values can be brought only by continuous improvement of market demands, which can trigger endogenous power for low-carbon breakthrough product innovation in manufacturing industries. Since the low-carbon breakthrough product innovation in manufacturing industries changes the industrial demand structure in the innovation process, it is viewed as an important core element to promote upgrading of industries.

Secondly, the low-carbon breakthrough innovation of manufacturing industries may change the dominant industries and associations among different industries, thus promoting upgrading of manufacturing industrial structure. The low-carbon breakthrough innovation of manufacturing industries forms abundant low-carbon innovations through R&D of new technologies, which are beneficial to open new application fields and technological fields, and promote development of new technological system. In addition, based on complementation of knowledge, capability and profession through integration, low-carbon breakthrough innovation changes associations among different industries and drive rapid development of relevant industries, and finally promote industrial upgrading and optimization toward rationality and a higher advanced level. However, the low-carbon breakthrough innovation of manufacturing industries will surely cause impacts to traditional industries in the innovation process and urges traditional industries to make thorough changes to adapt to the current trend. Based on industrial changes, all industries are integrated in a reasonable way to form a new industry [17].

Thirdly, the low-carbon breakthrough innovation of manufacturing industries opens new technological orbits and promotes the upgrading of manufacturing industries by changing technological structures. The low-carbon breakthrough innovation not only makes it possible to get rid of dependence on international technologies, but also provides an option and points out a direction to further increase the innovation technological opportunities. Additionally, the ability and independence of low-carbon breakthrough innovation are manifested by the independent technological orbit. The ability of low-carbon breakthrough innovation technology is improved continuously by accumulating the technological capabilities in the process of orbit development.

III. ANALYSIS ON INFLUENCING FACTORS OF INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY INNOVATION NETWORK

A. EFFECTS OF TECHNOLOGY SPILLOVER ON INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY BREAKTHROUGH INNOVATION NETWORK IN MANUFACTURING INDUSTRIES

Nature is the transformed object of the technological innovation. The technological innovation activity indeed is the transformation among materials, energy and information that participate in the whole ecosystem. Influenced by traditional values, human views nature as a plundered object only, but they don’t aware that humans are a part of the natural environment. Random emissions of various waste gases and wastes from indulged production by using materials and energy sources from nature cause serious threats to survival of other species. Now, this “edge” has hung over human beings. Moreover, traditional technological innovation develops energy reserves on earth without restraint for the purpose
of rapid economic development and pursuing more economic benefits, which has caused significant tremendous barriers against continuous development of human. Among them, technology spillover means that technological knowledge which is created by technological innovation activity crosses boundaries of an organization and spreads the produced positive external effects to the outer world. Total revenues from technological innovation activities are increased through technology spillover.

**B. EFFECTS OF SOCIAL CAPITALS ON INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY BREAKTHROUGH INNOVATION NETWORK IN MANUFACTURING INDUSTRIES**

1) INTERNAL SOCIAL COST AND TECHNOLOGICAL INNOVATION

In a technology innovation network, the internal social cost of an enterprise is mainly reflected by its ability to gain resources and its position in the network. Since it is difficult to master the technological development trend accurately and the innovation process of enterprises is often full of uncertainty, an enterprise has to collect external information continuously to maintain consistency between technological innovation activities and market orientation. Whether an enterprise can acquire key external resources for their technological innovation activities is determined by learning ability, relation maintaining and network position of the enterprise. Some studies pointed out that the enterprises with richer internal social capitals are more able to use various connections in the network. The enterprise which can make full and reasonable use of various relation modes in the network can gain high trusts from partners, thus increasing transfer efficiency of implicit knowledge in the network and promoting success of product innovation. Additionally, the position of enterprises in the network plays a very important role in the acquisition of network resources. For example, the enterprises at structural holes possess outstanding advantages in exchange of information and knowledge acquisition.

2) EXTERNAL SOCIAL COST AND TECHNOLOGICAL INNOVATION

The positive effect of external social capital of an enterprise on technological innovation is mainly manifested by its effective utilization of embedded resources in the network. The primary function of social capital is that the network members can acquire essential information resources in time through tight connections and improve the quality of information they possessed. External social capitals are in all other members except the enterprise as well as the network composed by these members. Therefore, the enterprises have to interact with other members in the network and acquire more extensive external knowledge to maintain high efficiency of innovative activities in order to promote their technological innovative activities. Knowledge in high-speed flow and continuously accumulated innovative resources in the network are one of important bases for enterprises to develop the innovative cooperation. To realize the high-efficiency utilization of external social capitals, the enterprises must improve their learning ability and increase the desire for organizing learning, hence the technological cooperation efficiency of enterprises can be increased.

**C. EFFECTS OF TECHNOLOGY ABSORPTION ON INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY BREAKTHROUGH INNOVATION NETWORK IN MANUFACTURING INDUSTRIES**

The technology absorption strategy is one of technological strategies. Generally, the technology absorption strategy mainly covers three contents. Firstly, the technologies are introduced. Secondly, the enterprises master and digest knowledge, principle and applications of introduced technologies to expand and strengthen their own technological bases. Thirdly, the enterprises implement various types of technological innovative activities, train their own abilities in independent innovation ability and acquisition of independent proprietary intellectual property rights to develop technologies for implementation of technological imitation strategy as well as technology following strategy and technology leading strategy. For example, the Samsung in Korea adopts the technology absorption strategy in 1980s and 1990s.

The absorbing ability of green innovation systems can be divided into acquisition ability of green technology, assimilation ability of green technology and integration ability of green technology. In view of acquisition ability of green technology, the settlement of transnational company is beneficial to replenish behavioral subjects of green innovation systems and increase openness of economic environment. This not only expands the scope of external green technology searching, but also increases the enthusiasm and success rate of acquiring external green technologies. For assimilation ability of green technology, transnational companies will strengthen the connections with local enterprises continuously to integrate into the local industrial chain and use local resources more quickly. Moreover, they will provide technological guidance and assistances under certain conditions. As a result, the technology assimilation ability of green innovation system in Chinese manufacturing industries is increased. From the perspective of integration ability of green technology, the transnational companies not only provide new advanced technologies and high-level machines as well as equipments, but also bring non-materialization technologies, including management philosophy and technological selection. These have good demonstration and references for green innovation system of Chinese manufacturing industries to integrate the external technologies and even achieve secondary innovation.

The acquisition ability of green technology is beneficial not only for green innovation system of Chinese manufacturing industries to acquire new external green technologies, but also for mutual transfer and flow of green technologies among different innovation subjects in the green innovation system.
These can increase the knowledge source and knowledge base for green innovation in the green innovation system of Chinese manufacturing industries. Assimilation technology of green technology can help enterprises to acquire tacit knowledge contained in external green technologies and assimilate them into internal knowledge reserve of the system. Improving green innovation performance of the system depends on the assimilation process of acquired technology, including analysis, processing and using. The integration process of green technology is actually a process of structural understanding, in which new and old green technologies are integrated by exploring principle and know-how the acquired green technologies. In this way, a green technology structure with emerging functions is formed, which can improve green innovation performance in Chinese manufacturing industries.

D. EFFECTS OF OTHER FACTORS ON INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY BREAKTHROUGH INNOVATION NETWORK IN MANUFACTURING INDUSTRIES

1) EFFECTS OF TRANSNATIONAL TECHNOLOGICAL TRANSFER ON INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY BREAKTHROUGH INNOVATION NETWORK IN MANUFACTURING INDUSTRIES

The transnational corporation is a carrier to disseminate environmental-friendly technologies to developing countries and it brings advanced technologies and management experiences in addition to funds. More importantly, they follow the global uniform production standards and environmental standards and set a good example for enterprises in the host country. In [18], the authors mentioned that foreign-invested enterprises generally apply more environmental-friendly production technologies and pollution processing technology than local enterprises, and they bring the host country an opportunity to get green production technologies and force the host country to “clean” production process of existing industries to improve environmental technological levels. However, the technology spillover of transnational corporations is restricted by the minimum social abilities of the host country, including technical properties, seller’s strategy, buyer’s capability and social responsibility of manufacturing enterprises in the host country.

In addition, the technology spillover of foreign direct investment (FDI) of transnational corporations stems from the accumulation of their knowledge assets [19]. Such knowledge achieves technology spillover effect gradually through the one-way pipeline from “technology transfer of the transnational parent company to branch in the host country → spillover to local enterprises → changes in technology assimilation of local company”. This reflects that no technology spillover occurs in the internal technology transfer of transnational corporation from transnational parent company to its branch in the host country, and the reason is that such internal technology transfer often has stronger silence. Meanwhile, the competitive edges of green technology formed by internal technological transfer in transnational corporate may impose adverse competitive effect on enterprises in the host country. However, green technologies of branch of transnational corporation in the host country will “leak” to local enterprises during external technology transfer, forming positive spillover effect.

The technology spillover of transnational corporation has both positive and negative impacts on green innovation of the host country. Some studies argued that the technology spillover of transnational corporation has positive impacts on green innovation. As mentioned in [20], the FDI from transnational corporations can not only increase environmental technological level, but also induce diffusion of environmental technologies. Such diffusion might occur in the same sector of an industry or between upstream and downstream associated industries. Through a study based on provincial panel data of China during 1999–2009, reference [21] pointed out that FDI from transnational corporations has positive impacts on technological innovation of pollution control in China. Reference [22] tested above impacts with data of enterprise level and found that FDI generated relatively significantly vertical spillover effects on environmental technology in the host country. Based on study in [22], [23] decomposed environmental technology into green production technology and end treatment technology. They carried out a further study that horizontal spillover of FDI has positive impacts on both green production technology and end treatment technology. Moreover, vertical spillover influences end treatment technology slightly, but it has positive forward linking effect on green production technology.

Negative impacts of technology spillover of transnational corporations on green innovation of the host country are mainly manifested as “market stealing effect”. Reference [24] stated that transnational corporations have crowding-out effect on investment of enterprises in the host country and they occupy local market shares with technological advantages. Moreover, [25] reported that FDI has significantly positive impacts on green R&D ability and green manufacturing ability, but it produces negative impacts on market development capability of green products.

2) EFFECTS OF SOCIAL RESPONSIBILITY OF MANUFACTURING ENTERPRISES ON INNOVATION PERFORMANCE OF LOW-CARBON TECHNOLOGY BREAKTHROUGH INNOVATION NETWORK IN MANUFACTURING INDUSTRIES

The enterprise social responsibility refers to the responsibility that an enterprise assumes to community of shared interests. Taking manufacturing enterprises in the background of low-carbon economy for example, the social responsibility is mainly reflected by responsibilities in low-carbon production, manufacturing and social environmental protection. According to the stakeholder theory [7], the subjects in a manufacturing enterprise to fulfill social responsibility are divided into creditors, shareholders, consumers, upstream
and downstream enterprises in the supply chain and social environment from perspectives of ownership, economic dependence and social benefits [26]. Through the studies, [27] pointed out that the enterprise’s innovation performance is affected to some extent by fulfilling social responsibility to stakeholders, which is especially reflected by the positive impacts on social performance and financial performance. From the perspective of financial support of technological innovation, [28] studied and concluded that an enterprise can gain more capital supports only when it fulfills social responsibility to stakeholders and creditors positively. [29] mentioned that the low-carbon demands of clients are an important source to promote product innovation and financial performance of customer demands is manifested by their purchases and use behaviors of supplied products. Subsequently, [30] proved through a case study that enterprises can strengthen the trusts and loyalty of consumers to them by fulfilling social responsibility, which can further promote the innovation performance of enterprises. Reference [31] argued the social responsibility that an enterprise may influence the participation behaviors of its suppliers. Moreover, [32] carried out an empirical study which found certain positive impacts of enterprise’s fulfillment of social responsibility on its innovation performance. Moreover, an enterprise can gain more supports (e.g. subsidies or reduction of carbon tax) from the government when it takes initiative to response to low-carbon constraint of government, which can decrease the enterprise cost for low-carbon technological innovation and increase its innovation performance.

In the low-carbon environment, the performance in enterprise social responsibility is vital to the reputation of enterprises in crowds. The low-carbon return to manufacturing enterprises for green production will be reflected directly on stakeholders of enterprises. As financial supporters to enterprises in low-carbon innovation, creditors and shareholders are beneficiaries of enterprise’s fulfillment in low-carbon social responsibility. Returns from low-carbon behaviors can be allocated to stakeholders as dividends and consolidates position of the enterprise in the manufacturing enterprise group, thus enabling to improve its reputation in the network. Consumers are product demanders of manufacturing enterprises and their low-carbon demands may exert important impacts on low-carbon transformation of manufacturing enterprises. Influence of the enterprise in the network can be improved by purchasing low-carbon products at a reasonable price, which can further improve the reputation of the enterprise in the network. Government urges manufacturing enterprises to adopt low-carbon production to reduce carbon emission. Collecting pollution tax and providing subsidies are main supervision means of government. Therefore, the manufacturing enterprises can receive relevant supports from the government by making low-carbon innovation, improve the production equipments and products, and decrease their production pollution behaviors positively. They can receive positive responses in both economic benefits and reputation benefits. Enterprises in heavy pollution industries assume more social responsibilities in employee protection and environmental protection to maintain a good image. Moreover, good social responsibilities of manufacturing enterprises are reflected by distribution of low-carbon innovation cooperative benefits and pricing strategy of low-carbon products. Therefore, the social responsibility of manufacturing enterprises has certain positive impacts on transaction fairness.

The actual development of enterprises and the development of innovative technology will also involve the influence of transnational technology transfer and social responsibility. Compared with other evaluation indicators, the influence is smaller. According to the relevant data and statistical reports published by the China Statistical Yearbook, the China Industrial Economic Statistics Yearbook and other official websites of the National Bureau of Statistics and the State Intellectual Property Office in recent years, each of them is refined. The weight of evaluation indexes can cluster the data of the enterprises of the same category and level in order to eliminate the influence of data level differences among the industries on performance evaluation indicators.

IV. CONSTRUCTION OF A FUZZY QUANTITATIVE EVALUATION MODEL BASED ON AHP AND GREY CORRELATION CLUSTERING ANALYSIS

A. ESTABLISHMENT OF A GREY EVALUATION INDEX SYSTEM BASED ON AHP AND CALCULATION OF WEIGHTS OF EVALUATION ELEMENTS

According to the relevant data and statistical reports published in recent years such as China Statistical Yearbook, China Industrial Economic Statistical Yearbook and other official websites of the National Bureau of statistics and the State Intellectual Property Office, together with different industrial structure and development mode of the industry, the proportion of industries at the same level of four levels is calculated by comparative analysis, and then three levels, two levels and one level are carried out respectively. The evaluation process is refined and the weights are given reasonably.

1) ESTABLISHMENT OF A PERFORMANCE EVALUATION SYSTEM

Considering the quantitative evaluation on innovation performance of low-carbon technology innovation network in manufacturing industries, there is a need to establish an evaluation system which involves integral, accurate, effective and multi-variable multi-dimensional indexes. Since there are many dynamic and static factors that can influence the innovation performance evaluation of low-carbon technology innovation network, this study determined four level-1 indexes, namely, Technology Spillover, Social Capital & Technological Innovation, Technology Assimilation and Others. These four level-1 indexes are further refined into 11 level-2 indexes and 27 level-3 indexes layer by layer. On this basis, a quantitative evaluation index system of innovation performance of low-carbon technological innovation network of manufacturing industry is constructed.
It should be noted that the quantitative evaluation process of manufacturing low-carbon technological innovation network innovation performance needs big data samples of all related industries. In this paper, we adopt the mode of combining principal component analysis and factor analysis to select the main factors and subordinate factors in order to eliminate the influence of objective ownership on the evaluation indexes.

The constructed 3-level evaluation index system contains 3 levels and 4 layers, including the target layer A, level-1 index layer B, level-2 index layer C and level-3 index layer D. The evaluation index system is shown in Figure 1.

2) WEIGHT CALCULATION OF INDEXES BASED ON AHP AND CONSISTENCY CHECK

Considering the different industrial structure and development mode of the industry, when selecting the evaluation object, the affiliated enterprises and the enterprises with competition and subordinate development are put together to carry out the industry comparison and quantification at the same level, and the proportion comparison of different levels is carried out by assigning weights respectively.

In this study, the priorities and weights of elements in the same layer are determined based on analytic hierarchy process (AHP). Weights of four evaluation factors in the level-1 index layer B, including Technology Spillover ($U_1$), Social Capital & Technological Innovation ($U_2$), Technology Assimilation ($U_3$) and Others ($U_4$), are calculated for example through the following process. As in [33]–[35], the AHP is introduced in the “1–9 scale method” (TABLE 1).

Notice that there will be inconsistency in the perspective of each evaluator, in this paper, we select several groups of experts for multiple reviews and calculate the mean value of the results, and calculate the judgment matrix and consistency test for many times, which basically can effectively carry out the priority of each index.

Based on the constructed quantitative evaluation index system for innovation performance of low-carbon technological innovation network in manufacturing industries, relative importance among different indexes is further determined by expert scoring and order of magnitudes and priority of elements in the same layer. The judgment matrix is expressed as follows:

$$B = \begin{pmatrix} 1 & 2 & 3 & 5 \\ 1/2 & 1 & 3 & 4 \\ 1/7 & 1/7 & 1 & 2 \\ 5/3 & 5/3 & 1 & 1 \\ 5/4 & 1 & 1 & 1 \end{pmatrix}.$$ 

According to $B_{w} = \lambda_{\text{max}}$, eigenvalue ($\lambda_{\text{max}}$) and eigenvector ($w$) of the maximum are calculated through the determinant calculation of the judgment matrix. Based on matrix modulus in MATLAB software, for the above mentioned
constructed according to scores as:

$\lambda_{\text{max}} = 4.0566$

and

$w = (0.8, 0.5361, 0.23337, 0.1344)$.

Next, the consistency of $\lambda_{\text{max}}$ is checked, where $CR$ is the test coefficient of the matrix and it is generally $CR \leq 0.1$. This indicates that this comparison matrix meets requirements. When $CR > 0.1$, the matrix has to be adjusted, where $CR = CI/RI = \frac{\lambda_{\text{max}} - n}{n-1}$, and $RI$ is the random coincidence indicator.

The number of orders of the judgment is $4$. Therefore, $CI = \frac{\lambda_{\text{max}} - 4}{4-1} = 0.01886667$ and $RI = 0.89$. The check coefficient of the matrix is $CR = \frac{CI}{RI} = 0.0211985$. Since $CR = 0.0211985 < 0.1$, it conforms to requirements of consistency check and the assignment is reasonable.

Due to the consistent conformity, the calculated eigenvectors have to be normalized and they are adjusted slightly to get the weight of level-1 index layer $B$:

$$Q = (Q_1, Q_2, Q_3, Q_4) = (0.469, 0.3137, 0.1376, 0.07969).$$

Moreover, the weights of factors in the level-2 index layer and level-3 index layer can be calculated in the same method.

B. CONSTRUCTION OF A GREY COMPREHENSIVE PERFORMANCE EVALUATION MODEL

In this section, a grey fuzzy evaluation model is constructed for the 3-level evaluation index system. If the evaluation object is $U$, the set of level-1 indexes is

$$U = \{U_1, U_2, \cdots, U_s\},$$

where $s$ is number of level-1 indexes. The set of level-2 indexes is

$$U_i = \{U_{i1}, U_{i2}, \cdots, U_{ip}\},$$

where $p$ is number of level-2 indexes which belong to level-1 indexes $U_i$ and $i = 1, 2, \cdots, s$. The set of level-3 indexes is

$$U_{ij} = \{U_{ij1}, U_{ij2}, \cdots, U_{ijk}\},$$

where $k$ is the number of level-3 indexes which belong to level-2 indexes $U_{ij}$ and $j = 1, 2, \cdots, p$.

1) ESTABLISHMENT OF MATRIXES FOR DIFFERENT LEVEL OF EVALUATION SAMPLES

Based on the statistics and game theory, $n$ evaluators are selected to give scores $d_{ijq}(q = 1, 2, \cdots, n)$ to each element $U_{ij}(t = 1, 2, \cdots, k)$ in $U_{ij} = \{U_{ij1}, U_{ij2}, \cdots, U_{ijk}\}$ according to standards. Therefore, the evaluation sample matrix is constructed according to scores as:

$$D_{ij} = \begin{pmatrix}
    d_{ij11} & d_{ij12} & \cdots & d_{ij1n} \\
    d_{ij21} & d_{ij22} & \cdots & d_{ij2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    d_{ijk1} & d_{ijk2} & \cdots & d_{ijkn}
\end{pmatrix}_{k \times n}$$ (1)

2) CONSTRUCTION OF AN EVALUATION WEIGHT COEFFICIENT MATRIX

Next, the corresponding thresholds are determined through grey class. Finally, a whitening function as in [3] $f_\epsilon (\epsilon = 1, 2, 3, \cdots, g)$ is set up, where $\epsilon$ is the number of grey levels and $g$ is the number of grey levels.

The scores $d_{ijq}$ of $n$ evaluators to level-3 evaluation indexes $U_{ij}$ belong to the evaluation coefficient of evaluation grey class $e$, which is denoted as

$$y_{ijte} = \sum_{q=1}^{g} f_\epsilon (d_{ijq}).$$

The sum of evaluation coefficients when level-3 evaluation indexes $U_{ij}$ belong to different evaluation grey classes is

$$Y_{ijt} = \sum_{e=1}^{g} y_{ijte}.$$

The grey evaluation weight coefficient $r_{ijte} = \frac{y_{ijte}}{Y_{ijt}}$ is gained through the normalization of all evaluation coefficients. Finally, the evaluation weight coefficients of evaluation object $U_{ij}$ are combined to establish a 3-level grey evaluation weight coefficient matrix ($r_{ij}$) as in [4], [5]. We have

$$r_{ij} = \begin{pmatrix}
    r_{i1j} \\
    r_{i2j} \\
    \vdots \\
    r_{ijn}
\end{pmatrix} = \begin{pmatrix}
    r_{ij11} & r_{ij12} & \cdots & r_{ij1n} \\
    r_{ij21} & r_{ij22} & \cdots & r_{ij2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{ijkn}
\end{pmatrix}_{k \times g} \quad (2)$$

3) CALCULATION OF COMPREHENSIVE EVALUATION RESULTS OF EVALUATION INDEXES AT DIFFERENT LEVELS

The weights $Q_{ij} = (Q_{ij1}, Q_{ij2}, \cdots, Q_{ijp})$ of evaluation indexes at three levels are multiplied by $r_{ij}$, thus getting comprehensive evaluation results ($R_{ij}$) of the corresponding level-2 indexes [6]. In other words, there’s $R_{ij} = Q_{ij}r_{ij}$.

The comprehensive evaluation indexes ($R_{ij}$) of level-2 indexes ($U_{ij}$) are combined to establish the level-2 grey evaluation weight coefficient matrix ($r_i$). Next, the comprehensive evaluation results ($R_i$) of level-1 indexes ($U_i$) are calculated according to comprehensive evaluation results of level-2 indexes $[7]$. In other words, there’s $R_i = Q_i r_i$.

The innovation properties of low-carbon technology innovation network in manufacturing industry are determined through grey fuzzy analysis and the final evaluation results ($R$) of the overall evaluation objective ($U$) are calculated by solving the comprehensive evaluation results of level-1 indexes ($U_i$): $R = Qr$. According to the maximum membership method in fuzzy theory, the grey class in correspondence to the maximum ($\beta_x = \max R = \max (\beta_1, \beta_2, \cdots, \beta_k)$) in evaluation results ($R$) of $U$ is the comprehensive evaluation results. Later, $g$ grey classes are evaluated. The first grey class, the second grey class and the $g$ grey class are determined $c_1$, $c_2$ and $c_g$, so that the quantitative vector of grey class is $C = (c_1, c_2, \cdots, c_g)$. The comprehensive evaluation results ($c$) is the product of evaluation results ($R$) and quantitative vector of grey class: $Z = RC^T$. 
C. ANALYSIS ON DATA SOURCE
In this paper, an empirical study is carried out based on manufacturing industries. Statistical data of 28 manufacturing industries in five successive years from 2010–2014 are used as samples and classified according to China’s National Economic Classification (GB/T4754-2011) which came into act in 2012. Due to adjustment in the new industrial classification and for the unification of industrial classification, data of “rubber manufacturing industry” and “plastic manufacturing industry” which is related with measurement indexes before 2012 is integrated into data of “rubber and plastic manufacturing industry”. Data of “automobile industry” and “railway, ship, aerospace and other transportation equipment manufacturing industry” which is related with measurement indexes during 2012–2014 is integrated into data of “transportation equipment manufacturing industry”. Considering the lack of continuity of data about “comprehensive waste resource recycling industry” and “metal products, machine and equipment maintenance industry” in statistical yearbook, these two industries are eliminated from this study for the sake of continuity of data and accuracy of data analysis.

In this study, the data is mainly collected from Statistical Yearbook of China (2010–2015), Statistical Yearbook of China Industrial Economy (2009–2015), Statistical Yearbook of Scientific Activities of Industrial Enterprises (2010–2015), Energy Statistical Yearbook of China (2010–2015), patent retrieval system of National Intellectual Property Administration of People’s Republic of China, WTO statistical database, and other official websites. In particular, the data which cannot be inquired directly from statistical yearbook is deduced indirectly from data processing methods in previous studies.

Note that the relevant data and statistical reports published in China Statistical Yearbook, China Industrial Economic Statistics Yearbook and other official websites such as the National Bureau of statistics, the State Intellectual Property Office and other official websites may have some data shortage, the incomplete data is available only, the mean filling method will be used for data with slight missing, and the regression filling will be used for data with a regular pattern. For the heavy data, both multiple imputation method and Markov chain Monte Carlo method are utilized. In addition, they are directly selected to eliminate for the case of the data missing seriously.

Note that the industrial structure and development mode of the industry will be affected by some uncontrollable factors from the outside, such as the war, tsunami, business merger and bankruptcy, etc., when collecting the sample data, the data will be analyzed first and some abnormal data will be eliminated to ensure the validity of the data required for subsequent evaluation.

D. MODEL SOLVING AND RESULTS ANALYSIS
A 3-level evaluation index system which can influence performance evaluation level is established based on collected performance data of innovation network in Chinese manufacturing industries and directions of hierarchical transmission. The quantitative evaluations are carried out with grey fuzzy theoretical model.

The 3-level evaluation index system for low-carbon technology network innovation in Fig. 1 determines the sets of evaluation indexes at three levels as \( U = \{ U_1, U_2, U_3, U_4 \} \), \( U_1 = \{ U_{11}, U_{12}, U_{13}, U_{14} \} \), \( U_2 = \{ U_{21}, U_{22}, U_{23}, U_{24} \} \), \( U_3 = \{ U_{31}, U_{32}, U_{33}, U_{34} \} \), and \( U_4 = \{ U_{41}, U_{42}, U_{43}, U_{44} \} \). The 3-level evaluation index system for low-carbon technology network innovation in Fig. 1 determines the sets of evaluation indexes at three levels as \( U = \{ U_1, U_2, U_3, U_4 \} \), \( U_1 = \{ U_{11}, U_{12}, U_{13}, U_{14} \} \), \( U_2 = \{ U_{21}, U_{22}, U_{23}, U_{24} \} \), \( U_3 = \{ U_{31}, U_{32}, U_{33}, U_{34} \} \), and \( U_4 = \{ U_{41}, U_{42}, U_{43}, U_{44} \} \). The quantitative evaluations are carried out with grey fuzzy theoretical model.

The quantitative evaluations are carried out with grey fuzzy theoretical model.

1) MATRIX DETERMINATION OF SAMPLE DATA
In this paper, five experts are invited to give scores (1 10) to three levels of evaluation index sets. Taking the level-3 evaluation element \( U_{111} \) for example, an evaluation sample matrix is constructed:

\[
D_{11} = \begin{pmatrix}
9 & 8 & 9 & 8 & 9 \\
7 & 8 & 8 & 7 & 8 \\
\end{pmatrix}
\]

Similarly, the evaluation sample matrixes of other three levels of evaluation elements can be constructed.

2) DETERMINATION OF EVALUATION GREY CLASSES AND WHITENING FUNCTION
Based on statistical analysis on collected performance data of innovation network of Chinese manufacturing industries, a total of five evaluation grey classes are divided: \( g = 5 \), \( e = 1, 2, \ldots, 5 \). These five grey classes are corresponding to five performance evaluation levels of Excellent, Good, Acceptable, Need Improvement and Unacceptable.

According to the evaluation grey classes and the corresponding thresholds, the whitening functions are set up, which are shown in (3)-(7):

\[
f_{e=1} = \begin{cases}
1, & d_{ijtq} \geq 9 \\
\frac{d_{ijtq}}{9}, & d_{ijtq} < 9 \\
\end{cases} \quad (3)
\]

\[
f_{e=2} = \begin{cases}
2 - \frac{d_{ijtq}}{7}, & d_{ijtq} \geq 7 \\
\frac{d_{ijtq}}{7}, & d_{ijtq} < 7 \\
\end{cases} \quad (4)
\]

\[
f_{e=3} = \begin{cases}
2 - \frac{d_{ijtq}}{5}, & d_{ijtq} \geq 5 \\
\frac{d_{ijtq}}{5}, & d_{ijtq} < 5 \\
0, & d_{ijtq} \geq 5 \\
\end{cases} \quad (5)
\]

\[
f_{e=4} = \begin{cases}
2 - \frac{d_{ijtq}}{3}, & 5 > d_{ijtq} \geq 3 \\
\frac{d_{ijtq}}{3}, & d_{ijtq} < 3 \\
0, & d_{ijtq} > 1 \\
1, & d_{ijtq} \leq 1 \\
\end{cases} \quad (6)
\]

3) CALCULATION OF COMPREHENSIVE EVALUATION RESULTS
The evaluation coefficient of evaluation grey class \( e \) is calculated by taking the evaluation element \( U_{111} \) for example.
When \( e = 1 \), there’s
\[
\gamma_{\text{111}} = \sum_{q=1}^{5} f_{e=1} (d^{\text{111}}_{1q}) = f_{e=1} (d^{\text{1111}}_{1}) + f_{e=1} (d^{\text{1112}}_{1}) + f_{e=1} (d^{\text{1113}}_{1}) + f_{e=1} (d^{\text{1114}}_{1}) + f_{e=1} (d^{\text{1115}}_{1}) = 4.7778.
\]
Therefore, the sum of evaluation coefficients for \( U_{\text{111}} \) belonging to different evaluation grey classes is recorded as
\[
Y_{\text{111}} = \sum_{q=1}^{5} \gamma_{\text{111}e} = \gamma_{\text{1111}} + \gamma_{\text{1112}} + \gamma_{\text{1113}} + \gamma_{\text{1114}} + \gamma_{\text{1115}} = 10.0349.
\]
Hence, the grey evaluation weight vectors composed of evaluation weight coefficients of different evaluation grey classes are
\[
r_{\text{111}} = (r_{\text{1111}}, r_{\text{1112}}, r_{\text{1113}}, r_{\text{1114}}, r_{\text{1115}}) = (4.7778, 3.8571, 1.4, 0, 0).
\]
The evaluation weight vectors \( r_{t1} \) for \( t = 1, 2 \) for other evaluation elements \( U_{t1} \) belonging to different grey classes can be calculated and combined to construct a grey evaluation weight coefficient matrix:
\[
r_{t1} = \begin{pmatrix}
0.4988 & 0.3788 & 0.1224 & 0 & 0 \\
0.3598 & 0.4126 & 0.2276 & 0 & 0
\end{pmatrix}.
\]
Similarly, other grey evaluation weight coefficient matrices could be established. Comprehensive evaluation results of level-2 indexes are combined with grey evaluation weight coefficient, thus getting the level-2 grey evaluation weight coefficient matrix. In the same method, the comprehensive evaluation results of level-1 indexes \( (R_i = Q_i r_i) \) can be gained:
\[
R_1 = Q_1 r_1 = (0.3835, 0.3947, 0.1933), \quad R_2 = Q_2 r_2 = (0.3425, 0.4032, 0.2542), \quad R_3 = Q_3 r_3 = (0.3426, 0.4104, 0.2466), \quad R_4 = Q_4 r_4 = (0.3311, 0.3977, 0.2712).
\]
On this basis, the total grey evaluation weight matrix \( r = (R_1, R_2, R_3, R_4)^T \) can be gained. According to calculation, the comprehensive evaluation results of innovation performance level of low-carbon technology breakthrough innovation network in Chinese manufacturing industries under the current global value chain are
\[
R = Q r = (0.3608, 0.3998, 0.2259).
\]
### V. Analysis of Research Results
The maximum vector in evaluation results of the constructed model is \( \beta_2 = 0.3998 \). Based on the maximum membership principle in fuzzy theory, the evaluation results are determined belonging to grey class 2. In other words, the innovation performance of low-carbon breakthrough innovation network of Chinese manufacturing industries in the global value chain is assessed good, which conforms to the latest test results. For quantification of qualitative evaluation results, assignments of all grey classes are accomplished and the quantitative vector of grey classes corresponding to the comprehensive evaluation results is determined \( C = (100, 85, 70, 55, 40) \) according to comprehensive evaluation results, thus getting the comprehensive evaluation value \( Z = RC^T = 85.8913 \).
In this paper, AHP is applied to determine influencing factors of innovation performance evaluation of low-carbon technology breakthrough innovation network of Chinese manufacturing industries. In AHP, Chinese manufacturing industries are viewed as a system and decisions are made according to the mode of thinking of decomposition and integration. Accordingly, the structural analysis and statistical analysis on innovation performance of low-carbon technology breakthrough network are performed. Moreover, the proportions of sub-factors in relevant influencing factors (e.g., scientific innovation capability, development level and social influence of manufacturing industries) which are difficult to be quantified are determined through the expert evaluation and comparison. On this basis, the performance evaluation factors are refined and quantized. Some conclusions could be drawn as follows.

1. The low-carbon technology breakthrough innovation has different impacts on performances of Chinese manufacturing industries. For electronics manufacturing industries like communication equipment, computer and other electronic equipment manufacturing industry and electrical mechanical industry, development prospects and evolution of innovation system in the low-carbon technology innovation network change quickly. The electronics manufacturing industries shall continue to promote the technological assimilation in the low-carbon technology innovation network and construction of an industrial policy feedback platform, strengthen openness and advancement of new low-carbon technologies, create a green manufacturing system under new low-carbon and innovation network model, realize an effective two-way feedback mechanism between low-carbon technology breakthrough innovations and macroscopic development of enterprises, as well as promote development of low-carbon technologies. For manufacturing industries of food, agricultural and sideline products, beverages, furniture and industrial products, the low-carbon technology breakthrough innovation just begins. It is suggested to continue to strengthen the knowledge diffusion and learning of low-carbon technologies, and increase the government support to relevant low-carbon technological development. According to current technological level and ability of manufacturing industries,
advanced technologies and market management modes in foreign countries can be learned and assimilated through transnational technology transfer and technological integration to promote low-carbon technological development and reasonable allocation of market resources. The traditional manufacturing industries including medicines, rubber, plastics, ferrous metal melting and rolling industries have inadequate low-carbon technology breakthrough innovation capacity and influences of enterprise social responsibility although they occupy great market shares. It is necessary to further strengthen the cognition and social responsibility of employees of relevant enterprises to low-carbon technological knowledge, strengthen benign development circle among knowledge, creativity and social influence, enhance interaction and learning of these manufacturing industries with universities, scientific research institute, Chinese and international famous enterprises and the masses, and form a government-industry-university-research cooperative development mode dominated by low-carbon technology innovation.

2. According to the calculation analysis of influences of the low-carbon technology breakthrough innovation on the performances of Chinese manufacturing industries, the overall macroscopic performances of Chinese manufacturing industries under the current global value chain are in the maturity and transfer stage, and the low-carbon technology network innovation has been integrated with manufacturing industries. Considering existing low-carbon technology innovation capability of Chinese manufacturing industries and cultural influences of enterprises, it is necessary to stabilize current development momentum, further improve knowledge and social responsibility consciousness of employees and executives of enterprises in low-carbon technology innovation, and protect the competitive edges of Chinese low-carbon technological manufacturing industries in international market competition in future based on the computation and R&D of manufacturers in low-carbon technology innovation as well as mutual trusts and assistances of relevant industries.

The innovation performance of the low-carbon technology breakthrough innovation network of Chinese manufacturing industries under the existing global value chain is assessed in good and sound development. If it is measured by 100 scores, the innovation performance score of low-carbon technology breakthrough innovation network of Chinese manufacturing industries is 85.8913. This indicates that low-carbon technology breakthrough innovation of Chinese manufacturing industries still has a long way to go in future.

VI. CONCLUSION AND ENLIGHTENMENTS

In the background of stable development of global value chain, it is urgent for manufacturing industries to integrate in low-carbon technology innovation network and create a high-efficiency and integrated Chinese manufacturing industrial development environment centered at low-carbon manufacturing. Since the influence factors against the innovation performance evaluation of low-carbon technology breakthrough innovation network in manufacturing industries are associated and superposed mutually, the comprehensive and systematic scientific quantification of pluralistic and overlapping performance evaluation indexes can provide valuable and specific references to future structural development of Chinese manufacturing industries. Focusing on innovation performance of low-carbon technology breakthrough innovation network of Chinese manufacturing industries, an innovation performance evaluation model of low-carbon technology innovation network is constructed based on AHP, grey theory and fuzzy clustering analysis method. According to data of 28 manufacturing industries during 2010–2014, the qualitative and quantitative evaluation of current innovation performance of the low-carbon technology breakthrough innovation network are performed. The results demonstrate that Chinese manufacturing industries still have some improvement spaces in the low-carbon technology breakthrough innovation and innovation integration of innovation network. Some conclusions and policy enlightenments are proposed.

1. The low-carbon technology breakthrough innovation can promote development of manufacturing industries significantly. The low-carbon technology breakthrough innovation stimulates speed and quality of organizational structure, manufacturing transformation and agglomeration upgrading of Chinese manufacturing industries to some extent. Under this circumstance, the innovation network and low-carbon technology breakthrough innovation are accompanied with a green and high-efficiency Chinese manufacturing industrial system. In return, the organizational structure, manufacturing transformation and agglomeration updating of Chinese manufacturing industries can promote low-carbon breakthrough product innovation, technological innovation and service innovation to some extent. Hence, Chinese manufacturing industries are suggested to continue to strengthen the innovation capacity of the low-carbon technologies and innovation network and establish a more reasonable agglomeration innovation network in order to realize the low-carbon technology innovation development.

2. The Chinese manufacturing enterprises still have some improvement spaces in cognition and innovation of agglomeration low-carbon technologies. In the present study, the innovation performance of low-carbon technology breakthrough innovation network is assessed based on the data of 28 Chinese manufacturing industries. The corresponding results show that the low-carbon innovation system of Chinese manufacturing industries can evolve from early formation to maturity more quickly and better as long as paying attentions to manufacturing enterprises’ cognition on low-carbon innovation technology and accelerating integration of low-carbon technology innovation network with organizational structure, manufacturing transformation and agglomeration upgrading of manufacturing industries. Therefore, it is suggested to strengthen the cognition of executives to the positive effects of low-carbon technology breakthrough innovation on industrial upgrading, coordinate the relation
network of enterprise social responsibility, reputation and word of mouth with low-carbon technology innovation performance, pay attention to the development of key low-carbon manufacturing technologies and low-carbon manufacturing activities, and create new low-carbon green manufacturing enterprises.

3. In this study, AHP is applied to determine the influence factors of the innovation performance evaluation of the low-carbon technology breakthrough innovation network. In AHP, Chinese manufacturing industries are viewed as a system and decisions are made according to the mode of thinking of decomposition and integration. The logic relations among low-carbon technology, innovation network and innovation performance of manufacturing industries are refined. Moreover, a comprehensive quantitative evaluation on current innovation performance of the low-carbon technology breakthrough innovation network of Chinese manufacturing industries is carried out with grey clustering fuzzy evaluation model in AHP and 27 level-3 indexes in the evaluation system. With considerations to current low-carbon situations, some suggestions are proposed to manufacturing enterprises. Firstly, Chinese low-carbon manufacturing industries shall pay more attention to low-carbon technology spillover effect, and promote learning, copy, assimilation, integration and innovation of advanced low-carbon innovative technologies, aiming to improve innovation performance of the low-carbon technology breakthrough innovation network. Secondly, the manufacturing enterprises shall increase social capitals and coordinated development of different innovative technologies, further increase social capital accumulation as well as R&D and assimilation of innovative technologies of existing Chinese low-carbon manufacturing enterprises, and strengthen industrial competitiveness of innovation system of low-carbon manufacturing industries. Thirdly, the low-carbon technological communication among Chinese manufacturing industries and business cooperation among low-carbon manufacturing enterprises shall be enhanced to facilitate great upgrading and transformation of manufacturing industries. It is recommended to further expand development channels for low-carbon manufacturing industries, as well as encourage and guide formation and development of new high-efficiency, green and low-carbon manufacturing system. In the aspect of competition and mutual assistance among manufacturing industries, the green innovation performance of green innovation system is positively correlated with industrial upgrading, structural upgrading and breakthrough innovation of low-carbon technology innovation network, which will aggravate the competition, merger and mutual assistance among enterprises at the same level.

In conclusion, the research conclusions of this study can provide the references for Chinese or other country’s manufacturing enterprises in low-carbon innovation development under the global value chain. However, the low-carbon technology innovation performance evaluation in manufacturing industries has some limitations due to restraints by territory of manufacturing enterprises, types of manufacturing industries and data samples. Hence, future studies can increase the sample size of manufacturing industries in order to get more accurate analysis data.

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