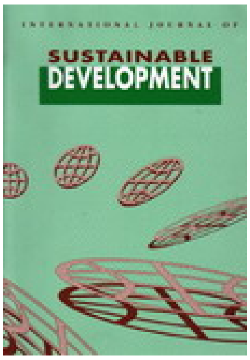

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Sustainable development of a low-carbon supply chain economy based on the internet of things and environmental responsibility

Zhenhua He, Shurui Gu

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Sustainable development of a low-carbon supply chain economy based on the internet of things and environmental responsibility

Zhenhua He

School of Logistics and Transportation and Tourism,
Jiangsu Vocational College of Finance and Economics,
Huaian 223003, Jiangsu, China
Email: hezhenhua1982@jscj.edu.cn

Shurui Gu*

Business School,
Guangzhou College of Technology and Business,
Guangzhou 510800, Guangdong, China
Email: srgu@foxmail.com
*Corresponding author

Abstract: This paper takes the flexible resource attributes of the low-carbon supply chain and its resource allocation as the main research objects, analyses and discusses the flexible resource allocation of the low-carbon supply chain and its resource attribute characteristics, and then studies the effective allocation of the flexible resources of the low-carbon supply chain from the perspective of resource attributes based on low-carbon supply chain theory and methods. This work studies the solution to the mixed algorithm and the robustness of the model and algorithm for the low-carbon supply chain flexible resource allocation model. The results show that this method effectively solves the problem of how to achieve the flexible resource allocation of the low-carbon supply chain. The robustness analysis of the model and algorithm can reasonably solve the problem of how to achieve flexible resource allocation in the low-carbon supply chain.

Keywords: sustainable development; internet of things; environmental responsibility; low-carbon.

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Biographical notes: Zhenhua He received his Doctor's degree from Gachon University, South Korea. Currently, he works as a full-time teacher and researcher at Jiangsu Vocational College of Finance and Economics. His research interests include educational administration and tourism management.

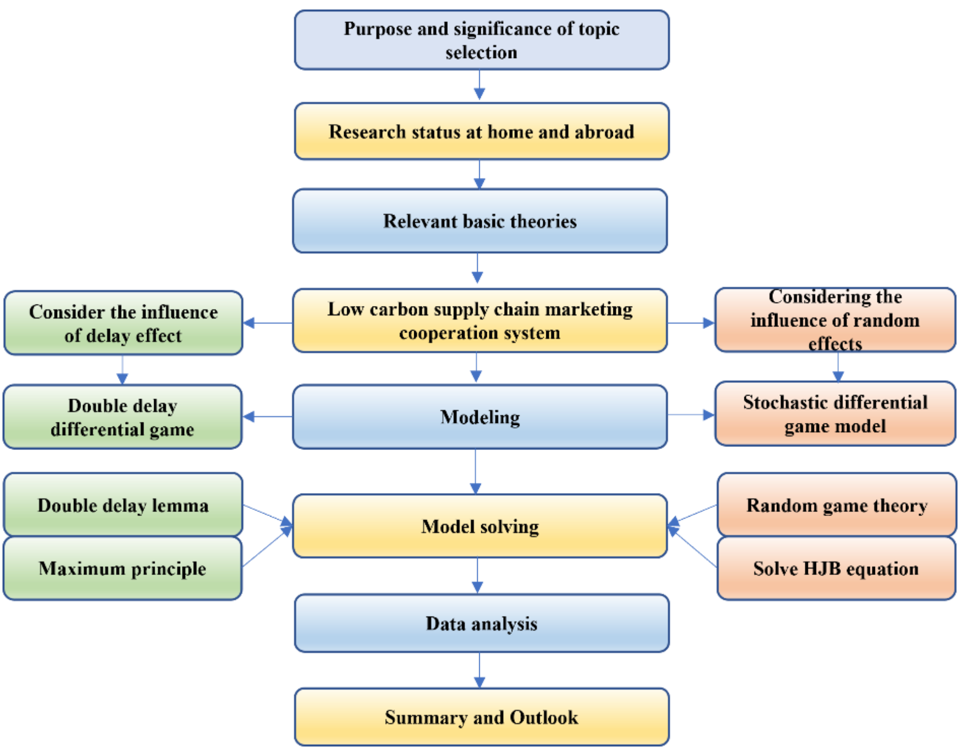
Shurui Gu is currently a full-time Lecturer from the Business School in Guangzhou College of Technology and Business, Guangzhou, Guangdong, China. Her research interest focuses on international business, international logistics and cross-cultural fields.

1 Introduction

Green supply chain management is the ‘green concept’ and ‘environmental consciousness’ into the supply chain management process, in the process of enterprise production implementation of green design, green procurement, green production, green packaging, green sales, green consumption and green recycling. Green supply chain management, keeps the whole supply chain on resource consumption and environmental impact to minimum, to realise the society, enterprises and natural environment sustainable development of a new strategic model. In recent years, China has been faced with increasingly serious environmental and resource problems. The emissions of industrial pollutants, especially carbon emissions, have exceeded the carrying capacity of resources and the environment, resulting in serious air pollution, acid rain and the continuous fermentation of smog in many cities. According to the latest statistics released by China, Carbon Brief, a research institute, calculated that China’s total carbon emissions in 2018 would reach 10 billion tons, up 2.3% from 2017 (when CO_2 emissions grew by 1.7%). These statistics mean that the world’s response to climate change has gone completely off course. According to the report, 27% of global carbon emissions in 2017 came from China, 15% from the USA, and 17% from India and European Union countries. In recent years, the complexity of environmental problems and a series of environmental changes have occurred in the process of enterprise industrialisation in China. Therefore, how to deal with carbon emissions is an important problem facing society and enterprises. Moreover, with the development of supply chain node enterprises, the levels of resource consumption and carbon emissions of low-carbon supply chains are becoming increasingly serious. These results are closely related to the carbon dioxide reduction, energy efficiency and carbon emissions of supply chain node enterprises. The research technology roadmap is shown in Figure 1.

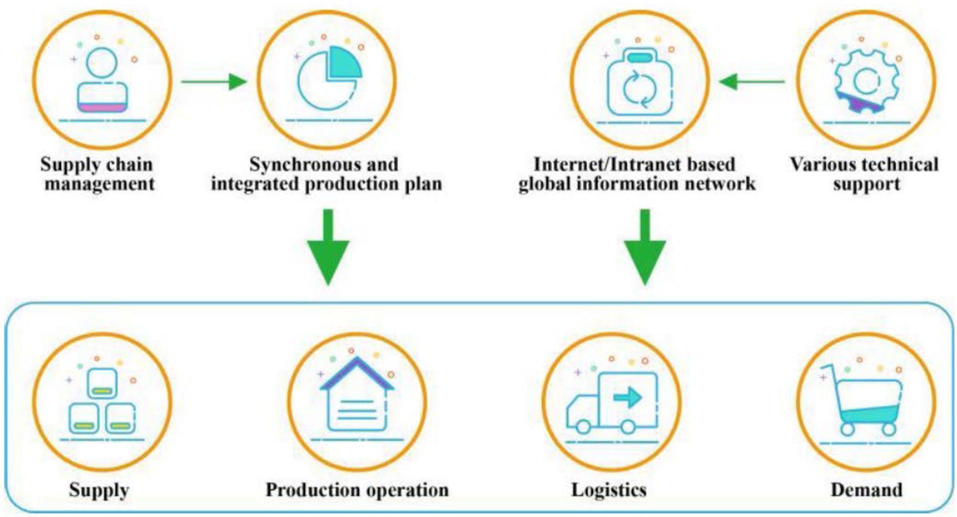
With the continuous increase in the amount of supply chain resources and energy consumption, environmental pollution and ecological destruction, increasing pressure is being placed on the need for environmental protection, governance and carbon emission reduction. Due to differences across industries, different industries have varying energy demand structures for their respective supply chains, patterns of resource element allocation, production process flows, and supply chain resource attributes (Alkawsi et al., 2020; Cheryl et al., 2021). The main players of the node enterprises in the supply chain should have their own positioning and roles, but they need to cooperate with each other and work together. By promoting the low-carbon development of the whole supply chain and focusing on the energy saving and emission reduction of node enterprises, better results can be achieved. In recent years, many well-known international manufacturing enterprises have achieved good environmental and social benefits through low-carbon supply chain management. Yao et al. (2021) believe that with the rapid development of China’s economy, it becomes crucial to achieve a correct balance between economic development and environmental protection. Green growth is an important way in which to identify the relationship between economic development and the environment. Low-carbon development and ecological protection are two important aspects of green development that greatly affect the resource-based supply chain of enterprises. Therefore, this paper attempts to explore the income distribution mechanism of a resource-based supply chain against the background of green development (Yao et al., 2021). The working principle of the internet of things is to embed the sensor into the environment or object to be monitored, collect the data information in real time, and then collect the collected information resources with the help of the network. Then, the monitoring personnel can use the data information to monitor the environment in real time and exert effective management means. The significance of low-carbon supply chain research is also emphasised in the low-carbon development plan (2016–2020), the implementation guide of low-carbon manufacturing projects (2016–2020), Made in China 2025, and the research report on the development of the low-carbon supply chain in China's manufacturing industry in 2018. Therefore, against the above research background, this paper starts from the perspective of low-carbon supply chain resource attributes, draws on the research achievements of the low-carbon supply chain both at home and abroad, realises the effective allocation of low-carbon supply chain flexible resources from the perspective of resource attributes, and effectively improves the low-carbon performance of the flexible resource allocation of the low-carbon supply chain (Ghosh et al., 2020; Wang et al., 2021). The supply chain management structure diagram is shown in Figure 2.

Figure 1 Research technology roadmap (see online version for colours)



The research scope of this paper on the model and algorithm of the flexible resource allocation of the low-carbon supply chain covers six parts. The first part is the research background and significance of the paper. The second part is a literature review that summarises the research progress of the low-carbon supply chain, the network chain structure model of the low-carbon supply chain and the supply chain management platform. The third part involves the carrying out of related theoretical analysis: in view of the actual situation, multiattribute, multigranularity and utility function theory are applied to analyse and study the flexible resource allocation of the low-carbon supply chain and its flexible resource attribute characteristics. In the fourth part, through the above research, the paper constructs a low-carbon supply chain flexible resource allocation model based on the attribute perspective: the construction of such a model based on interval information and the multiattribute effect. In the fifth part, on the basis of the above analysis, flexible resource allocation based on interval information, flexible resource allocation based on attribute association and flexible resource allocation based on attribute weight are studied. The robustness and control of the low-carbon supply chain flexible resource allocation model and its hybrid quantum neural network algorithm are discussed in depth, and the main research conclusions of the paper are presented.

Figure 2 Supply chain management structure diagram (see online version for colours)



2 Literature review

The application of the internet of things to the monitoring of environmental protection can enable the monitoring personnel to timely understand the emissions of various substances in the environment, and provide data support for various environmental protection, pollution control and disaster prevention and mitigation policies. In the early study of flexibility, many scholars believed flexibility to be a measure of the strain capacity of supply chain resources. Lin et al. (2021) established a dynamic game model in the low-carbon supply chain, which was composed of a single manufacturer and a single retailer with social preferences. The present work studies the complex dynamic characteristics of pricing decisions and carbon emission reduction strategies in the supply chain, focusing on the impact of retailers' social preferences on pricing decisions, carbon emission reduction strategies, profits, supply chain coordination and the complexity of dynamic models. We find that the adjustment parameters of pricing and carbon emission reduction should be kept within a certain range; otherwise, the system becomes unstable or even chaotic through periodic bifurcations or waveform chaos. Retailers' stronger social preferences are always conducive to reducing carbon emissions among manufacturers and to helping maintain the stability of the supply chain system. However, the impact on the long-term profitability of the supply chain is related to the state of the system. Compared with the setting of centralised decision-making, regardless of whether or not retailers have social preferences, the optimal carbon emission reduction strategy and supply chain profit in decentralised decision-making are always less than those in centralised decision-making. Therefore, a side payment self-executing contract is designed to coordinate the supply chain and achieve Pareto improvement. The coordination mechanism proposed in this study not only leads to Pareto improvement but also improves the stability of the supply chain system. Finally, this study provides inspiration for low-carbon supply chain management (Lin et al., 2021). The workflow of internet of things mainly includes three links: information collection, information transmission and information processing. Corresponding to these three links, the architecture of internet of things can be divided into perception layer, network layer and application layer. At the same time, it is concluded that the higher the degree of flexibility of resources, the stronger their ability to cope with changes to manufacturing objects. They suggested that the concept of supply chain flexible resources is considered from an integrated, customer-oriented perspective and defines the flexibility of the supply chain as output flexibility, new product flexibility, and response flexibility, among others. They studied resource flexibility and methods for flexible resource allocation and pointed out that production flexibility is determined by resource allocation flexibility and the relationship between resources. They presented an overall resource flexibility measurement model for supply chain system integration that provides a more accurate measurement of chain equipment, even performing better than the conventional measurement model. In addition, the measurement model allows for multiobjective vector performance for all connected equipment, and the simple measurement approach provides a good way to improve basic capabilities. They highlighted supply chain flexibility resource clustering trends. Supply flexibility assessment can identify the need to improve product flexibility and determine the best direction through which to improve the uniqueness of flexible products. Among others, built a manufacturer-led Stackelberg game model in a dual-channel supply chain to examine the government's response under the centralised or decentralised decision-making structures of different low-carbon strategies. The results show that regardless of whether or not the government invests in emission reduction, it can obtain higher profits by taking incentive or punishment measures in the centralised decision-making supply chain. Moreover, for the decentralised decision-making mode, increasing low-carbon subsidies to retailers can achieve a win-win situation between the supply chain and the government. Finally, channel competition is conducive to improving the supply chain and social benefits. Therefore, the government has the responsibility to adopt reasonable subsidy policies, formulate low-carbon standards for the industry, and properly guide competition among supply chain members to achieve higher profits (Zhang and Zhang, 2022). An example of such a low-carbon model is shown in Figure 3.

Figure 3 Network chain structure model of the low-carbon supply chain (see online version for colours)

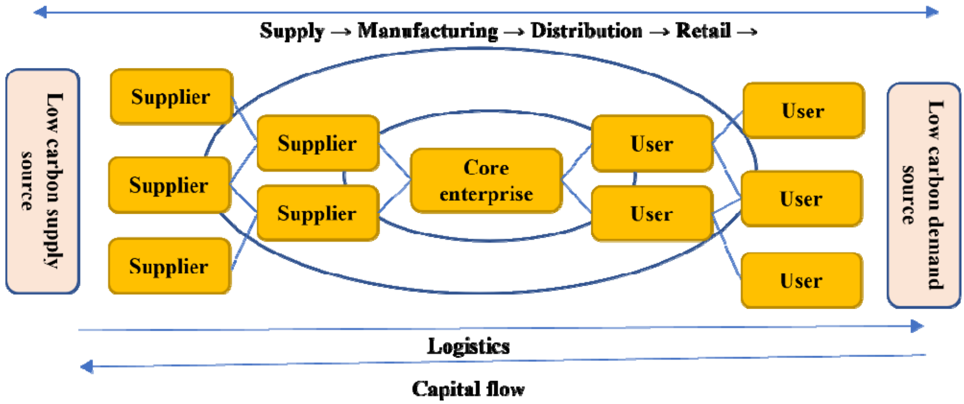
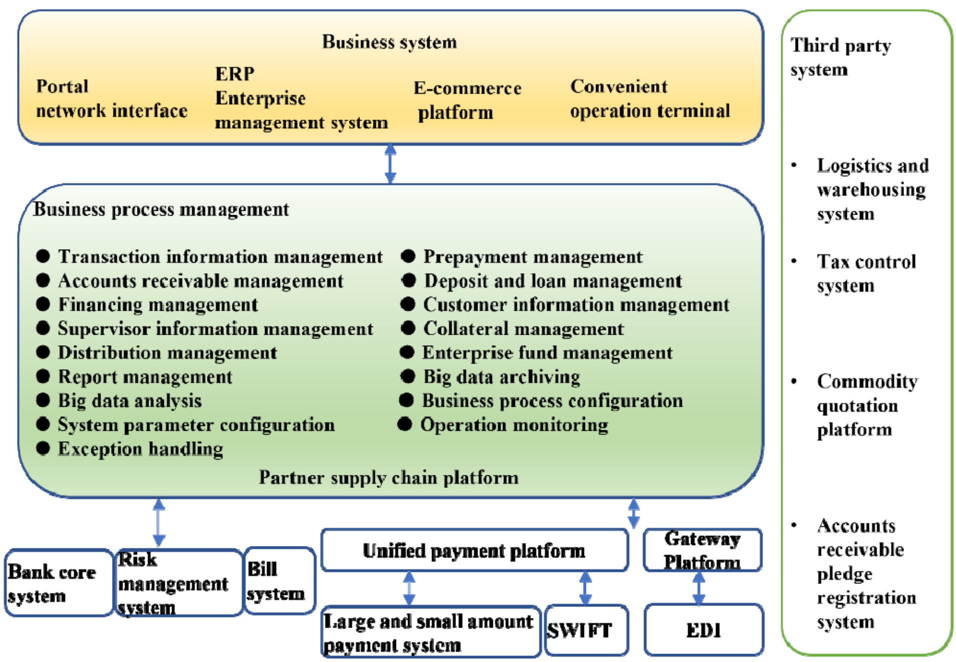


Figure 4 Supply chain management platform diagram (see online version for colours)



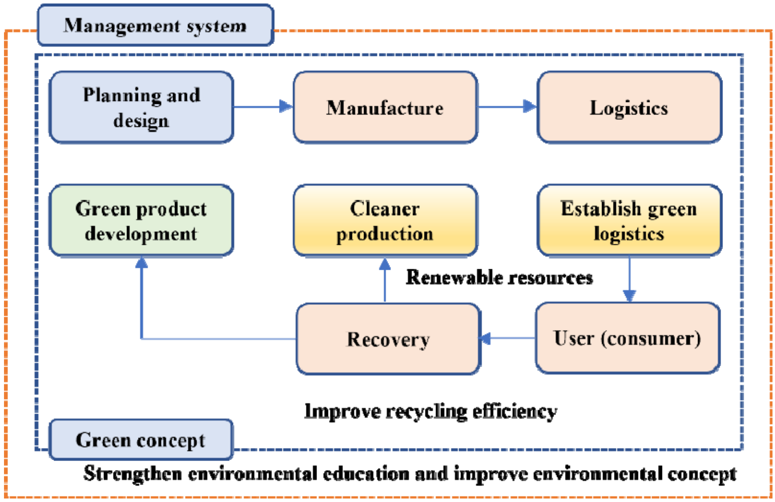
The generation and development of the internet of things thanks to the communication network and the rapid development and popularisation of the internet, with the aid of recognition perception technology and functional device to perceive the external world, and then through the internet to data information transfer, and with the aid of information processing system to collect data processing and analysis, provide the information of the user of judgment and decision basis. Low-carbon performance is an important embodiment of the low-carbon supply chain and the low-carbon performance of companies in the export improvement industry. Therefore, it is important to emphasise the importance of low-carbon content in the management of the low-carbon supply chain. They examined the drivers of low-carbon technology and the impact of the innovation of such technology on low-carbon materials and described various types of low-carbon electric motors. Low-carbon content, innovative technology and environmental characteristics have a major impact on whether low-carbon performance can be achieved. Some scientists have argued that pollution control has a major negative impact on the degree of efficiency of low-carbon emissions by industry standards and the environmental characteristics of capital. Moreover, the given layer affects the degree of efficiency of the business as a whole. At the same time, it has been pointed out that the direct effect of the pollution control of low-carbon materials is greater than is the indirect effect and that the degree of low-carbon efficiency can be improved by improving the environmental characteristics of the supply chain equipment (Liu et al., 2021a). A platform management device is shown in Figure 4.

3 Research method

3.1 Sustainable development requirements of the low-carbon supply chain economy based on the internet of things and environmental responsibility

The workflow of internet of things mainly includes three links: information collection, information transmission and information processing. Corresponding to these three links, the architecture of internet of things can be divided into perception layer, network layer and application layer. The perception layer mainly refers to the connection with the external physical world. This layer system involves many hardware devices and technologies, including cameras, barcode readers, etc. With the help of these recognition devices, the information in the physical environment can be converted into usable data information. The network layer is mainly responsible for transmitting the collected data information to the application layer in a timely and accurate manner. This series of work needs to be based on the communication network and the internet, and plays an important central role in the work of the whole internet of things. In the application layer of the internet of things, all kinds of data should be summarised and processed, and the reasonable transformation of data into the form of data directly used by decision makers, so as to meet the needs of the application of these data in different fields. Managing low-carbon chains is an important link through which the industry can obtain a greater competitive advantage. As the concept of the low-carbon industry has become popular, people’s awareness of environmental protection is increasing day by day, and consumers are choosing products that are more environmentally friendly. The green supply chain is related to the sustainable development of the national economy. China’s green supply chain management is relatively backward compared to that of developed countries. At present, the amount of carbon emission reduction of China accounts for approximately one-third of the amount of overall carbon emission reduction in the global market, ranking second in the world. This finding shows that China is still trading high energy consumption and high pollution for GDP growth. This inclination and dislocation of social resource allocation will eventually affect the sustainable development of enterprises and society as a whole (Liu et al., 2020), as shown in Figure 5.

Figure 5 Diagram of the supply chain management system (see online version for colours)



3.2 Realisation of a basic algorithm for the sustainable development of a low-carbon supply chain economy based on the internet of things and environmental responsibility

3.2.1 Model description

This essay investigates the product marketing cooperation system of a low-carbon supply chain, which consists of a single manufacturer (D) and a single retailer (C) under the influence of a delay effect (Peng et al., 2020). In the process of low-carbon product marketing, manufacturers and retailers in this system can create green, low-carbon and environmentally friendly brand images for their products, which is defined as the 'low-carbon goodwill' of enterprises. Manufacturers, as the core enterprises in the supply chain, use news media to promote low-carbon products, improve product quality and function, and build low-carbon brand goodwill. Retailers should promote the low-carbon goodwill of their products through reasonable promotion and distribution strategies, such as good advertising and the establishment of appropriate sales channels.

- *Hypotheses 3-1:* Both parties aim to maximise their own benefits, are completely rational and have complete information. The efforts of manufacturers and retailers in the marketing of low-carbon products are $E_D(t)$ and $E_C(t)$, respectively, and $\lambda_D > 0$ and $\lambda_C > 0$ represent the marketing cost coefficients of manufacturers and retailers.

The actual expressions of the marketing costs of both parties, $C_D(t)$ and $C_C(t)$, are shown in equation (1) (Hayat et al., 2022):

$$C_D(t) = E_D 2(t); C_C(t) = E2(t) \tag{1}$$

- *Hypothesis 3-2:* The better the low-carbon goodwill image of a product is, the more the firm can improve consumers' purchase intention and trust in the product.

Figure 6 Comparison of retailers' marketing efforts and strategies (see online version for colours)

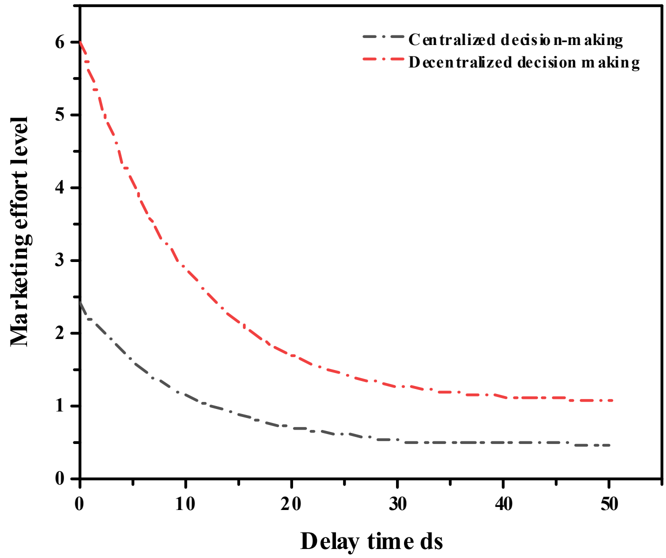
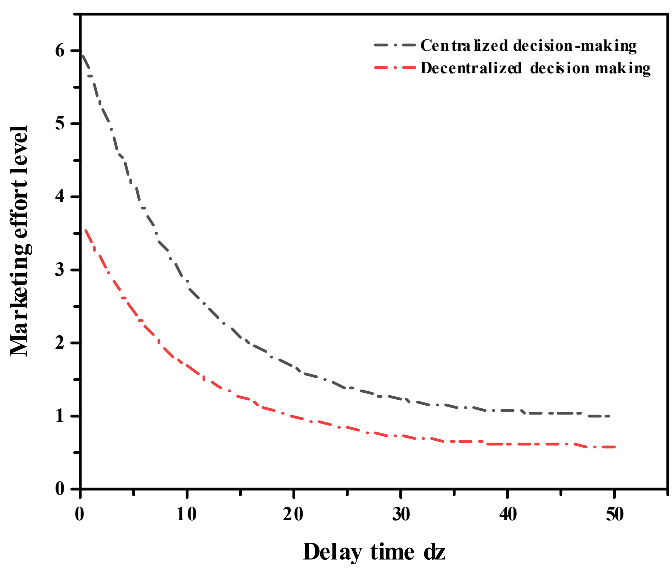


Figure 7 Comparison of manufacturers' marketing effort strategies (see online version for colours)



Suppose that $G(t)$ represents low-carbon goodwill in the supply chain, where the initial state of the system is $G(0) = G_0$; α and β represent the degree of influence of the efforts of the manufacturer and retailer, respectively, in low-carbon product marketing on low-carbon goodwill, namely, the marketing effort level coefficient; *ds* and *dz* represent the time delays of marketing effort strategy ε of the manufacturer and retailer, respectively. The low-carbon supply chain marketing efforts of manufacturers and retailers are shown in Figures 6 and 7, respectively. $\delta > 0$ represents the attenuation coefficient of low-carbon goodwill in the low-carbon product marketing system. Based on the N-A model, considering the delay characteristics of marketing efforts in practice, the following delay differential equation is used to describe the dynamic change in product goodwill (2):

$$G(t) = \alpha ED(t - dz) + \beta EC(t - ds) - \delta G(t), \quad G(0) = G0 \tag{2}$$

Figure 8 Evolution of low-carbon goodwill when *ds* is greater than *dz* (see online version for colours)

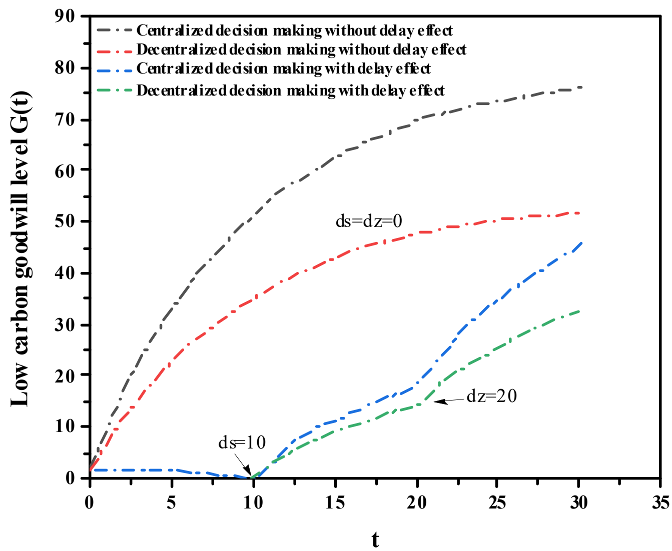


Figure 9 Evolution of low-carbon goodwill when *ds* is less than *dz* (see online version for colours)

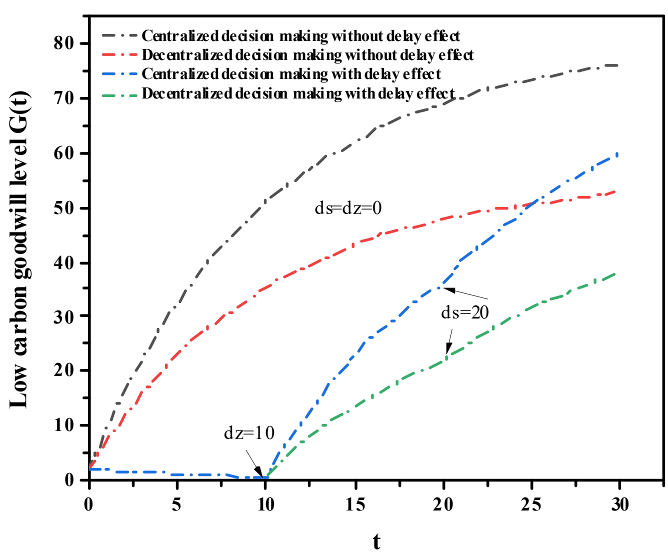
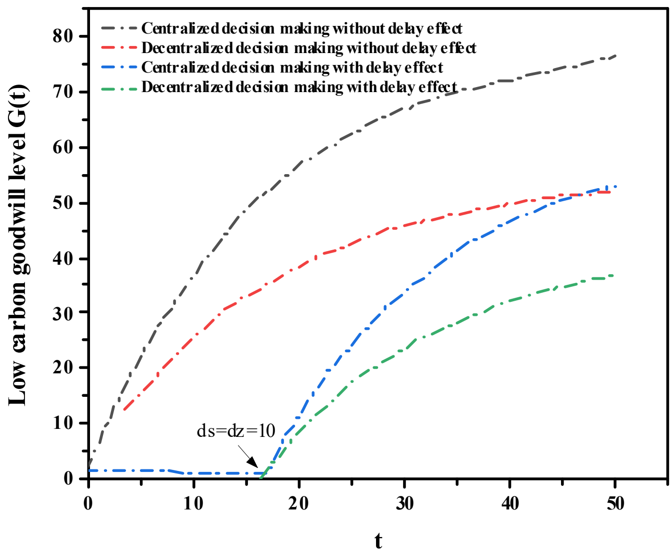


Figure 10 Evolution of low-carbon goodwill when *ds* equals *dz* (see online version for colours)



The delay time exists in three cases: those when *ds* is greater than *dz*, when *ds* is less than *dz*, and when *ds* is equal to *dz*. As an example, if *ds* is greater than *dz*, then the $G(t)$ segment is brought into the evolution of low-carbon goodwill. In the whole time range, its interval is [0, *ds*), [*ds*, *dz*), and [*ds*, ∞). The first time interval is the initial point of G0, the initial value of the second interval is the right endpoint of the first interval, etc., as shown in Figures 8, 9, and 10.

- *Hypothesis 3-3:* The income obtained from the marketing cooperation system of the low-carbon product supply chain is distributed between the two cooperative entities, and the income distribution coefficient is determined for both parties in advance.

In such a case, the retailer gets (0, 1) and the manufacturer gets 1-. In actual production, to encourage retailers to conduct low-carbon product marketing, manufacturers take the initiative to bear marketing cost (*t*) for retailers. (*t*) (0, 1) represents the 'subsidy factor'. In the infinite time period, the goal of both companies is to seek the optimal marketing effort strategy to ensure the maximisation of their respective incomes. Both parties discount their future earnings at a fixed rate of 0. The manufacturer's objective function is as follows:

$$Y_D = \int_0^\infty e^{-pt}\left[(1-\omega)\left(\varepsilon E_D(t)+\gamma E_C(t)+\xi G(t)\right)-\frac{\lambda_D}{2}E_D^2(t)-\theta(t)\frac{\lambda_C}{2}E_C^2(t)\right]dt \tag{3}$$

3.3 Delayed effect

As shown in equation (4),

$$dx(t) = E\left[t, x(t), u_1(t), u_2(t), ..., u_n(t)\right]dt + \sigma\left[t, x(t)\right]dW(t), x\left(t_0\right) = x_0 \tag{4}$$

In this formula, E is the mathematical expectation; t, $x(t)$ is the matrix $m * \theta$; $dW(t)$ is the Wiener process of θ, and the initial state is x_0.

The delay effect is included in the study of the marketing cooperation system of the low-carbon supply chain, and the case in which the delay effect exists in the marketing effort strategies of both the manufacturers and retailers of low-carbon products is also considered. A two-delay differential game model is constructed under a dynamic environment, and the evolution process diagram of the low-carbon goodwill of products is drawn according to the different relationships between the two delay times. The influence of the delay effect on the system's optimal profit and level of low-carbon goodwill is analysed. The decision basis and the effect of the manufacturer's subsidy ratio on the retailer's marketing effort under the double delay effect are explored. This approach allows for the corresponding management enlightenment to be identified (Muhammad et al., 2022) to obtain a valuable decision-making basis for the members of the low-carbon supply chain marketing cooperation system and provide correct theoretical guidance for the promotion of the development of low-carbon supply chain marketing cooperation. From the perspective of low-carbon supply chain product marketing, we consider the impact of manufacturer and retail marketing efforts on low-carbon goodwill, and establish a dynamic differential model based on the double-delay effect. Based on the maximum principle and the double-delay lemma, this paper studies the changes of the optimal marketing effort strategy, low-carbon goodwill and optimal profit of low-carbon products under centralised and decentralised decision-making

3.4 Low-carbon supply chain energy saving technology in economic production

A key step in managing the green chain is green production, which will use energy efficiency, reduce consumption and reduce emissions, and use technology and management tools. This was identified as reducing and eliminating the impact of manufacturing on human health and the ecological environment. Monitor, inspect and implement pollution prevention and control measures in the production process to ensure pollution prevention and control and improve the two objectives of comprehensive measurement. Therefore, first, this approach seeks to increase the level of investment in science and technology; increase the amount of new democratic capabilities; and measure the levels of integration, modification, and use of technology in the industry. Second, this approach aims to improve the development and use of low-carbon sources such as nuclear power and hydropower and the carbon sequestration of ecosystems. Third, this approach aims to tighten the level of government regulation and to urge companies to promote regulation and reduce energy consumption during operations. Furthermore, this approach aims to improve low-carbon capabilities and reduce the level of energy consumption by driving the industry at high speeds (Sule et al., 2022).

Green supply chain management is a completely new management concept that encourages companies to focus on long-term interests, bring all products to the same starting point, and build a network of partnerships. Moreover, such management aims to share information among all members, with senior leaders in charge of changing and improving their strategies to address their knowledge of the stable development of the industry. Environmental protection is the desired goal in the field of improving human health and the economy. Company leaders should actively link business goals, environmental goals, and relationship goals to the supply chain so that employees and vendors can have access to them. Furthermore, emphasis should be placed on the importance of the environmental protection of the industry (GKallal, 2022; Liton e al., 2022). The structural model of the low-carbon resilience mechanism is shown in Figure 11.

Figure 11 Structural model of the flexible resource allocation mechanism in the low-carbon supply chain based on attribute characteristics (see online version for colours)

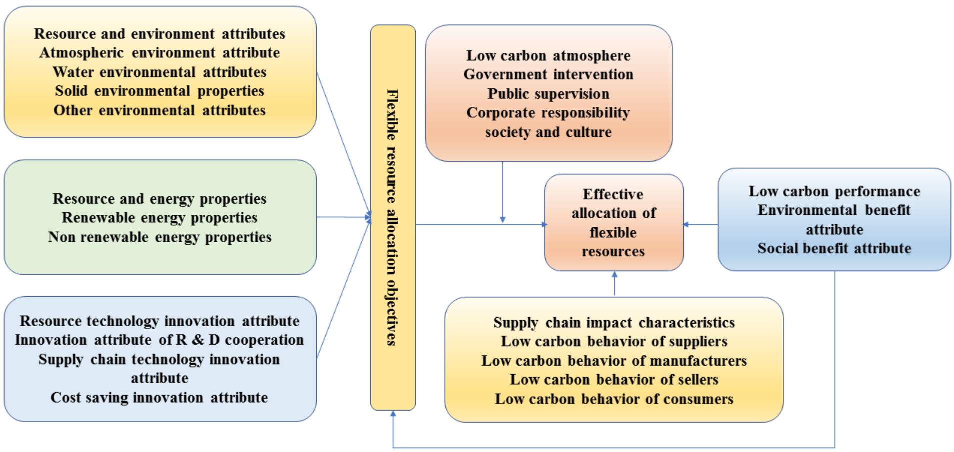


Table 1 Suitability index test of the basic model of resource allocation in the low-carbon supply chain

Simulation fit index	*Parameter value*	*Critical value*	*Structure*
GFI	0.913	> 0.9	Acceptance
RMSEA	0.06	> 0.9	Acceptance
NFI	0.954	> 0.9	Acceptance

Table 2 Verification table of the influence path data of flexible resource allocation in the low-carbon supply chain

Research on path	*Estimation*	*Standard estimation*	*CR*	*SE*
Renewable energy	0.113	0.148	0.031	2.874
Nonrenewable energy	0.152	0.397	0.037	3.371
Technology	0.502	0.453	0.046	6.757
Research and development	0.101	0.117	0.028	3.361

Enterprises should focus on the green supply chain as a guide by which to restructure the enterprise operation system, set up green management departments, formulate statistics, monitor and assess methods for carbon emission reduction, improve the management system and supervision and implementation mechanism, and provide institutional guarantees for low-carbon production and manufacturing. We should actively adjust the production system; speed up the phasing out of outdated production capacities, processes, technologies and equipment; strengthen energy conservation in production and buildings; carry out green procurement and green services; and actively solve resource- and environment-related problems that affect the sustainable development of enterprises. Green supply chain management emphasises cooperation among all enterprises in the supply chain, while for suppliers, such cooperation is found in the upstream of the whole supply chain (Zhu et al., 2021). The actions of suppliers are transmitted to every node in the supply chain, and cost savings can be transmitted to all parts of the supply chain, thereby improving overall efficiency. Therefore, leading US companies take suppliers very seriously and, thus, choose them very carefully (Meng et al., 2021). Their usual practice is to use environmental capabilities as a prominent criterion for evaluating vendors. According to the requirements of environmental laws and regulations and their own requirements, the corresponding index system is set up, the data of suppliers is obtained through questionnaire survey, and quantitative and qualitative analysis is conducted as the scientific basis for selecting suppliers. After choosing a good supplier, not through supervision and evaluation, cooperate with suppliers, but through guidance, and establish a win-win partnership with suppliers through guidance, support and help. Tables 1 and 2 show the test tables of the suitability index of the basic model of resource allocation in the low-carbon supply chain.

4 Design of resource allocation parameters for the low-carbon supply chain based on the internet of things and environmental responsibility

4.1 Design of flexible resource allocation parameters for the low-carbon supply chain

To effectively improve the characteristics of flexible substrates in low-carbon materials and to improve the efficiency and level of resource distribution, this article specifically designs the process of the exchange of capital of low-carbon products. This study design aims mainly at improving low-carbon performance through the effective allocation of the environmental attributes of low-carbon supply chain flexible resources to effectively improve the efficiency of low-carbon supply chain flexible resource allocation. Parameter design is very complex in the process of the flexible resource allocation of the whole low-carbon supply chain. The parametric design diagram of a hybrid neural network model is shown in Figure 12.

Therefore, it is necessary to design the configuration parameters according to the attributes of flexible resources in the low-carbon supply chain and finally achieve the overall optimisation goal of having flexible resource allocation parameters in the low-carbon supply chain. In the analysis of the resource and environmental attribute lists of the low-carbon supply chain, attention should be paid to the collection of data, the extraction of effective attribute characteristics, and the elimination of redundant characteristic attributes (Dhiman et al., 2021). Then, a complete set of flexible resources and environmental attributes of the low-carbon supply chain can be established to analyse their characteristics and other relevant information to clarify the level of consumption of flexible resources in the supply chain and the influence of environmental attributes. The reasonable allocation of flexible resources in a low-carbon supply chain should be ensured to achieve the overall optimisation goal of reducing the levels of energy consumption and environmental pollution. Therefore, it is difficult to analyse the allocation of flexible resource attributes in the low-carbon supply chain. The flexible resource allocation parameter design of the low-carbon supply chain is also reflected in the uncertainty of the data and the unbalanced performance of the neural network structure in the configuration process, which is also related to the below robustness analysis of the configuration model and hybrid algorithm. The attribute characteristic scale of flexible resource allocation in the low-carbon supply chain is shown in Tables 3 and 4 (Shriram et al., 2021).

Figure 12 Structural parameter design of a hybrid neural network based on a radial basis function (see online version for colours)

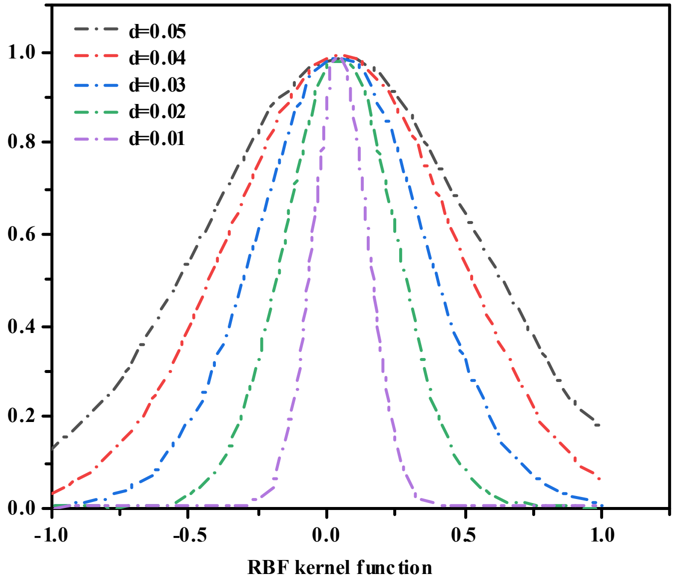


Table 3 Attribute characteristic scale of flexible resource allocation in the low-carbon supply chain

Attribute feature name	*Code*	*Characteristic measurement term*
Atmosphere	RS1	Carbon dioxide emissions
Water	RS2	Waste water discharge
Solid state	RS3	Solid waste disposal rate

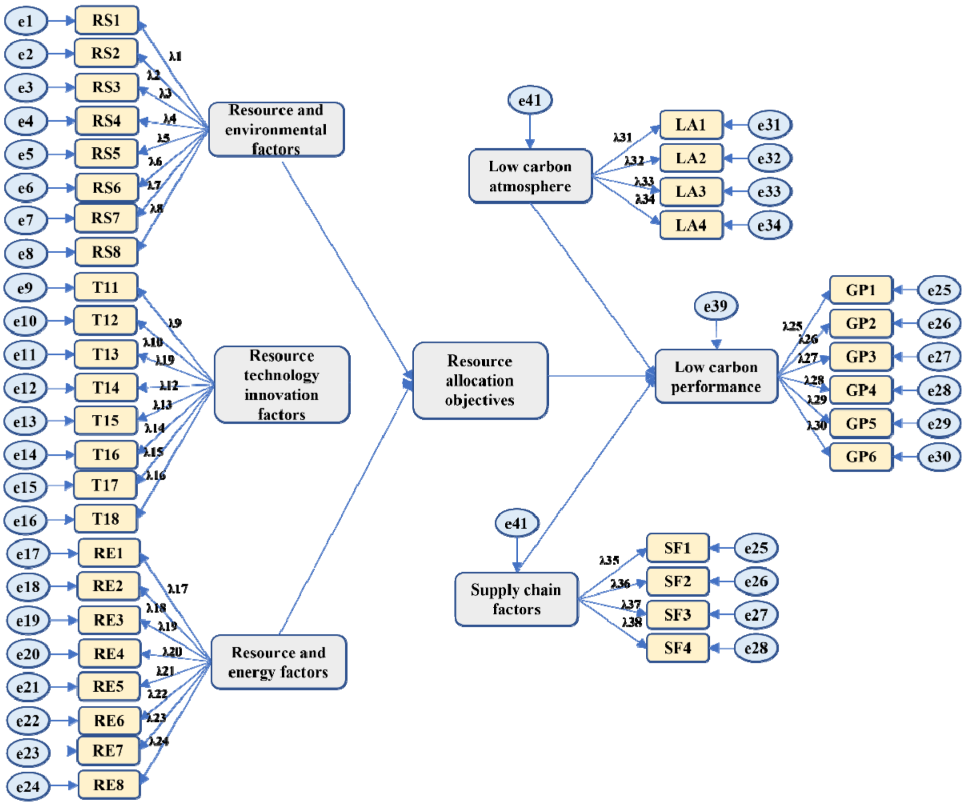
Table 4 Descriptive statistical analysis of research samples

Attribute code	*N*	*Statistical value*	*Standard error*	*Quantity of statistics*	*Quantity of statistics*	*Quantity of statistics*	*Quantity of statistics*
RS1	500	4.32	0.039	0.877	0.769	–0.837	0.875
RS2	500	4.21	0.038	0.843	0.711	–0.339	0.757
RS3	500	3.27	0.036	1.032	1.066	–1.640	0.252
RS4	500	3.25	0.040	1.003	1.077	–1.654	0.365
RS5	500	3.35	0.039	0.976	0.952	–1.843	0.415

Therefore, the parameter design of flexible resource allocation in the low-carbon supply chain should consider mainly the following aspects: in the structure of a hybrid quantum neural network, the learning efficiency value should be considered. The larger the learning rate of the hybrid quantum neural network, the larger the weight modification of the hybrid quantum neural network structure, and the shorter the learning time of the network, leading to the slower convergence rate of the network learning process. Therefore, this essay proposes the improvement of the convergence performance of the algorithm by applying the adaptive learning rate of the structure activation function design of the hybrid quantum neural network based on the radial basis function of the

Gaussian function (Liu et al., 2021b). The basic structural equation model of the resource allocation elements of the low-carbon supply chain is shown in Figure 13.

Figure 13 Basic structural equation model of the resource allocation elements in the low-carbon supply chain (see online version for colours)



The cloud-based hybrid quantum neural network algorithm must first correct the radial root function and its target error. The maximum weight vector generated by the network is used to process the new hidden neurons of the hybrid neural network structure so that the iteration finally reaches the maximum number of neurons. Moreover, this paper uses the hybrid quantum particle optimisation algorithm to optimise and repair the hybrid neural network and uses the network weight training algorithm to achieve the most efficient results in terms of body weight training. In this work, in the process of exchanging capital in the low-carbon supply chain, the behaviour of flexible resources is divided according to the clustering criterion of the system, thus reducing the degree of error of flexible resource allocation in the low-carbon supply chain.

4.2 *Hybrid quantum neural network algorithm for the low-carbon supply chain*

The parameters of the hidden structural layer of the hybrid quantum neural network based on the cloud model need to be selected, and the activation function of the hybrid network structure should be optimised. The hybrid algorithm can improve the overall performance of the network structure by using quantum particle swarm optimisation. If the proper basis function is selected, then the approximation ability of the function can be improved, and thus, the convergence speed of the algorithm can be reduced. Therefore, to ensure the convergence performance of hybrid network structure learning and effectively improve the generalisation ability of the algorithm network structure, this study applies the appropriate hidden layer node number and appropriate basis function of the network structure. In this work, the combined calculation of the hidden layer connection weight is designed to effectively improve the level of network structure stability. In this way, the hybrid quantum particle swarm optimisation algorithm can effectively avoid the unstable performance of the network structure caused by improper parameter selection and effectively improve the control performance of the hybrid quantum neural network structure. The algorithm structure is shown in Figure 14.

Figure 14 Basic algorithm structure diagram (see online version for colours)

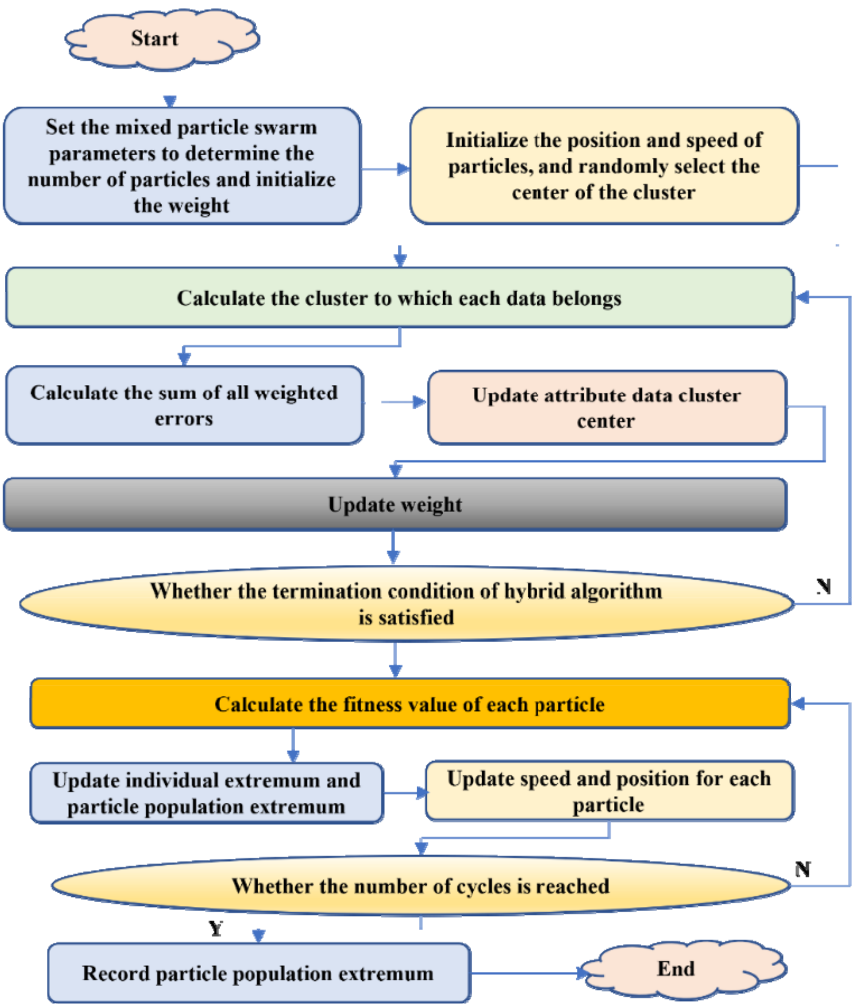
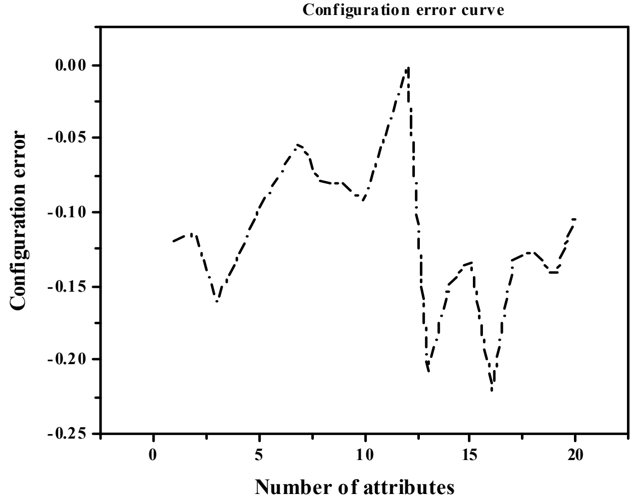
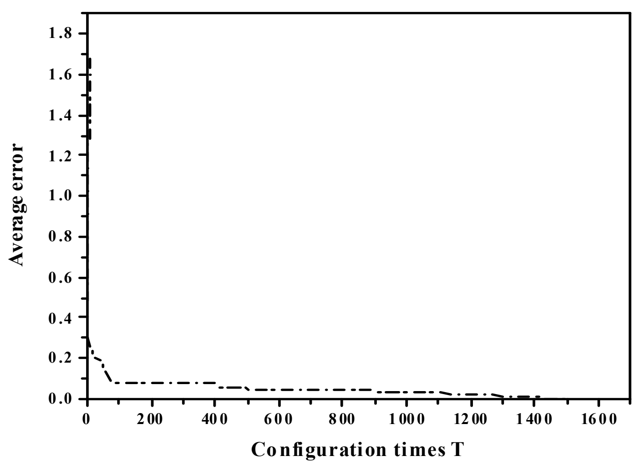


Figure 15 Experimental error of flexible resource allocation based on a hybrid quantum neural network (see online version for colours)



(a)



(b)

In this study, a Gaussian function is selected as the activation function of the neural network when constructing the structure of the hybrid quantum neural network based on the cloud model. The specific activation function design of the hybrid network structure is as follows:

$$\varphi J(\mathrm{X}) = \exp(X - cj)/2\sigma\, j,\ j = 1, 2, \ldots, J \tag{5}$$

where $\varphi J(X)$ is the j^{th} radial basis function of the hybrid network structure. The hybrid quantum neural network algorithm based on the cloud model selects an appropriate fitness function, and the calculation method of the fitness function of the hybrid quantum neural network algorithm is as follows:

$$F = 1/N\left(Y_n - Y_J\right) \tag{6}$$

where Y_n-represents the output value of the hybrid quantum neural network structure after training, Y_J is the actual value of the hybrid network structure, and N is the sample size of the hybrid quantum network structure, as shown in Figures 15 (a) and 15(b).

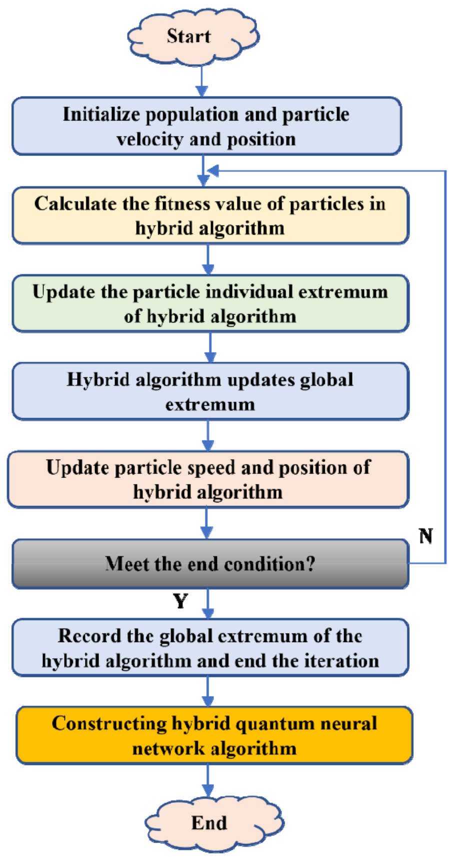
4.3 Flexible resource allocation solution based on multiattribute utility association

Based on the study of the flexible resource allocation model of the low-carbon supply chain, this work studies some points to which attention should be paid in the actual allocation process from the perspective of the flexible resource attributes of the low-carbon supply chain. First of all, the allocation of flexible resources in the low-carbon supply chain should consider the environmental attributes and energy attributes of flexible resources from the perspective of the whole resource. Secondly, the allocation of flexible resources in the low-carbon supply chain should be analysed and considered on the basis of previous research results. Thirdly, the flexible resource allocation model of low-carbon supply chain constructed by attribute utility, function theory and multi-attribute theory should be applied reasonably and scientifically to the actual resource allocation system. In this study, the relevance of resource attribute utility is considered in the configuration process. In the following, the law of resource allocation and the result of such allocation are analysed through the association of flexible resource attributes in several low-carbon supply chains (Huang et al., 2021; Zou et al., 2020). The resource allocation is analysed from the perspective of resource attributes, and then, the specific analysis is conducted to obtain experimental results. The flow chart of the hybrid quantum neural network algorithm of the flexible resource allocation model is shown in Figure 16.

4.4 Discussion

There are many factors reflecting the low-carbon performance of the node enterprises of the low-carbon supply chain, which should be based on reducing the amount of carbon emissions of the supply chain as much as possible and fully reflecting the low-carbon performance of the node enterprises of the supply chain. The environmental cooperation between upstream and downstream enterprises of the low-carbon supply chain can significantly improve the environmental performance of the flexible resources of the low-carbon supply chain. Under the joint emission reduction mode of the supply chain, we can improve the enthusiasm of supply chain node enterprises for reducing the carbon emissions of units of products of supply chain node enterprises to protect the ecological environment. The social and ecological benefits of supply chain node enterprises can be improved by stimulating low-carbon technology innovation activities, and supply chain node enterprises can be guided and encouraged to promote low-carbon technological innovation (Guo et al., 2021). Therefore, the core enterprises of the supply chain should establish a sense of social responsibility to actively promote the low-carbon development of the industry, strengthen their cooperation with the node enterprises of the supply chain, and form stable, strategic relationships in terms of research and development with the node enterprises of the supply chain to promote low-carbon activities among enterprises in the supply chain to realise the effective use of the flexible resources of the low-carbon supply chain. This approach can reduce resource consumption and maximise the utility of resource and environmental attributes by maximising their utility. Moreover, this approach can improve the efficiency of resource allocation through the joint and collaborative emission reduction (reduction in the amount of carbon dioxide emissions) of supply chain node enterprises and the utilisation efficiency of clean energy and renewable resources of supply chain node enterprises to improve resource allocation efficiency. These aims can be analysed considering the flexible resources of the low-carbon supply chain to find effective methods through which to improve the efficiency of flexible resource allocation of the low-carbon supply chain.

Figure 16 Flow chart of the hybrid quantum neural network algorithm for the flexible resource allocation model (see online version for colours)



5 Conclusions

In terms of the current degree of global economic integration, environmental issues have become globalised. In the face of the increasingly rapid development of globalisation, to achieve the development goals of the 13th Five-Year Plan, nodal enterprises in the supply chain should establish and implement the sustainable development concept of low carbon. We should pursue the maximisation of the economic benefits of the low-carbon supply chain to achieve a balance between the economic and environmental benefits of enterprises at each node of the supply chain. The flexible resource allocation in the low-carbon supply chain has become a popular yet difficult area. This paper, by combining the theories and methods of operations management, supply chain management, informatics, decision-making science, machine learning and other disciplines, carries out in-depth innovative and exploratory research on the flexible resource allocation of the low-carbon supply chain from the perspective of resource attributes. Its research results have enriched the theory of flexible resource allocation of the low-carbon supply chain. At the same time, this work also provides new ideas and perspectives for low-carbon supply chain management decision-making under uncertain environments. This study provides new methods and means for the effective allocation of the low-carbon supply chain resources of enterprises. At the same time, this work provides a good reference and guidance for enterprises in improving the efficiency of low-carbon supply chain resource allocation. Therefore, through the specific analysis and in-depth study of the above aspects, we can see that the research results of this paper have good theoretical value and certain practical significance. The research in this essay focuses mainly on the configuration model and its hybrid neural network algorithm. Although many simulation experiments are applied to carry out relevant verification in the research process, due to the limitations of time and ability, there are still many deficiencies in this research, which need to be further studied and explored.

Based on the two starting points of the delay effect and random effect, this paper studies the advertising marketing behaviour strategies of low-carbon supply chain members affected by type of each effect. However, due to objective factors such as the difficulty in solving such a problem, it is not possible to study whether the level of advertising and marketing cooperation of low-carbon supply chain members is affected by both delay effects and random effects, which can be a possible direction for future research.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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