Research on Diffusion Mechanism of Green Innovation of Cloud Manufacturing Enterprises Based on BA Scale-Free Agglomeration Network Game

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ABSTRACT Based on the characteristics of a complex network structure and “Internet Plus” platform, this paper uses evolutionary game theory to establish a Barabási–Albert (BA) scale-free agglomeration network evolutionary game model between the government and cloud manufacturing enterprises. MATLAB is used for a numerical simulation analysis to explore the evolution of the green innovation behaviour and network structure of enterprises in the innovation network under a scale-free network carrier. The results show that green synergy benefits, cloud platform supervision, and government incentives and punishment can promote the maintenance of green innovation cooperation and the network agglomeration of cloud manufacturing enterprises. Only when the above parameters exceed a certain threshold will the maintenance of green cooperation emerge among cloud manufacturing enterprises, which causes the network to evolve in a Pareto-optimal direction. Moreover, when the network size is larger, the speed of network evolution is slower. The research results not only provide a scientific basis for governments and platforms to regulate cloud manufacturing enterprises but also help to promote the collaborative green innovation of cloud manufacturing enterprises and enhance their core competencies.

INDEX TERMS BA scale-free agglomeration network evolutionary game, cloud manufacturing enterprises, government regulation, green innovation.

I. INTRODUCTION

With the increasingly serious problems of global warming, environmental pollution and resource depletion, various regions have experienced different degrees of public environmental pollution problems, which have become the management focus of local governments, and green economics has also become a focus of academic attention [1]. The “Made in China 2025” directive issued by the State Council of China puts forward a development policy of “innovation-driven green development” that emphasizes the important position of the green economy [2]. Meanwhile, with the rapid development of information technology and “industry 4.0”, the world has increasingly implemented Internet-based economic strategies. The cooperation and sharing economy based on the “Internet Plus” mode has also been favoured as a new collaborative innovation mode [3], [4]. Therefore, under the new era of global sustainable development and China’s “Internet plus” development, green innovation has become the general strategy pursued in the information manufacturing industry. After integrating cloud computing, the Internet of things and other emerging technologies [5], the “cloud manufacturing” mode can seamlessly connect the information and resources of manufacturing enterprises and allow...
manufacturing resources to be easily shared under cloud services, which can promote the development of the manufacturing industry to become more agile, service-oriented, green and intelligent [8]. Cloud manufacturing enterprises can build virtual enterprise alliances through cloud manufacturing platforms to share green technology or manufacturing resources to improve the speed of technological innovation and enterprise performance [9], [10], which has accelerated the realization of “agile manufacturing”, “service-oriented manufacturing”, “green manufacturing” and “created in China” [6], [7]. Therefore, it is particularly important to accelerate the implementation of the green technology innovation of cloud manufacturing enterprises.

However, although enterprises learn from one another’s green technologies and use one another’s core resources, many cloud manufacturing enterprises are unwilling to adopt these green technologies due to high costs and technical barriers, and even fewer enterprises are willing to participate in cooperation to protect their own technological advantages [11], [12]. Manufacturing enterprises not only choose green innovation cooperation in the cloud manufacturing network environment but also play an interest game in the cooperation, which also poses new challenges to the government’s supervision capability under the traditional economic mode [13], [14]. What type of regulatory concept should the government establish? Which reward and punishment systems promote green innovation among cloud manufacturing enterprises? To answer these questions, it is necessary to understand how cloud manufacturing enterprises choose appropriate green cooperation strategies to maximize the expected interests of both sides, how the government promotes and encourages cloud manufacturing enterprises to carry out green innovation [15], and how this approach can provide a more accurate basis for decision making [16].

Consequently, by exploring in depth the behavioural selection of community members in the process of green innovation cooperation and clarifying the variation of selection among cloud manufacturing enterprises over time and the related parameters, we can analyse and explore the evolutionary mechanism of green innovation cooperation behaviour. This exploration can not only fill the blank of green innovation cooperation theory research of cloud manufacturing enterprises, but also provide certain reference value for the government and cloud platform to formulate relevant policies.

Therefore, the research objectives of this study are as follows: (1) to construct the evolutionary game model of green innovation network of cloud manufacturing enterprises, by combining the simulation model and related examples; (2) to explore the scale-free agglomeration network related micro factors on the cloud manufacturing enterprise green innovation strategy choice; (3) to provide a theoretical basis for cloud manufacturing enterprises to choose green innovation cooperation strategies, and to provide policy recommendations for the government and cloud platform to regulate the cooperative behavior of cloud manufacturing enterprises.

The rest of the paper is organized as follows: section II summarizes the literature on innovation practice of cloud technology in manufacturing enterprises and the evolution of green innovation diffusion. The section III describes the research problems and establishes the game model under the government regulation and the evolution rules of green innovation network. In Section IV, we simulate the above model in a BA scale-free aggregation network and analyse the influence of different parameters on the evolution results. Finally, in Section V, conclusions and suggestions are provided. And the theoretical framework of this paper is shown in Figure 1.

II. LITERATURE REVIEW

A. INNOVATION PRACTICES OF CLOUD TECHNOLOGY IN MANUFACTURING ENTERPRISES

Currently, Industry 4.0 is driving a new round of industrial revolution. Accordingly, traditional enterprises are facing unprecedented business challenges [17]. Enterprises need to realize a more efficient, more automatic, and more flexible personalized and digital production mode of products and services in a large-scale competitive business environment. Industry 4.0 has the greatest impact on the manufacturing industry, which may have a potential effect on various processes of enterprises, including not only improving production processes and optimizing operational performance but also developing products or services and managing the supply chain. Cloud manufacturing is proposed to achieve the comprehensive sharing and collaboration of manufacturing resources and capabilities and improve the utilization of manufacturing resources [18]. Thus far, some researchers have studied the application of cloud technology to manufacturing enterprises, but there seems to be a lack of comprehensive analyses of the impact of cloud technology on manufacturing enterprises from the perspective of technology and management and a lack of an overall analysis of different viewpoints.

Therefore, this paper attempts to analyse the practice of cloud technology in manufacturing enterprises and its impact on enterprise innovation management through the following table, including the entire production process, from product design and manufacturing to service and final recycling.

Table 1 shows the management practice of cloud technology in cloud manufacturing enterprises.

B. THE EVOLUTION OF GREEN INNOVATION DIFFUSION

Researchers from all over the world have conducted long-term studies on green collaborative innovation that show that the implementation of green collaborative innovation activities can not only reduce waste and improve productivity but also establish the green image of enterprises, improve the core competitiveness of enterprises, and realize environmentally sustainable development [44]. A cloud platform encourages enterprise members to share multi-product and multi-level information. Through cloud technology, resource consumption and emissions can be greatly saved, and the
"service" of a circular economy can be increasingly more realized. Thus far, researchers have studied the innovation cooperation game of manufacturing enterprises from many aspects. For example, from the aspect of the green innovation cooperation game, Barari et al. [45] studied how manufacturers and sellers can maximize profits by improving the green degree of products based on evolutionary game theory. Cao et al. [46] explored the influence of three stakeholders on green innovation behaviour and the green innovation diffusion of enterprises. In terms of the cloud platform cooperation game, some researchers have compared the traditional organization cooperation game with the virtual organization cooperation game system under the cloud manufacturing service platform and introduced the punishment factor to construct the cooperative game model [47]. In the framework for capacity Shapley in cloud manufacturing (FCSCM), the cooperative game algorithm and fuzzy engine based on the Gale Shapley model can select the capability allocation strategy according to the enterprise utility function and then evaluate the performance of cloud manufacturing capability sharing [48]. However, at present, academic circles seldom consider integrating the green innovation system resources of cloud manufacturing enterprises to realize the integration of green innovation resources. Only some researchers think that resource data integration can be achieved by using the Internet of things technology and that the allocation decision can be optimized by using the cooperative differential game, which can ensure the optimal allocation of resources in a green innovation system. At present, the analysis of the cloud manufacturing resource-sharing mode is mainly based on the classical game method or the replication dynamic evolution mechanism based on the differential equation to analyse the macro behaviour process of cooperation. If the topological characteristics and individual heterogeneity of the real network are not taken into account, then the resource-sharing behaviour of enterprises is often restricted and affected by partners, and it is unable to maximize their own interests [49]. To solve this problem, researchers began to give attention to the evolutionary law of innovation that is subject to cooperation behaviour under different network structures. For example, a scale-free network can promote the emergence of the cooperative behaviour of innovation subjects [50]. From the perspective of network aggregation, the cooperative behaviour of innovation subjects with high intermediate value at the network level is more likely to appear in the network. From the perspective of individual preference [51], bounded rationality [52] and expectation [53], when the individual cooperation preference is stronger, the degree of decision-making rationality is higher, and the willingness to cooperate is stronger, and all can promote the cooperation of innovation subjects in the network. Increasingly more researchers have discussed the evolutionary law of the cooperative behaviour of innovation subjects in the process of dynamic network evolution. For example, from the perspective of cooperation frequency, the increase of transfer probability has been found to enhance network heterogeneity and promote the cooperation of innovation subjects in the network [54]. From the perspective of the time scale, the increase of individual learning frequency can promote the emergence of innovative subjects and the cooperative behaviour of innovation subjects in scale-free networks [55]. Some researchers have discussed this from the perspective of government participation and combined it with the promotion of the external environment. Using network evolutionary game theory, this paper analyses the cooperative behaviour of innovation subjects and the evolutionary law of the network structure in the interaction process.
under government participation and proposes that government incentives can promote innovation subjects to maintain cooperative behaviour and network agglomeration [56].

Through a literature review, domestic and foreign researchers have conducted some research on the innovation of cloud manufacturing enterprises and the evolution of green innovation diffusion, which also provides an important theoretical basis for this research. However, the existing research has the following shortcomings.

1. Most studies have not combined the cloud manufacturing mode with green innovation management and have failed to deeply explore how manufacturing enterprises use the advantages of a cloud platform to share green innovation resources and realize the process of green technology innovation cooperation. They have especially ignored the role of a cloud platform and government in the diffusion of green innovation.

2. The existing research mainly focuses on classical game theory or the replication dynamic evolution mechanism based on a differential equation to analyse cooperative behaviour but fails to consider the topological characteristics of a real network. Moreover, the research methods also lack the use of a complex cluster network evolutionary game method to study the evolution of enterprise green innovation cooperation behaviour.

3. Existing studies only analyse the problem based on the simulation network model, which lacks scientific rigor and authenticity compared with a real cooperative network. In view of these shortcomings, this paper takes the green innovation network of cloud manufacturing enterprises established by relevant patent data as an example and constructs the green innovation cooperation game model of cloud manufacturing enterprises based on complex network evolutionary game theory. Accordingly, this paper uses MATLAB.

| Influence | Specific application description |
|-----------|---------------------------------|
| Promote new product design | Specific customer requirements in the network can be transferred to the cloud platform for storage, calculation and analysis [19],[20], which can promote the design of collaborative new products among manufacturing enterprises [21]. |
| Realize intelligent purchasing and supply management | Enterprises can evaluate and optimize the workshop layout through cloud technology so that companies can implement more flexible and potential outsourcing and purchasing strategies [22],[23]. Cloud technology can enhance the advanced demand assessment and prediction mechanism [24] and allow all participants in the supply chain to communicate [25] to coordinate regional manufacturing resources and achieve effective sharing and optimal allocation [26]. |
| Organize and manage all aspects of supply chain planning | Cloud technology can establish a stakeholder network in the supply chain and promote sharing and exchange [27]. In fact, research shows that companies that use cloud technology tend to work more effectively with their partners [28]. |
| Enhance supply chain integration and automation | Cloud technology can track the product processing process [24] and synchronize the information between the production system and the storage system [28] to achieve the optimal dynamic lean control [19]. The CPPs system based on cloud computing and data analysis can realize the planning [30], evaluation [31] and intelligent scheduling management of the entire production process [32]. At the same time, virtual engineering objects (VEO) and virtual engineering processes (VEPs) can virtualize the technology, functional attributes and real-time state of an intelligent factory in cyberspace through semantic web technology [33]. By combining the Internet of things [34] and cloud technology to provide basic software services (SaaS) and platform services [35], enterprises can improve the ability of connection [36] and information exchange among different resources [37]. Simultaneously, with the help of the cloud, this combination can improve the speed of the automatic integration of operational data and the remote monitoring of the Internet of things [38]. |
| Identify and track the handling and storage of internal logistics | Cloud technology can track the product processing process [24] and synchronize the information between the production system and the storage system [28] to achieve the optimal dynamic lean control [19]. The CPPs system based on cloud computing and data analysis can realize the planning [30], evaluation [31] and intelligent scheduling management of the entire production process [32]. At the same time, virtual engineering objects (VEO) and virtual engineering processes (VEPs) can virtualize the technology, functional attributes and real-time state of an intelligent factory in cyberspace through semantic web technology [33]. By combining the Internet of things [34] and cloud technology to provide basic software services (SaaS) and platform services [35], enterprises can improve the ability of connection [36] and information exchange among different resources [37]. Simultaneously, with the help of the cloud, this combination can improve the speed of the automatic integration of operational data and the remote monitoring of the Internet of things [38]. |
| Schedule and control the production system and virtualize manufacturing resources | Simulation and modelling techniques are used to virtualize manufacturing resources [28] and can also be used to preview production plans and performance evaluations [38]. The combination of cloud technology and the energy optimization algorithm can reduce energy consumption [39]. At the same time, the cloud platform can further monitor the data to analyse the accurate energy consumption trend to monitor the energy consumption in real time and activate service-oriented energy management [40]. CPS can monitor manufacturing assets in real time through the gateway data stored in the cloud to detect anomalies [22], carry out predictive maintenance in the early stage, display the location and diagnosis to users and technicians, and provide an intelligent maintenance scheme [19] so that the company can achieve high production efficiency and reduce resource consumption in the shortest time. |
| Establish connections and information exchanges among production resources | Cloud technology can provide a personalized and customized service experience according to customer needs [19]. On the cloud service platform, suppliers can establish contact with customers so that enterprises can provide relevant services and improve customer satisfaction by collecting consumer behaviour data [41]. Cloud technology enhances the reverse logistics tracking of post-consumer products, enables enterprises to reuse, remanufacture or recycle product components, and speeds up the transition to a circular economy [42]. The application of cloud technology to low-cost large-scale remanufacturing may be a future research direction [43]. |
| Use simulation and modelling techniques in production processes | Simulation and modelling techniques are used to virtualize manufacturing resources [28] and can also be used to preview production plans and performance evaluations [38]. The combination of cloud technology and the energy optimization algorithm can reduce energy consumption [39]. At the same time, the cloud platform can further monitor the data to analyse the accurate energy consumption trend to monitor the energy consumption in real time and activate service-oriented energy management [40]. CPS can monitor manufacturing assets in real time through the gateway data stored in the cloud to detect anomalies [22], carry out predictive maintenance in the early stage, display the location and diagnosis to users and technicians, and provide an intelligent maintenance scheme [19] so that the company can achieve high production efficiency and reduce resource consumption in the shortest time. |
| Manage energy | CPS can monitor manufacturing assets in real time through the gateway data stored in the cloud to detect anomalies [22], carry out predictive maintenance in the early stage, display the location and diagnosis to users and technicians, and provide an intelligent maintenance scheme [19] so that the company can achieve high production efficiency and reduce resource consumption in the shortest time. |
| Diagnose faults and conduct predictive maintenance | Cloud technology can provide a personalized and customized service experience according to customer needs [19]. On the cloud service platform, suppliers can establish contact with customers so that enterprises can provide relevant services and improve customer satisfaction by collecting consumer behaviour data [41]. Cloud technology enhances the reverse logistics tracking of post-consumer products, enables enterprises to reuse, remanufacture or recycle product components, and speeds up the transition to a circular economy [42]. The application of cloud technology to low-cost large-scale remanufacturing may be a future research direction [43]. |
| Manage customer relationships | Cloud technology can provide a personalized and customized service experience according to customer needs [19]. On the cloud service platform, suppliers can establish contact with customers so that enterprises can provide relevant services and improve customer satisfaction by collecting consumer behaviour data [41]. Cloud technology enhances the reverse logistics tracking of post-consumer products, enables enterprises to reuse, remanufacture or recycle product components, and speeds up the transition to a circular economy [42]. The application of cloud technology to low-cost large-scale remanufacturing may be a future research direction [43]. |
| Manage after sales | Cloud technology can provide a personalized and customized service experience according to customer needs [19]. On the cloud service platform, suppliers can establish contact with customers so that enterprises can provide relevant services and improve customer satisfaction by collecting consumer behaviour data [41]. Cloud technology enhances the reverse logistics tracking of post-consumer products, enables enterprises to reuse, remanufacture or recycle product components, and speeds up the transition to a circular economy [42]. The application of cloud technology to low-cost large-scale remanufacturing may be a future research direction [43]. |
between heterogeneous agents and ignores the growth of higher than that of B-type enterprises.

Advantages and resource advantages, and its technical level is asymmetric. Cloud manufacturing enterprise A has technical which have bounded rationality—and that information is work G (V, E) that mainly involves two types of subjects—A-type and B-type cloud manufacturing enterprises both of development of cloud manufacturing enterprises' cooperative policies and economic levers to promote the evolution and relationship of cloud manufacturing enterprises through laws, time, the government guides and coordinates the cooperation behaviour by considering the benefits and costs. At the same cloud manufacturing enterprises will adjust their cooperation in the evolutionary process of a green innovation network, policies and economic levers to promote the evolution and development of cloud manufacturing enterprises, this paper puts forward the following assumptions.

- H1: Suppose that the green innovation network of cloud manufacturing enterprises, which is more in line with the actual conditions under which enterprises choose neighbouring enterprises for a cooperative game. Therefore, it is assumed that in the game process, a cloud manufacturing enterprise node with a degree only participates in the game in the neighbourhood as the centre.

- H2: This paper only considers the cooperative game of A-type and B-type cloud manufacturing enterprises that participate in green innovation activities, including the updating of green innovation subjects and then affect the evolution and development of the innovation network. In this paper, we introduce the supervision of the cloud platform, government subsidies and government punishment for default enterprises to improve the game model under the market mechanism, which establishes the game payment matrix of A-type and B-type enterprises, as shown in Table 2.

- H3: Enterprises can only choose the strategy of “cooperative sharing” or “non sharing”, and the probability of choosing a given strategy is related to the expected profit of cooperation; thus, there is a possibility of misjudging and not selecting the optimal strategy. When an enterprise uses the same strategy to update the rules, the choice of strategy completely depends on the last game result, and the memory length is 1.

### Table 2. Green innovation network game payment matrix of cloud manufacturing enterprises.

|                | Cooperation | Uncooperative |
|----------------|-------------|---------------|
| **A-type enterprises** |             |               |
| Cooperation    | $\pi_A + \omega + I_A - (1 - \alpha)C$ | $\pi_A + Z - (1 - \alpha)C - T_A - M$ |
| Uncooperative  | $\pi_B + I_B - (1 - \alpha)C - C_0$ | $\pi_B + T_A - C_0 - Z$ |
| **B-type enterprises** |             |               |

2020 software to simulate and analyse the evolutionary law of cloud manufacturing cooperation behaviour and the network structure in the interactive process under cloud platform supervision and government regulation. This paper studies the operation mechanism of the green innovation network of enterprises from the process perspective and then reveals the process law of the green innovation diffusion behaviour of cloud manufacturing enterprises with the changes of cooperation and synergy benefits, platform supervision and government regulation. By comparing the results of the evolutionary stability strategy through a simulation, this is expected to provide a theoretical basis for the optimization of the green innovation diffusion process of cloud manufacturing enterprises and fill the research gap of the evolution mechanism of green cooperation behaviour of the cloud manufacturing industry under a complex network. This paper can thus provide a decision-making reference for cloud manufacturing enterprises to participate in a green innovation cooperation practice and reference policies for government and the cloud platform to formulate relevant policies.

### III. PROBLEM DESCRIPTION AND MODEL CONSTRUCTION

#### A. BASIC ASSUMPTIONS

In the evolutionary process of a green innovation network, cloud manufacturing enterprises will adjust their cooperation behaviour by considering the benefits and costs. At the same time, the government guides and coordinates the cooperation relationship of cloud manufacturing enterprises through laws, policies and economic levers to promote the evolution and development of cloud manufacturing enterprises’ cooperative innovation networks. Based on the game model of a scale-free agglomeration network and the practical consideration of the green collaborative innovation of cloud manufacturing enterprises, this paper puts forward the following assumptions.

- H1: Suppose that the green innovation network of cloud manufacturing enterprises is a heterogeneous complex network G (V, E) that mainly involves two types of subjects—A-type and B-type cloud manufacturing enterprises both of which have bounded rationality—and that information is asymmetric. Cloud manufacturing enterprise A has technical advantages and resource advantages, and its technical level is higher than that of B-type enterprises.

- H2: This paper only considers the cooperative game between heterogeneous agents and ignores the growth of nodes and connected edges in the network. Due to the limitation of information costs and other conditions, enterprises cannot establish contact with all enterprises in the global network, which is more in line with the actual conditions under which enterprises choose neighbouring enterprises for a cooperative game. Therefore, it is assumed that in the game process, a cloud manufacturing enterprise node with a degree only participates in the game in the neighbourhood as the centre.

#### B. GAME MODEL CONSTRUCTION

The green cooperative innovation revenue of the cloud manufacturing network, the supervision of the cloud platform, and the constraints of government are the important factors of the resource allocation of cloud manufacturing enterprises. These factors can directly affect the cooperative behaviour of innovation subjects and then affect the evolution and development of the innovation network. In this paper, we introduce the supervision of the cloud platform, government subsidies and government punishment for default enterprises to improve the game model under the market mechanism, which establishes the game payment matrix of A-type and B-type enterprises, as shown in Table 2.

**Strategy 1:** Both A-type and B-type cloud manufacturing enterprises choose a cooperation strategy. At this time, the total income of enterprise A is $\pi_A + \omega + I_A - (1 - \alpha)C$, and the total income of B-type enterprises is $\pi_B + \omega + I_B - (1 - \alpha)C - C_0$.

where $\pi_i$ is the basic income that cloud manufacturing enterprises do not derive from green innovation, and $R_0^i$ is the collaborative income obtained by both A-type and B-type cloud manufacturing enterprises that participate in green innovation activities, including the updating of green innovation technology and the social benefits of enterprises’ green innovation. $R_1^f$ is the benefit of manufacturing enterprises that participate in cloud platform innovation to improve the level of informatization, $C$ is the channel cost for manufacturing.
enterprises to enter the cloud platform network to carry out green innovation activities, $\alpha$ is the government subsidy to enterprises that participate in green innovation cooperation, and $C_0$ is the access cost that B-type enterprises need to pay due to the technology gap.

**Strategy 2**: A-type enterprises choose a cooperation strategy, and B-type enterprises choose a betrayal cooperation strategy. At this time, the total income of A-type enterprises is $\pi_A + I_A - T_A + Z + M - (1 - \alpha)C$, and the total income of B-type enterprises is $\pi_B + T_B - Z - C_0 - M$, where $R_i^T$ is the technical loss cost that the other enterprise needs to bear when one side of the enterprise chooses not to cooperate, while the other party shares various professional knowledge or data resources and other core technologies. $Z$ is the government punishment for the enterprise that betrays the cooperation, and $M$ is the punishment for the default enterprise according to the platform.

**Strategy 3**: B-type enterprises choose a cooperation strategy, and A-type enterprises choose a betrayal cooperation strategy. At this time, the total income of A-type enterprises is $\pi_A - Z - T_B - M$, and the total income of B-type enterprises is $\pi_B + I_B - T_B + Z + M - (1 - \alpha)C - C_0$.

**Strategy 4**: A-type and B-type enterprises both choose a non-cooperation strategy. At this time, the total incomes of A-type and B-type enterprises are their basic income, namely, $\pi_A - Z + T_B$ and $\pi_B + T_A - Z - C_0$.

**C. EVOLUTION RULES OF SCALE-FREE AGGREGATION NETWORKS**

This paper analyses the dynamic evolution mechanism of the green cooperation behaviour of cloud manufacturing enterprises by using a scale-free clustering network model [57]. In the green innovation network, the innovation subject has limited rationality. While pursuing the maximization of their own interests, cloud manufacturing enterprises will adjust their cooperation strategies according to the rules of replication dynamics [58] to change their cooperation behaviour. The cooperation behaviour can be measured by the index of network partner density $\rho$ [59]. At the initial moment of the game, the enterprise chooses the cooperation strategy according to probability $x(0 < x < 1)$ as the initial strategy of the game; then, the proportion of the co-operators in the entire enterprise group at time $t$ becomes the partner density at the moment:

$$f_A(t) = n_A(t)/N$$

where $n_A(t)$ is the number of collaborators in the network group at time $t$, and $N$ is the total number of the group.

In each round of the game, each enterprise plays with its neighbouring enterprises that have direct connections with one another. The strategy adopted by enterprise $i$ in a game can be expressed as strategy vector $S_i$. Then, the weighted utility function to measure the $t$-th game revenue of enterprise $i$ is

$$U_i(t) = a \cdot [\sum_{j \in \Omega_i} \pi(s_i, s_j) + (1 - a)[\sum_{j \in \Omega_i} \pi(s_i, s_j)/k_j]$$

where $\Omega_i$ is the neighbour set of enterprise $i$ determined by the network structure, $S_i$ is the strategy vector of the enterprise at time $t$, $k_j$ is the number of neighbours of enterprise $i$, and $a(0 \leq a \leq 1)$ is the weight parameter of cumulative revenue in the utility function. The cumulative game revenue of all enterprises is the game income of each enterprise and is the sum of the game profits with all neighbours. In the next round, each enterprise will adjust its strategy according to the rules of replication dynamics, that is, to imitate the strategy of the better player according to the game return difference and probability. A neighbouring enterprise $j$ is randomly selected for data comparison. If the game profit of enterprise $j$ is greater than its own game revenue $U_i$, then $U_j > U_i$, and individual $i$ imitates individual $j$'s strategy with probability $P_i$ in the next round:

$$P_i(s_i \leftarrow s_j) = (U_j - U_i)/D \cdot \max(k_i, k_i)$$

where $U_i$ and $U_j$ represent the game returns of enterprises $i$ and $j$, respectively, and $\max(k_i, k_i)$ represent the larger number of neighbours of enterprises $i$ and $j$. $D$ is the difference between the maximum parameter and the minimum parameter in the game situation.

When cloud manufacturing enterprise $i$ chooses to learn its neighbour’s strategy with a given probability, it connects with other heterogeneous enterprises in the network according to probability $\lambda_{ij}$. Considering that cloud manufacturing enterprises are all bounded rational individuals and have certain preferences when choosing partners, this paper uses the reconnection mechanism with preference connection to determine the random probability of innovation subject $j$’s connection $j$ as follows:

$$\lambda_{ij} = \frac{P_i^j}{P_i^j + P_i^j}$$

where $P_i$ is the income of innovation subject $i$, and $G_T$ is the collection of innovation subject $i$. When $T = 1, G_1$ is the collection of cloud manufacturing enterprises of category A; when $T = 1, G_1$ is the collection of cloud manufacturing enterprises of category A. $\alpha$ refers to preference tendency, and $\alpha = 0$ means a non-preference connection tendency, i.e., a random connection, whereas $\alpha = 1$ means that the preference is more obvious. In this paper, we choose high preference $\alpha = 1$ for simulation.

For given network and game conditions, at the last moment of enterprise group evolution, the number of partners $n_{A}(k)$ with connectivity $k$ is statistically analysed. Then, the average income of the partners is

$$U_A(k) = [\sum_{i \in \Omega_A(k)} U_i]/n_A(k)$$
IV. SIMULATION ANALYSIS OF THE GREEN INNOVATION NETWORK OF CLOUD MANUFACTURING ENTERPRISES

A. CONSTRUCTION OF COOPERATIVE INNOVATION NETWORK

Based on the patent database of China’s State Intellectual Property Office (SIPO) as the data source, this paper uses the high-frequency vocabulary statistical method to search the relevant patents that correspond to the high-frequency keywords in the green innovation field of cloud manufacturing enterprises in China and selects the obtained patents according to the international patent classification (IPC) technology classification (retrieval date: June 16, 2020). Python software is used to mine the text information such as the name, abstract and sovereign item in related patents to further refine the high-frequency keywords in this field. Then, the data are deduplicated, and a total of 316 patents jointly applied for green innovation of cloud manufacturing enterprises are selected and sorted, which are taken as the research object of this paper.

UCINET 6.0 software is used to visually process the selected patent data, and the undirected and unauthenticated network map of the new energy vehicle of industry and university research cooperation on innovation is constructed, as shown in Figure 2. In the figure, there are 98 network nodes, which represent cloud manufacturing enterprises. The node size indicates the size of the node degree value; the connection indicates that both sides of the connection have a joint application relationship.

B. SIMULATION STEPS

(1) In the process of simulation and analysis, three scale-free network models are adopted. Model 1 is the green innovation network diagram of cloud manufacturing enterprises established by the patent data in Figure 3 (number of nodes = 98). In addition, to study the evolutionary law of cloud manufacturing’s green cooperation behaviour and network structure in the interactive process, this paper uses MATLAB software to simulate the other two scale-free network models with the network scales of 200 and 500 (i.e., the number of node enterprises increases to 200 and 500), and models 2 and 3 are shown in Figures 4 and 5, respectively. The nodes represent the enterprises that participate in cooperation, and the
behaviour network as measurement indexes and studies the and speed of the enterprises’ green innovation cooperation enterprises constructed above, this paper takes the evolution depth profit of enterprises are recorded.

According to the green innovation network of cloud manufacturing enterprises, two game strategies of cooperation and non-cooperation are randomly assigned to each innovation subject in the network, and the initial cooperation level is set as 50%, that is, the network cooperation density is 0.5.

The game process is conducted among cloud manufacturing enterprises. In each round of the game, all enterprises play games with their neighbours and accumulate the profits of each innovation enterprise according to the game model.

Strategy updating and the edge breaking reconnection process of cloud manufacturing enterprises occur. In each round of the game, each innovation subject updates its strategy according to the replication dynamics rule in formula 2 and adjusts its partners according to the reconnection mechanism of preferred connection (equation 4). At the end of the game, the density of network cooperation and the average profit of enterprises are recorded.

According to the game model of the green innovation cooperation behaviour of cloud manufacturing enterprises constructed above, this paper takes the evolution depth and speed of the enterprises’ green innovation cooperation behaviour network as measurement indexes and studies the influencing characteristics of each parameter’s value change on enterprises’ green innovation cooperation behaviour.

C. PARAMETER DESCRIPTION

According to the evolutionary game model and specific algorithm of the green innovation network of cloud manufacturing enterprises, MATLAB 2020a simulation software is used for the simulation analysis. We refer not only to the rules of numerical simulation parameters set by Luo Jianqiang [61] and Cao Xia [58] but also to the consultation results of cloud manufacturing green innovation enterprises and experts in complex network-related fields. Accordingly, the simulation parameters of the cooperative innovation network evolution game are set as follows (Unit = ¥100, 000): game rounds are \( N = 200 \) times; the basic income of a class A enterprise \( \pi_A = 6 \); the basic income of a class B enterprise \( \pi_B = 5 \); the informatization income of a class A enterprise that accesses the network platform is \( I_A = 1 \); and the informatization income of a class B enterprise that accesses the network platform is \( I_B = 3 \). The channel cost of enterprises that participate in green cooperative innovation is \( C = 4 \), and the access cost of class B enterprises that access the network platform is \( C_0 = 1 \). The additional benefit of type A enterprises’ betrayal is \( T_A = 2 \), that is, the cost of the technology loss of enterprise B is \( T_B = 4 \); the additional benefit of type B enterprise’s betrayal is that of enterprise A’s technology loss cost, which is \( T_A = 4 \). The synergy benefit of green innovation cooperation between the two enterprise types is \( \omega \).

The government’s incentive subsidy coefficient for green innovation cooperative enterprises is \( \alpha \). The punishment of the government and the platform for the default enterprise is \( Z \) and \( M \), respectively. The initial network cooperation density is \( \rho = 0.5 \), and the number of simulation iterations is \( n = 100 \). To ensure the stability of the simulation results, we test each group of parameters 200 times and select the average value of the network evolution index to study the evolution of the cooperative behaviour network.

D. SIMULATION ANALYSIS

To more accurately explore the impact of cooperative innovation revenue \( \omega \), government incentive \( \alpha \) and the government’s punishment for enterprises’ betrayal \( Z \) on the cooperation density of cloud manufacturing enterprises’ green innovation network, the three scale-free networks set in 3.1 are used as carriers to simulate the prisoner’s game, while the other parameters remain unchanged.

First, we set the revenue parameter \( \omega = 1, 3, \) or \( Z = 5 \), and the incentive subsidy coefficient of green innovation \( \alpha = 5 \). Figures 6–8 show the change of the cooperation density of cloud manufacturing enterprises’ green innovation network under different cooperative innovation benefits. Among them, Figures (a) and (b) show the change of the network cooperation density and average network cooperation income of cloud manufacturing enterprises under different cooperative innovation revenues.
According to Figures 6 to 8, in the green innovation cooperation network of cloud manufacturing enterprises under different network scales, when the synergy benefit of enterprises’ green innovation is less than 10, the compensation effect of the synergy benefit on the cooperation cost is not significant. Some enterprises have poor collaborative ability, and when the network evolution result degenerates to 0, all enterprises in the network choose not to cooperate. However, due to the “herd effect”, when the network nodes exceed 200, these enterprises will also tend to synchronize with the network evolution trend, and finally, the network evolution depth of cooperative behaviour tends to be a stable state of 1. When the synergy revenue of green innovation is greater than 10, the network evolution depth tends to 1, and with the expansion of the network scale, the evolutionary speed gradually slows. This is due to the increase of the cooperative benefit, which makes the innovation subject choose to maintain the cooperation strategy so that the cooperation behaviour preference of the innovation subject changes from betrayal cooperation to maintaining cooperation. Furthermore, in the process of decision making, the innovation subject constantly adjusts its cooperative behaviour to determine the optimal cooperation strategy, which affects the interactive efficiency between the cooperative behaviour of the innovation subject and the network structure, reduces the speed of network evolution and prolongs the time of network evolution.

**Conclusion 1:** The increase of innovation synergy benefits can promote the maintenance and cooperation behaviour of innovation subjects in the green innovation network of cloud manufacturing enterprises and make the network evolve in
a Pareto-optimal direction. When the cooperative innovation revenue is lower than a certain threshold, the effect of innovation synergy revenue in the green innovation network is not obvious; only when the cooperative innovation income is higher than a certain threshold value can the maintaining cooperation behaviour of cloud manufacturing enterprises emerge in the network. In addition, the increase of the number of nodes in the green cooperative innovation network will slow the network's evolution and delay its process.

Figure 9 shows the change of the network cooperation density of a green innovation network of cloud manufacturing enterprises (\( M = 2, 4, 6 \)) under different network scales and platform constraints (\( Z = 3 \)). As seen from the figure, when the platform constraint is greater, fewer cloud manufacturing enterprises choose to betray the cooperation strategy; that is, the platform constraint can promote the cloud manufacturing enterprises in the green innovation network to choose maintaining cooperation behaviour. When the platform constraint force is lower than a certain threshold, cloud manufacturing enterprises tend to choose betrayal cooperation because of the benefit of free riding and speculation. Therefore, the role of platform constraint in the green innovation network of cloud manufacturing enterprises is not obvious. At this time, government regulation is necessary to ensure and support the evolution and development of the innovation network. Moreover, it can be found that with the increase of the network scale, cloud manufacturing enterprises that emerge in the network are dissatisfied because of the default behaviour of their partners in the process of cooperation strategy selection, which urges them to change their partners and changes the network structure, reduces the speed of network evolution and prolongs the network evolution time.

Figure 10 shows the change of the network cooperation density (\( Z = 2, 4, 6 \)) of the green innovation network
of cloud manufacturing enterprises under different network scales and types of government punishment \((M = 3)\). According to the figure, the network evolution speed when the government default penalty is 3 is significantly faster than the network evolution speed when the default penalty is 1, and with an increase in government punishment, the network cooperation density gradually increases. This is because the government punishes the speculation and free riding behaviour of cloud manufacturing enterprises through economic punishment and a deduction of incentive subsidies to increase the betrayal cost in the process of green cooperation and innovation among cloud manufacturing enterprises; in this way, it restrains the speculation of cloud manufacturing enterprises. In addition, when the network scale is larger, under the effect of the reputation mechanism, more cloud manufacturing enterprises gather together through “group heating” to form larger cooperation clusters to obtain more benefits and make the network more connected. Increasingly more innovation subjects tend to choose to maintain cooperation strategies to obtain greater benefits. However, when the scale of the network becomes larger, more cloud manufacturing enterprises adjust their cooperation behaviour due to the change in partners and profits under the limited rationality; therefore, the speed of network evolution will decrease.

**Conclusion 2:** The perfect punishment mechanism can promote the evolution of a green cooperative innovation network and achieve the stable state of cooperation more quickly, which greatly limits the opportunistic behaviour caused by the technology spill over of enterprises and thus ensures green cooperative innovation. When the punishment is stronger, the more the cooperative behaviour network will evolve towards a Pareto-optimal condition. Furthermore, the impact of the government’s punishment on the network cooperation behaviour is more obvious.

Figure 11 shows the change in the network cooperation density \((\alpha = 0.1, 0.3, 0.5, 0.7, 0.9)\) of cloud manufacturing enterprises’ green innovation network under different network scales and government green subsidies \((M = 3)\). It can be found that with the increase of government subsidies, the density of network cooperation increases. This is because the government subsidizes the green innovation of cloud manufacturing enterprises by supporting and rewarding benefits to reduce the cooperative R&D cost and the risk of the innovation subject. Under limited rationality, the innovation subjects tend to choose the maintaining cooperation strategy, which makes the network cooperation density gradually increase. By comparing the network cooperation density under different government subsidies, we find that when the government subsidies are lower than the threshold level, the network cooperation density is small and shows a non-cooperative trend; when there is a small change, the network cooperation density changes considerably. This is due to the increase of government subsidies; on the one hand, government subsidies can directly subsidize the green R&D of cloud manufacturing enterprises, and on the other hand, they also indirectly release relevant positive signals to the market. Therefore, due to the direct and indirect functions of government subsidies, innovation subjects are more sensitive to government subsidies. In addition, with the increase of the network scale, the speed of network evolution becomes slower, but the density of network cooperation increases. This is because the increase of the network is conducive to promoting increasingly more cloud manufacturing enterprises to carry out information exchange and cooperative research and development and encourages cloud manufacturing enterprises to participate in green innovation and choose more suitable partners, which makes the network structure change and expand its own benefits.

**Conclusion 3:** The increase of government green subsidies can promote the maintenance and cooperation behaviour of innovation subjects in the green innovation network of cloud manufacturing enterprises. Under the effect of government green subsidies, when the subsidy is greater, the innovation subject tends to choose the maintaining cooperation strategy, that is, the innovation subject is more sensitive to the government subsidy. In addition, when the level of government subsidies is lower than the threshold level, this is not conducive
to maintaining cooperative relationships among innovation subjects.

V. CONCLUSION

Based on the game theory of complex network evolution, this paper analyses the cooperative behaviour of enterprises in a cloud manufacturing green innovation network from the perspective of government regulation and simulates and analyses the green innovation process of enterprises by using a scale-free agglomeration network carrier. By analysing the selection strategies of cloud manufacturing enterprises in the process of green innovation, the evolutionary game process of the selection of cooperation strategies of cloud manufacturing enterprises with the changes of time and network structure parameters is clarified, and the influencing mechanisms of collaborative interests, government rewards and punishments, platform supervision and the network scale on the evolution depth and speed of the green innovation network are further clarified. The results show the following.

First, cloud manufacturing enterprises should reasonably participate in green innovation projects according to their own advantages and collaborative benefits, scientifically select partners, and curb the risks that may be created by opportunistic behaviours in the process of cooperation. Second, under the premise of promoting enterprise cooperation, the cloud manufacturing platform should appropriately strengthen its supervision and punishment, limit the risk of opportunistic behaviour, and help cloud manufacturing enterprises form a good cooperation atmosphere. Third, in the process of green innovation cooperation, the government should increase policy support and financial incentives, especially in the early stage of cooperation, and effectively reduce the barriers of B-type emerging enterprises embedded in the cloud manufacturing network. Furthermore, effective supervision and reasonable punishment should be carried out to promote the stability of cooperation.

The research significance of this paper on the green innovation management of cloud manufacturing enterprises is as follows. First, this study fills in the blank of the green cooperation behaviour evolution mechanism of cloud manufacturing enterprises, provides a theoretical basis to promote the evolution of cloud manufacturing enterprises’ green innovation network, and provides a certain reference and suggestions for enterprises to choose innovation strategies. Second, this paper analyses the evolutionary game process of a cloud manufacturing green innovation network by combining examples and simulation models, which can more intuitively explain the influence of the relevant parameter changes on the system’s diffusion process of green innovation through graphical results. Third, the members of cloud manufacturing enterprises can better understand one another’s behaviour selection strategies. By adjusting and controlling the relevant parameters, they can effectively control the cooperation conflict and avoid the risk of technological loss, which in a certain sense, promotes the development of green innovation cooperation projects.

However, there are still some deficiencies in the research. First, this paper analyses only the evolutionary law of the cooperative behaviour and network structure interaction process of enterprise innovation subjects from the perspective of government regulation but ignores the participation of many heterogeneous entities in reality, including consulting, design, etc. Second, this paper discusses a weightless network and fails to explore the impact of the structural characteristics and relationship characteristics of cloud manufacturing enterprises’ green innovation network on the diffusion behaviour of green innovation. In addition, the dynamic external environment, the possible fairness preference and the collusion behaviour of decision makers will be the focus of our follow-up research work.

COMPETING OF INTERESTS

The author declares that there are no competing interests regarding the publication of this paper.

AUTHOR’S CONTRIBUTION

Conceptualization, J.X., X.L. and J.Z.; methodology, J.Z. and X.L.; software, J.Z. and X.L.; validation, J.X.; formal analysis, J.Z.; investigation, J.Z and F.L.; resources, J.X.; data curation, J.Z. and F.L.; writing—original draft preparation, J.Z. and F.L.; writing—review and editing, J.Z. and X.L.; visualization, J.Z.; supervision, J.X.; project administration, J.X. and X.L.; funding acquisition, J.X and X.L. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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