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Sustainable design and optimization of coal supply chain network under different carbon emission policies

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ABSTRACT

In recent years, coal power has obvious advantages in terms of safety, economy and stability. As people gradually realize the importance of the environment, low carbon has become one of the core indicators of power system evaluation, so it is particularly important to guide the coal enterprises to achieve a win-win situation of economic and environmental benefits. Combined with the carbon emission policies, this paper takes the coal supply chain network as the research object and aims to develop a comprehensive decision model for sustainable design of coal supply chain. First, this paper extracts the influencing factors of low-carbonization in coal supply chain and constructs an interpretative structural model (ISM). The results show that low-carbon green technology, low-carbon production cost, utilization level of green energy and energy efficiency are the most basic manifestations of low-carbonization of coal supply chain and interact with each other, therefore this paper builds an optimization model with the objective of minimizing the low-carbon production costs in the coal supply chain. Concurrently, this paper introduces four policies (emission cap, carbon tax, carbon trade and carbon offset) as constraint condition. Then, in the aspect of model solving, this paper combines the differential evolution (DE) strategy to mutate, cross and select the leaders generated in each iteration of the salp swarm algorithm (SSA), further increases the diversity of the salp swarm, avoids the algorithm falling into a local optimum, and proposes the salp swarm algorithm based on differential evolution (DE-SSA). Finally, this paper compares the effects of four different carbon emission policies on the optimization of coal supply chain network through empirical analysis, and finds that coal enterprises have the best emission reduction effect under the carbon trade policy. The development and implementation of this paper not only enriches the related research of efficient supply chain, but also provides scientific and quantifiable decision-making technology for coal enterprises.

1. Introduction

The ecological concept of “low energy-consumption, low-pollution and low-emission” has reached a consensus in the world. Since the concept of “low-carbon economy” was first put forward by the British government in the energy white paper in 2003, carbon emissions in economic activities have attracted wide attention in the world, especially in China (Yang et al., 2016). In 2009, the Chinese government promised that carbon intensity would be reduced 40% - 50% of the total volume in 2005 before 2020. In 2015, China proposed to achieve emission peaks around 2030 and strive for early realization in the Intended Nationally Determined Contribution (Su and Sun, 2019a). In 2016, China’s “the 13th Five-Year Plan of Work on Controlling Greenhouse Gas Emissions” stipulated that by 2020, carbon intensity would be 18% lower than that in 2015, and carbon emissions would be effectively controlled (Liu et al., 2017). Currently, carbon emission policies implemented in the world include the United Nations Framework Convention on Climate Change, European Union’s Emissions Trading Scheme (EU-ETS), American Clean Energy and Security Act (ACESA) and China’s “the Guidance on the Development of Low-Carbon Economy”, etc. At the same time, due to the influence of resource environment, industrial policy and technological development, thermal power has been playing a leading role in China’s power supply structure. Since the 12th Five-Year Plan was put

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forward, China's economy has entered "the new normal" and its industrial structure has been further optimized, which shows that the industries with high energy consumption and pollution are facing transformation and upgrading. Meanwhile, the new energy industry is developing rapidly and the proportion of new energy installed is increasing year by year. Therefore, how to change the development mode of the thermal power industry to adapt to the economic development and new energy landscape in the future has become the focus of social attention. The ultimate goal of supply chain management is to reduce the cost in the production chain. One of the main tasks to reduce supply chain costs is how the economic activities of enterprises affect the relevant costs in the supply chain (Kim et al., 2016). In order to realize the comprehensive and sustainable development of the society, the members of the supply chain need to pursue economic interests and take corresponding social responsibilities. Different carbon emission policies will lead to different costs in the supply chain.

Under this background, it is particularly important to optimize the development of coal power under the carbon emission policies and guide the coal enterprises to achieve a win-win situation of economic and environmental benefits. Therefore, combined with the carbon emission policies, this paper takes the coal supply chain network as the research object, aims to develop a comprehensive decision model for sustainable design of coal supply chain, and provides scientific and quantifiable decision-making technology for coal enterprises.

2. Literature review

In recent years, carbon emission policy and its application in supply chain network have received extensive attention. With increasing environmental pressure, companies have to think about sustainability. It is of great significance to minimize the carbon emission while minimizing the cost of enterprises. Supply chain network can help enterprises obtain more profits with low environmental risk, high ecological efficiency and high energy use efficiency, and maintain the lowest cost within a certain range (Su and Sun, 2019b). Many literatures on green supply chain or supply chain network environment are analyzed by using mixed integer programming model. Ramudhin et al. (2008a) established a comprehensive mathematical model combining the sensitivity of carbon market with optimization of low-carbon supply chain network under carbon trade constraints. Benjaafar et al. (2013a) studied the supply chain network considering carbon emissions. Finally, a supply chain network optimization model based on carbon emission cap, carbon tax, carbon trade and carbon offset was constructed on the issue of the timing and quantity of replenishment in the supply chain. Chaabane et al. (2012) established a mixed integer programming model for supply chain network design problem under carbon trade. In view of NP-hard characteristics, Xiao-Chao et al. (Ramezani et al., 2014) solved the four-level supply chain network optimization model by genetic algorithm. The supply chain network planning model established in this paper is based on salp group algorithm of differential evolution to solve the model. By selecting half of salp, the pre-search process of SSA is global and random, and the low-carbon production cost is finally minimized in the coal supply chain.

In the selection of supply chain network, many supply chain articles are selected part of the supply chain. In the paper of Ramudhin et al. (2008b)et al., the main decisions of total supply chain cost are suppliers, subcontractors, production centers and other nodes. Benjaafar et al. (2013b)et al. analyzed the impact of supply processes such as suppliers and customers on carbon emission. Xiao-Chao et al. (Ramudhin et al., 2008a) discussed manufacturer-led emission reduction methods in supply chain enterprises. Pisvahee et al. (Bidhandi et al., 2009) Integrated production processes such as suppliers, factories and warehouses to analyze supply chain environmental network design problems. The analysis in this paper is relatively comprehensive, from the beginning of the coal supply chain to coal preparation plant, coal distribution center, power plant and other aspects of the analysis.

Because process industries are considered to be the biggest contributors to carbon emissions, their supply chains are increasingly constrained by national carbon policies. In order to reduce environmental pressure, industrial enterprises in various countries are responding to carbon emission reduction policies to reduce their carbon footprint. According to different carbon emission policies, there are also relevant literatures to make an analysis on the supply chain. Carbon caps affect companies' costs and the environment. The carbon cap policy provides specific carbon emission limits for industry [13, 14]. Entezaminia, A. et al. (Entezaminia et al., 2017) showed that carbon emission caps can help enterprises achieve more economic benefits and carbon emission reduction. However, the implementation of carbon emission cap policy cannot make the production cost of enterprises the lowest. Under the influence of the carbon trading policy, it is allowed to sell or buy carbon emissions on the trading market (Wang et al., 2018a). Carbon trading policies have a crucial impact on reducing carbon emissions, and the establishment of a carbon trading market will help achieve the goal of carbon emission reduction (Guo et al., 2019). In terms of carbon tax policy, Li Wet al (Li et al., 2018). Analyzed the impact of carbon tax policy on energy price, and the results showed that the decline of fossil energy price would increase carbon emissions, while carbon tax could alleviate the pressure on carbon emissions. Wang-Helmreich Het al (Wang-Helmreich and Kreibich, 2019) pointed out that carbon offset would affect the revenue of carbon tax. Boaitey et al. (2019) combined greenhouse gases with livestock, and the research results showed that the balance of environment and economy was broken, and the existing carbon offset policies were no longer able to attract producers.

After describing the impacts of four carbon emission policies on carbon emissions, the following literature analyzes and compares the advantages and disadvantages of the four carbon emission policies. Some researchers are more supportive of a carbon tax than four, because it can be incorporated directly into a country's tax policy, making it easier to implement [15, 21]. However, Entezaminia et al. believe that when the carbon tax rate is high enough, carbon offset can help reduce emissions.

Zakeri et al. (Marti et al., 2015) compared the two carbon policies, carbon tax and carbon trading, and the results showed that the carbon tax policy was preferable to the carbon emission policy. He,L.; Xu, Zet al (He et al., 2014) studied the carbon policy through the carbon emission elasticity, and the results showed that the carbon emission cap policy was superior to the carbon tax policy. Through research, Zakeri, A. et al. (Zakeri et al., 2015) show that in energy-intensive industries such as aluminum, carbon emission trading policy can reduce emissions better than carbon tax policy. Marufuzzaman et al. (2014)observed that carbon emission cap policy had the greatest impact on SCND, and believed that carbon emission cap was more effective than carbon tax and carbon offset. Carbon policies with mandatory caps are more effective than those without, but not always. A carbon tax might be better, but it would be far more expensive for companies to implement. Chen,J (Xu et al., 2019a) suggest a combination of two or more medium carbon policies instead of a single one. The effectiveness of carbon tax policy depends on the initial carbon emission level and the accuracy of carbon tax rate. When the price of carbon is low, a combination of a cap and a tax on carbon emissions can maximize carbon reductions. Xu (Xu et al., 2019b) believe that carbon emission caps

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and carbon tax policies are the most important drivers of reducing carbon footprint, followed by carbon emission caps and carbon offset policies. By contrast, carbon caps are considered the most effective way to reduce emissions. At the same level, carbon offsets and carbon taxes have similar effects. Carbon caps and taxes are sound policies. Carbon emission caps, carbon offsets and carbon emission caps and trading policies can save energy and reduce emissions while keeping costs relatively low. In short, all four policies (emission cap, carbon tax, carbon trade and carbon offset) can promote energy conservation and reduce environmental pressure (Waltho et al., 2019). In this paper, four kinds of carbon emission policies are compared. Through model test, it is concluded that coal enterprises have the best emission reduction effect under the carbon trade policy.

It can be seen from previous studies that different supply chain networks need to choose different optimization objective functions and choose appropriate solutions according to their optimization characteristics. Different carbon emission policies will also lead to different costs and emission effects of enterprises. There is no literature study considering the lowest carbon emission reduction and the lowest enterprise cost under the four carbon emission policies respectively. Although some relevant papers also involve supply chain network design and carbon emission policy research, there are few relevant literatures that study the situation of the highest carbon emission reduction and the lowest enterprise cost under the four carbon emission policies at the same time. By analyzing the network structure of coal and power supply chain under four different carbon emission reduction policies, this paper concludes that the carbon emission reduction effect is the best under the carbon trading policy, which improves the overall carbon emission reduction rate of coal and power supply chain, and provides theoretical reference for enterprises to minimize the cost under the constraint of low-carbon policies. In addition, in terms of technology, the current study lacks a detailed analysis of the actual optimization results of the model, and the current application of SSA model has problems of slow convergence rate and imprecision.

In this paper, the explanatory structure model (ISM) is used to select the objective function of the optimization model, and the test function is selected to verify the convergence of the proposed algorithm, and at the same time, the environmental pressure is minimized.

With more and more attention to China's environmental

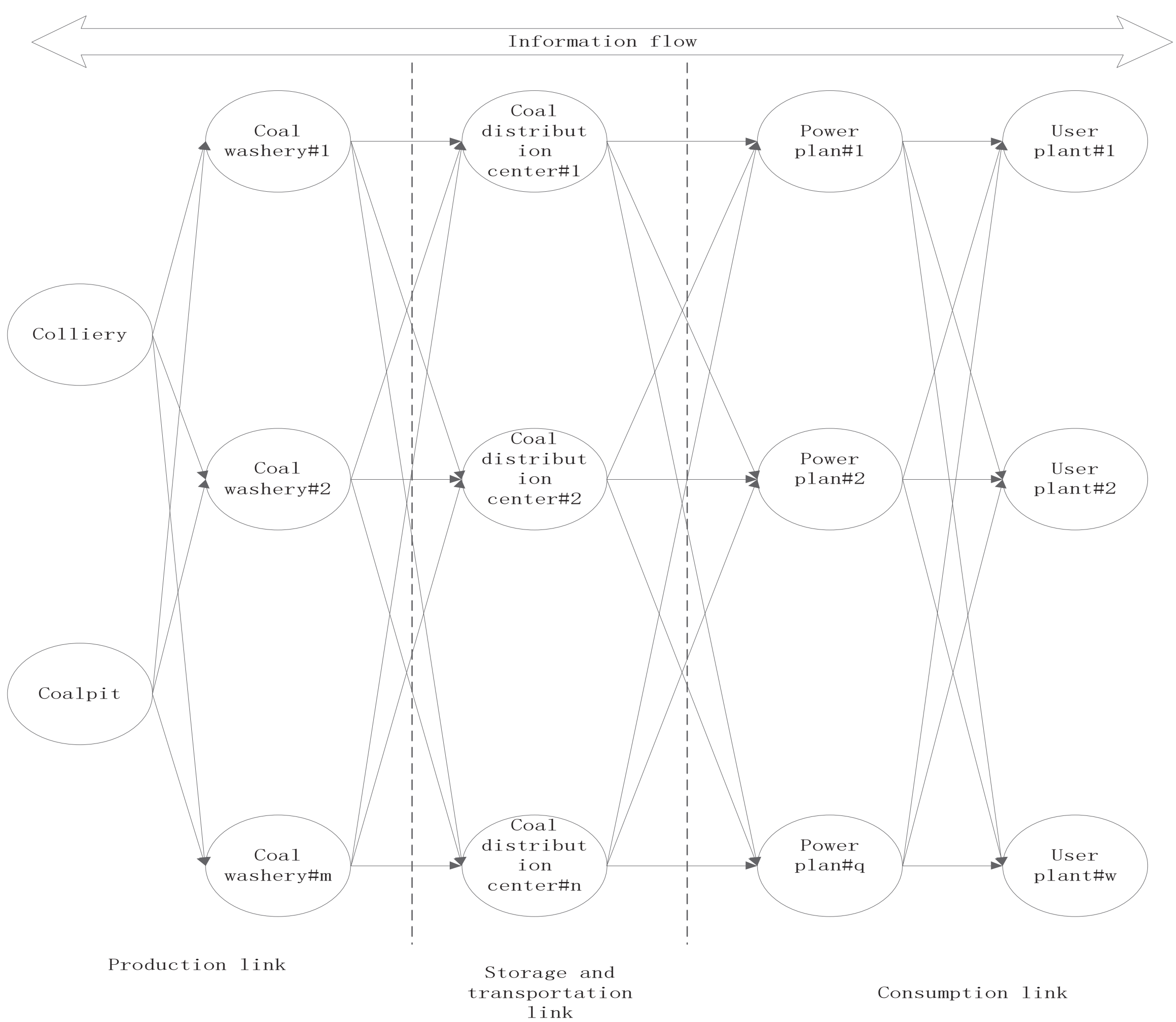

Fig. 1. Network structure of coal supply chain.

pollution, low carbonization has become the mainstream of energy development, and coal is a traditional high-carbon energy, and its production and utilization process is controversial. On the basis of traditional supply chain network design, this paper firstly classifies the influencing factors of low carbonization in coal supply chain by using the ISM. Then, according to the hierarchical relationship of the influencing factors, an optimization model of supply chain network under different carbon emission policies is constructed to further study the coal supply chain allocation plan which achieves a balanced optimization between cost and carbon emissions. Moreover, salp swarm algorithm based on differential evolution algorithm (DE-SSA) is proposed to solve the model. Finally, through empirical research, the paper compares the influence of different carbon emission policies on the decision-making of coal supply chain, improves the overall carbon emission reduction rate of coal and power supply chain, provides theoretical support for the development of low-carbon coal supply chain, and provides reference for the formulation and implementation of relevant policies.

The main contributions of this paper are as follows:

(1) In this paper, four new optimization models are proposed to solve the problem of combining carbon emission policy with coal supply chain network optimization, so as to achieve the minimization of carbon emission and the lowest cost of enterprises. In practical applications, it is not only in line with the policy of sustainable development and minimize the pressure on the environment, but also conducive to the development of enterprises, thus promoting the economic development.

(2) This paper proposes a new supply chain network optimization algorithm. After verification, the results show that the DE-SSA algorithm proposed in this paper has faster convergence speed and higher convergence accuracy than the improved particle swarm optimization algorithm (IPSO) and the traditional SSA algorithm, and is more suitable for solving the supply chain network optimization model. This algorithm is a promising one, which can provide high precision and high convergence rate algorithm for future research. Moreover, DESSA can avoid the local optimal dilemma of SSA, and overcome the problems of local optimal stagnation and low convergence rate of SSA, which can significantly improve the performance of SSA. In terms of solving methods, it lays a foundation for the research on SSA methods later.

The rest of this paper is structured as follows: Section 3 puts forward the optimization model of coal supply chain network under different carbon emission policies and its solving algorithm. A case analysis is proposed in Section 4 to validate the optimization model established in this paper. Section 5 discusses and compares the impact of different carbon emission policies on low carbonization in coal supply chain network. The conclusions of this research are drawn in Section 6.

3. Problem description and model formulation

3.1. Problem description

The coal supply chain network is described as follows: the supply

Table 1
Symbolic explanation of the optimization problem of coal supply chain network.

Symbol	Explanation	Symbol	Explanation
p	Total number of coal mines	v	Coal mine number
m	Total number of coal washery	i	Coal washery number
n	Total number of coal distribution centers	j	Coal distribution center number
q	Total number of power plants	k	Power plant number
CP_v	Production in coal mine v	EF_v	CH_4 emission factor under type and depth of coal mine v
TF	CH_4conversion factor	S_v	Mining area of coal mine v
p_v^s	Safety cost of ton coal under type of coal mine v	N_v^s	Total number of mining-district of coal mine v
T_v^{cm}	life of coal mine v	C_v^{pd}	Power distribution cost of coal mine v
p_v^c	Compensation fee for the responsibility of soil and water loss per ton of coal in coal mine v	CC_i	Total number of coal in coal washery i
p_i^w	Washing cost per ton of coal in coal washery i	C_i^{pd}	Power distribution cost of coal washery i
C_i^{ea}	Equipment depreciation costofcoal washery i	Q_{vi}	Coal transportation quantity from coal mine $v$to coal washery i
Q_{ij}	Coal transportation quantity from coal washery i to coal distribution center j	Q_{jk}	Coal transportation quantity from coal distribution center j to power plant k
L_{vi}	Distance of coal transportation from coal mine$v$to coal washery i	L_{ij}	Distance of coal transportation from coal washery i to coal distribution center j
L_{jk}	Distance of coal transportation from coal distribution center j to power plant k	y_{vi}	Fuel consumption of 100-km per ton of coal from coal mine v to coal washery i
y_{ij}	Fuel consumption of 100-km per ton of coal from coal washery i to coal distribution center j	y_{jk}	Fuel consumption of 100-km per ton of coal from coal distribution center j to power plant k
v_{vi}	Average combustion value from coal mine v to coal washery i	v_{ij}	Average combustion value from coal washery i to coal distribution center j
v_{jk}	Average combustion value from coal distribution center j to power plant k	a_{vi}	Carbon content released by fuels from coal mine v to coal washery i
a_{ij}	Carbon content released by fuels from coal washery i to coal distribution center j	a_{jk}	Carbon content released by fuels from coal distribution center j to power plant k
a	Fixed cost of coal transportation	p_{vi}^t	Unit cost of coal transportation from coal mine v to coal washery i
p_{ij}^t	Unit cost of coal transportation from coal washery i to coal distribution center j	p_{jk}^t	Unit cost of coal transportation from coal distribution center j to power plant k
CS_j	Coal storage capacity in coal distribution center j	b	Fixed cost of coal storage in coal distribution center j
p_j^{su}	Unit cost of coal storage in coal distribution center j	CR_k	Coal combustion quantity in power plant k
q_4	non-full burning loss boiler equipment in power plant	E	Carbon emission released per ton of coal
L	carbon emission cap prescribed by the government	α	Carbon tax price
p_t	Carbon trade price	p_n	Carbon offset price
e^+	Carbon credits for outward purchases	e^-	Carbon credits for outward sales

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chain network is a four-level network structure, including coal mines, coal washery, coal distribution centers and power plants (Fig. 1) (Ding et al., 2018), in which the available reserves of coal mines and the generation demand of power plants are known, transportation products in the supply chain are all standard coal, the mode of transportation in the same road cannot be changed, meanwhile the mode and the unit cost of transportation are known.

The symbol of coal supply chain network optimization model is described as Table 1, which lays the foundation for the later construction of the model.

3.2. Selection of optimization objective function of low carbonization in coal supply chain network based on the interpretative structural model

3.2.1. Extraction and analysis of the influencing factors of low carbonization in coal supply chain

The effective implementation of low-carbon supply chain needs the support of the social environment, including policy, market, corporate culture, science and technology innovation system and so on (Hoejmose et al., 2012). In addition, the proportion of green energy used in mining, processing, transportation and other coal supply chain links, as well as the direct manifestation of low carbonation such as energy output effect, are the constraints for the high-energy-consuming coal industry to achieve low carbonization (Zhang et al., 2007).

On the basis of summarizing the literature, this paper further consults the scholars who are engaged in the research of coal supply chain management, and then demonstrates the rationality of the influencing factors of low carbonation in coal supply chain. After that, this paper visited the node enterprises of the coal supply chain, interviewed their managers, and continued to optimize and improve the influencing factors. Finally, 12 factors affecting the low carbonization in coal supply chain are obtained, which are incentive and guidance of policies (S_1), regulatory constraints of regulations (S_2), planning and standards for low carbonation (S_3),environmental preferences of consumers (S_4), low carbon consciousness (S_5), high quality human resources support (S_6), information level (S_7), organization and management of coal supply chain (S_8), low-carbon green technology (S_9), low-carbon production cost (S_{10}), utilization level of green energy (S_{11}) and energy efficiency (S_{12}).

3.2.2. ISM for the influencing factors of low carbonization in coal supply chain

According to the influencing factors of low carbonization in coal supply chain and the implementation steps of ISM, the ISM group is formed. The ISM group in this paper is composed of 10 people who are managers in coal enterprises or researchers of coal supply chain management. After clarification of key issues, the team members analyze the relationship among the influencing factors. The adjacency matrix A and reachability matrix M are obtained as follows:

$$A=\begin{bmatrix}1&0&1&0&1&0&0&0&0&0&0&0\\0&1&1&0&0&0&0&0&0&0&0&0\\0&0&1&0&1&1&0&0&0&0&0&0\\0&0&0&1&1&0&0&0&0&0&0&0\\0&0&0&0&1&0&0&0&0&0&0&0\\0&0&0&0&0&1&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0&0&0&0\\0&0&0&0&1&1&1&1&0&0&0&0\\1&1&1&1&1&0&1&0&1&1&0&0\\1&0&0&1&0&0&1&1&1&1&1&0\\1&1&1&1&1&0&0&0&1&1&1&1\\0&1&1&0&0&0&1&0&1&1&1&1\end{bmatrix}$$

$$M=\begin{bmatrix}1&0&1&0&1&1&0&0&0&0&0&0\\0&1&1&0&1&1&0&0&0&0&0&0\\0&0&1&0&1&1&0&0&0&0&0&0\\0&0&0&1&1&0&0&0&0&0&0&0\\0&0&0&0&1&0&0&0&0&0&0&0\\0&0&0&0&0&1&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0&0&0&0\\0&0&0&0&1&1&1&1&0&0&0&0\\1&1&1&1&1&1&1&1&1&1&1&1\\1&1&1&1&1&1&1&1&1&1&1&1\\1&1&1&1&1&1&1&1&1&1&1&1\\1&1&1&1&1&1&1&1&1&1&1&1\end{bmatrix}$$

According to the reachability matrix M, the antecedent set $A(S_i)$ and the reachable set $R(S_i)$among the influencing factors are sorted out as shown in Table 2.

In hierarchical processing, $A(S_i)\cap R(S_i)=R(S_i)$ is the condition for determining the highest level of factors. Finally, the ISM for the influencing factors of low carbonization in coal supply chain is constructed as shown in Fig. 2.

Through the construction of ISM, it can be found that: low-carbon green technology, low-carbon production cost, utilization level of green energy and energy efficiency are the basic factors of low carbonization in coal supply chain. Therefore, this paper takes the minimum the low-carbon production cost in the coal supply chain as the objective function of the optimization model.

3.3. Introduction of mathematical model and related parameters

According to the ISM for the influencing factors of low carbonization in coal supply chain, the objective function selected in this

Table 2
Influence of the relationship between various influencing factors.

	$A(S_i)$	$R(S_i)$	$A(S_i)\cap R(S_i)$
S_1	S_1, S_9, S_{10}, S_{11}, S_{12}	S_1, S_3, S_5, S_6	S_1
S_2	S_2, S_9, S_{10}, S_{11}, S_{12}	S_2, S_3, S_5, S_6	S_2
S_3	S_1, S_2, S_3, S_9, S_{10}, S_{11} ,S_{12}	S_3, S_5, S_6	S_3
S_4	S_4, S_9, S_{10}, S_{11}, S_{12}	S_4, S_5	S_4
S_5	S_1, S_2, S_3, S_4, S_5, S_8, S_9, S_{10}, S_{11}, S_{12}	S_5	S_5
S_6	S_1, S_2, S_3, S_6, S_8, S_9, S_{10}, S_{11}, S_{12}	S_6	S_6
S_7	S_7, S_8, S_9, S_{10}, S_{11}, S_{12}	S_7	S_7
S_8	S_8, S_9, S_{10}, S_{11}, S_{12}	S_5, S_6, S_7, S_8	S_8
S_9	S_9, S_{10}, S_{11}, S_{12}	S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}	S_9, S_{10}, S_{11}, S_{12}
S_{10}			
S_{11}			
S_{12}			

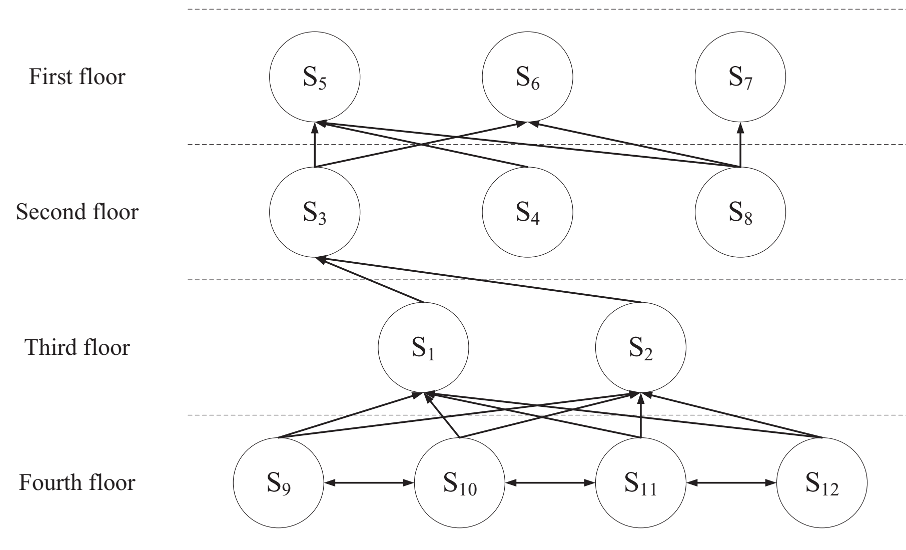

Fig. 2. ISM for the influencing factors of low carbonization in coal supply chain.

paper is to minimize the low-carbon production cost, namely minimize the total cost and carbon emission. Combined with the constraints of the four carbon emission policies (emission cap, carbon tax, carbon trade and carbon offset), an optimization model of the coal supply chain network is constructed as shown in Fig. 3.

3.4. Modeling of basic optimization of coal supply chain network

Before establishing the optimization model of coal supply chain network under the carbon emission policies, this paper firstly takes the minimum total cost as the objective function according to the basic relationship of coal supply chain network, and then constructs the basic optimization model of coal supply chain network.

$$CP_v \le CP_v^M, CC_i \le CC_i^M, CS_j \le CS_j^M, CR_k \le CR_k^M \tag{4}$$

$$Q_{vi} \ge Q^m, Q_{ij} \ge Q^m, Q_{jk} \ge Q^m \tag{5}$$

$$CR_k \ge CR_k^m \tag{6}$$

Where the objective function (1), $1000 \cdot S_v$ is the fee of mining right employ prescribed by regulation for the royalties and prices of right of prospecting and mining (Li et al., 2009); $p_v^s \cdot CP_v$ is the safety cost of equipment mining prescribed by cost management methods of coal industry enterprises (Lu and Li, 2019); $10000 \cdot S_v + 5000 \cdot N_v^s + 5000 \cdot T_v^{cm}$ is the mining geological environment treatment rehabilitation margin prescribed bylaw of the people's republic of china on mineral resources (Ren and Xia, 2017);

$$\begin{aligned} \min F = & \sum_{v=1}^{p} \left(1000 \cdot S_v + p_v^s \cdot CP_v + 10000 \cdot S_v + 5000 \cdot N_v^s + 5000 \cdot T_v^{cm} + C_v^{pd} + p_v^c \cdot CP_v\right) \\ & + \sum_{i=1}^{m} \left(CC_i \cdot p_i^w \times 70.2\% + C_i^{pd} + C_i^{ea} + \frac{1000 \cdot CC_i}{10000 \times 50} \times 200\right) + \sum_{v=1}^{p} \sum_{i=1}^{m} (a + p_{vi}^t \cdot Q_{vi} \cdot L_{vi}) \\ & + \sum_{i=1}^{m} \sum_{j=1}^{n} \left(a + p_{ij}^t \cdot Q_{ij} \cdot L_{ij}\right) + \sum_{j=1}^{n} \sum_{k=1}^{q} \left(a + p_{jk}^t \cdot Q_{jk} \cdot L_{jk}\right) + \sum_{j=1}^{n} \left(b + CS_j \cdot p_j^{su}\right) \end{aligned} \tag{1}$$

$$s.t. \quad CP_v \ge CP_v^m \tag{2}$$

$$\begin{aligned} CP_v = \sum_{i=1}^{m} Q_{vi}, \sum_{v=1}^{p} Q_{vi} = CC_i = \sum_{j=1}^{n} Q_{ij}, \sum_{i=1}^{m} Q_{ij} = CS_j \\ = \sum_{k=1}^{q} Q_{jk}, \sum_{j=1}^{n} Q_{jk} = CR_k \end{aligned} \tag{3}$$

$p_v^c \cdot CP$ is the compensation fee for the responsibility of soil and water loss prescribed by the law of land management of the people's republic of china (Wang et al., 2018b); $CC_i \cdot p_i^w \times 70.2\%$ is the cost of coal washing, where 70.2% is the rate of coal washing prescribed by annual report on the development of the coal industry in 2017 (Wang et al., 2018c); $\frac{1000 \cdot CC_i}{10000 \times 50} \times 200$ is the technical service fee for coal testing, where the weight of selected coal samples in a coal washery is 1/10,000 of the total weight of coal directly pulled from the coal mines, the weight of each coal sample is 50 kg, and the cost of coal testing per coal sample is 200 yuan; $\sum_{v=1}^{p} \sum_{i=1}^{m} (a +$

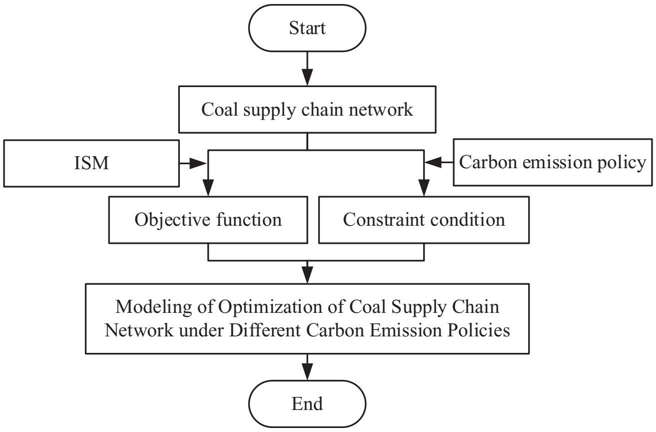

Fig. 3. The framework for constructing the optimization model of coal supply chain network.

$p^t_{vi}\cdot Q_{vi}\cdot L_{vi})$, $\sum_{i=1}^{m}\sum_{j=1}^{n}(a + p^t_{ij}\cdot Q_{ij}\cdot L_{ij})$, $\sum_{j=1}^{n}\sum_{k=1}^{q}(a + p^t_{jk}\cdot Q_{jk}\cdot L_{jk})$ are the cost of coal transportation from coal mine to coal washery, coal washery to coal distribution center and coal distribution center to power plant, respectively; $\sum_{j=1}^{n}(b + CS_j\cdot p^{su}_j)$ is the cost of coal storage. The constraint condition (2) can ensure the minimum production in coal mine; the constraint condition (3) can make the input of every supply chain depot equal to the output; the constraint condition (4) can guarantee the maximum capacity of every supply chain depot; the constraint condition (5) indicates that the coal transportation quantity must be bigger than the minimum transportation quantity stipulated by the transportation company before transportation can be carried out; the constraint condition (6) shows that the power generation demand of power plants must be satisfied.

3.5. Modeling of optimization of coal supply chain network under different carbon emission policies

3.5.1. Optimization model of coal supply chain network based on emission cap

Under the emission cap policies, coal enterprises can only produce within a given cap. If coal enterprises exceed the emission cap, they will be ordered to stop production until their emissions meet the cap (Yang et al., 2018). Therefore, under the emission cap policies, a new constraint on emissions is added to the basic model. To describe the impact of such policies on decision-making of coal supply chain, an optimization model of coal supply chain network based on emission cap is constructed as follows:

$$
\begin{aligned}
\min F = {} & \sum_{v=1}^{p}\left(1000\cdot S_v + p^s_v\cdot CP_v + 10000\cdot S_v + 5000\cdot N^s_v + 5000\cdot T^{cm}_v + C^{pd}_v + p^c_v\cdot CP_v\right) \\
& + \sum_{i=1}^{m}\left(CC_i\cdot p^w_i \times 70.2\% + C^{pd}_i + C^{ea}_i + \frac{1000\cdot CC_i}{10000\times 50}\times 200\right) + \sum_{v=1}^{p}\sum_{i=1}^{m}(a + p^t_{vi}\cdot Q_{vi}\cdot L_{vi}) \\
& + \sum_{i=1}^{m}\sum_{j=1}^{n}\left(a + p^t_{ij}\cdot Q_{ij}\cdot L_{ij}\right) + \sum_{j=1}^{n}\sum_{k=1}^{q}\left(a + p^t_{jk}\cdot Q_{jk}\cdot L_{jk}\right) + \sum_{j=1}^{n}\left(b + CS_j\cdot p^{su}_j\right)
\end{aligned}
$$

$$
s.t.\begin{cases}
\sum_{v=1}^{p}(CP_v\cdot EF_v\cdot TF) + \sum_{v=1}^{p}\sum_{i=1}^{m}\frac{Q_{vi}}{100}\cdot L_{vi}\cdot y_{vi}\cdot v_{vi}\cdot a_{vi} + \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{Q_{ij}}{100}\cdot L_{ij}\cdot y_{ij}\cdot v_{ij}\cdot a_{ij} \\
\quad + \sum_{j=1}^{n}\sum_{k=1}^{q}\frac{Q_{jk}}{100}\cdot L_{jk}\cdot y_{jk}\cdot v_{jk}\cdot a_{jk} + \sum_{k=1}^{q}[1000\times CR_k\cdot(1-q_4)\cdot E] \le L \\
CP_v \ge CP^m_v \\
CP_v = \sum_{i=1}^{m}Q_{vi}, \sum_{v=1}^{p}Q_{vi} = CC_i = \sum_{j=1}^{n}Q_{ij}, \sum_{i=1}^{m}Q_{ij} = CS_j = \sum_{k=1}^{q}Q_{jk}, \sum_{j=1}^{n}Q_{jk} = CR_k \\
CP_v \le CP^M_v, CC_i \le CC^M_i, CS_j \le CS^M_j, CR_k \le CR^M_k \\
Q_{vi} \ge Q^m, Q_{ij} \ge Q^m, Q_{jk} \ge Q^m \\
CR_k \ge CR^m_k
\end{cases}
$$

Where $\sum_{v=1}^{p}(CP_v \cdot EF_v \cdot TF)$ is the emission of coal bed gas in the coal mining process; $\sum_{v=1}^{p}\sum_{i=1}^{m}\frac{Q_{vi}}{100}\cdot L_{vi}\cdot y_{vi}\cdot v_{vi}\cdot a_{vi}$, $\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{Q_{ij}}{100}\cdot L_{ij}\cdot y_{ij}\cdot v_{ij}\cdot a_{ij}$ and $\sum_{j=1}^{n}\sum_{k=1}^{q}\frac{Q_{jk}}{100}\cdot L_{jk}\cdot y_{jk}\cdot v_{jk}\cdot a_{jk}$ are the carbon emission of the coal transportation from coal mine to coal washery, coal washery to coal distribution center and coal distribution center to power plant respectively; $\sum_{k=1}^{q}[1000\times CR_k\cdot(1-q_4)\cdot E]$ is the carbon emission in the coal power generation process.

3.5.2. Optimization model of coal supply chain network based on carbon tax

The carbon tax is a tax on carbon emissions (Wesseh and Lin, 2018). Under the carbon tax policies, the government levies an emission tax on every unit of carbon emitted by coal enterprises at tax α. Therefore, the total cost of a coal enterprise must include the emission cost, and there is a trade-off rule between the operation cost and the emission cost in the total cost, coal enterprises must balance the operation cost and the emission cost according to different carbon tax in order to optimize the total cost.

It can be seen that the objective function in the model is the total cost of the coal enterprise under the carbon trade policy. The new constraint is emission constraint, which means that each coal enterprise is given a certain carbon emission cap L under the carbon trade policy. Enterprises arrange production on the basis of this cap. If the actual emissions are greater than L, they must purchase the emission credits e^+. If the actual emissions of coal enterprises are less than L, they can sell the extra emission credits e^-.The carbon trade cost $p_t\cdot(e^+ - e^-)$ is included in total cost.

3.5.3. Optimization model of coal supply chain network based on carbon offset

The carbon offset is a product or service that an enterprise purchases or invests to reduce its carbon emissions. Enterprises usually pay third-party organizations to absorb excess carbon emissions by planting trees or developing green environmental protection projects (Fisher et al., 2018). Its basic principle is similar to the carbon trade policy, but the difference is that under the carbon offset policy, enterprises must purchase the emission credits; On the contrary, the extra emission credits cannot be sold out.

$$
\begin{aligned}
\min F = {} & \sum_{v=1}^{p}\left(1000\cdot S_v + p_v^s\cdot CP_v + 10000\cdot S_v + 5000\cdot N_v^s + 5000\cdot T_v^{cm} + C_v^{pd} + p_v^c\cdot CP_v\right) \\
& + \sum_{i=1}^{m}\left(CC_i\cdot p_i^w \times 70.2\% + C_i^{pd} + C_i^{ea} + \frac{1000\cdot CC_i}{10000\times 50}\times 200\right) + \sum_{v=1}^{p}\sum_{i=1}^{m}(a + p_{vi}^t\cdot Q_{vi}\cdot L_{vi}) \\
& + \sum_{i=1}^{m}\sum_{j=1}^{n}\left(a + p_{ij}^t\cdot Q_{ij}\cdot L_{ij}\right) + \sum_{j=1}^{n}\sum_{k=1}^{q}\left(a + p_{jk}^t\cdot Q_{jk}\cdot L_{jk}\right) + \sum_{j=1}^{n}\left(b + CS_j\cdot p_j^{su}\right) + p_t\cdot(e^+ - e^-)
\end{aligned}
$$

$$
s.t.\left\{
\begin{aligned}
& \sum_{v=1}^{p}(CP_v\cdot EF_v\cdot TF) + \sum_{v=1}^{p}\sum_{i=1}^{m}\frac{Q_{vi}}{100}\cdot L_{vi}\cdot y_{vi}\cdot v_{vi}\cdot a_{vi} + \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{Q_{ij}}{100}\cdot L_{ij}\cdot y_{ij}\cdot v_{ij}\cdot a_{ij} \\
& \quad + \sum_{j=1}^{n}\sum_{k=1}^{q}\frac{Q_{jk}}{100}\cdot L_{jk}\cdot y_{jk}\cdot v_{jk}\cdot a_{jk} + \sum_{k=1}^{q}[1000\times CR_k\cdot(1-q_4)\cdot E] + (e^- - e^+) = L \\
& CP_v \ge CP_v^m \\
& CP_v = \sum_{i=1}^{m}Q_{vi}, \sum_{v=1}^{p}Q_{vi} = CC_i = \sum_{j=1}^{n}Q_{ij}, \sum_{i=1}^{m}Q_{ij} = CS_j = \sum_{k=1}^{q}Q_{jk}, \sum_{j=1}^{n}Q_{jk} = CR_k \\
& CP_v \le CP_v^M, CC_i \le CC_i^M, CS_j \le CS_j^M, CR_k \le CR_k^M \\
& Q_{vi} \ge Q^m, Q_{ij} \ge Q^m, Q_{jk} \ge Q^m \\
& CR_k \ge CR_k^m
\end{aligned}
\right.
$$

$$\min F = \sum_{v=1}^{p}\left(1000\cdot S_v + p_v^s\cdot CP_v + 10000\cdot S_v + 5000\cdot N_v^s + 5000\cdot T_v^{cm} + C_v^{pd} + p_v^c\cdot CP_v\right)$$
$$+\sum_{i=1}^{m}\left(CC_i\cdot p_i^w \times 70.2\% + C_i^{pd} + C_i^{ea} + \frac{1000\cdot CC_i}{10000\times 50}\times 200\right) + \sum_{v=1}^{p}\sum_{i=1}^{m}(a + p_{vi}^t\cdot Q_{vi}\cdot L_{vi})$$
$$+\sum_{i=1}^{m}\sum_{j=1}^{n}\left(a + p_{ij}^t\cdot Q_{ij}\cdot L_{ij}\right) + \sum_{j=1}^{n}\sum_{k=1}^{q}\left(a + p_{jk}^t\cdot Q_{jk}\cdot L_{jk}\right) + \sum_{j=1}^{n}\left(b + CS_j\cdot p_j^{su}\right) + p_n\cdot e^+$$

$$s.t.\begin{cases}\sum_{v=1}^{p}(CP_v\cdot EF_v\cdot TF) + \sum_{v=1}^{p}\sum_{i=1}^{m}\frac{Q_{vi}}{100}\cdot L_{vi}\cdot y_{vi}\cdot v_{vi}\cdot a_{vi} + \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{Q_{ij}}{100}\cdot L_{ij}\cdot y_{ij}\cdot v_{ij}\cdot a_{ij} \\ \quad + \sum_{j=1}^{n}\sum_{k=1}^{q}\frac{Q_{jk}}{100}\cdot L_{jk}\cdot y_{jk}\cdot v_{jk}\cdot a_{jk} + \sum_{k=1}^{q}[1000\times CR_k\cdot(1-q_4)\cdot E] \le L + e^+ \\ CP_v \ge CP_v^m \\ CP_v = \sum_{i=1}^{m}Q_{vi}, \sum_{v=1}^{p}Q_{vi} = CC_i = \sum_{j=1}^{n}Q_{ij}, \sum_{i=1}^{m}Q_{ij} = CS_j = \sum_{k=1}^{q}Q_{jk}, \sum_{j=1}^{n}Q_{jk} = CR_k \\ CP_v \le CP_v^M, CC_i \le CC_i^M, CS_j \le CS_j^M, CR_k \le CR_k^M \\ Q_{vi} \ge Q^m, Q_{ij} \ge Q^m, Q_{jk} \ge Q^m \\ CR_k \ge CR_k^m \end{cases}$$

It can be seen that the new constraint is the emission limitation under the carbon offset policy. The government sets a basic emission cap L for enterprises. Enterprises arrange production according to this cap. If the enterprise's emissions exceed the given emission cap, they need to pay carbon offset cost for extra emission credits e^+, which is included in the total cost.

3.6. Model solution by salp swarm algorithm based on differential evolution (DE-SSA)

Salp Swarm Algorithms (SSA) is a swarm intelligence optimization algorithm proposed by Seyedali et al. inspired by the swarm behavior characteristics of salp in 2017 (Mirjalili et al., 2017). Each food location of SSA is a possible solution of the optimization problem, and its fitness value is the quality of the corresponding solution. Unlike the general swarm intelligence algorithm, the salp does not distribute in the way of "swarm", but in the way of "chain" which moves with each other in turn, this greatly protects diversity of salps.

The predation space is a $N\times D$-dimensional Euclidean space, where N is the size of the salp swarm, and D is the dimension of the space. There is food $F=[F_1,F_2,\cdots,F_D]^T$ in the space, and the location of salp can be expressed as $X_n=[X_{n1},X_{n2},\cdots,X_{nD}]^T$, $n=1,2,\cdots N$. The upper bound of predation space is $ub=[ub_1,ub_2,\cdots,ub_D]$ and the lower bound is $lb=[lb_1,\ lb_2,\ \cdots,\ lb_D]$. The random initialization population is shown as follows:

$$X_{N\times D} = rand(N,D)\times(ub-lb)+lb \tag{11}$$

In the population, each one-dimensional state of the salp leader is $X_d^1(d=1,2,\cdots,D)$, and that of the salp follower is $X_d^m(d=1,2,\cdots,D;m=2,3,\cdots,N)$.

The salp leader is responsible for searching food in the space and guiding the movement of the whole population. Therefore, the leader's location update should be highly random and is shown as follows.

$$X_d^1 = \begin{cases} F_d + c_1\cdot((ub_d-lb_d)\cdot c_2 + lb_d) & c_3 \ge 0.5 \\ F_d - c_1\cdot((ub_d-lb_d)\cdot c_2 + lb_d) & c_3 < 0.5 \end{cases} \tag{12}$$

Where, both c_2 and c_3 are random numbers between $[0,1]$, and their functions are to enhance the randomness of leader's movement and individual diversity of population; c_1 is called convergence factor, balances the exploration and development ability of SSA in the iteration process and is shown as follows

$$c_1 = 2e^{-(4l/l_{\max})^2} \tag{13}$$

Where l and $l_{\max}$ are the current and maximum number of iterations respectively.

In SSA, followers do not move in random, but in the way of chain which moves with each other in turn. Therefore, follower's location

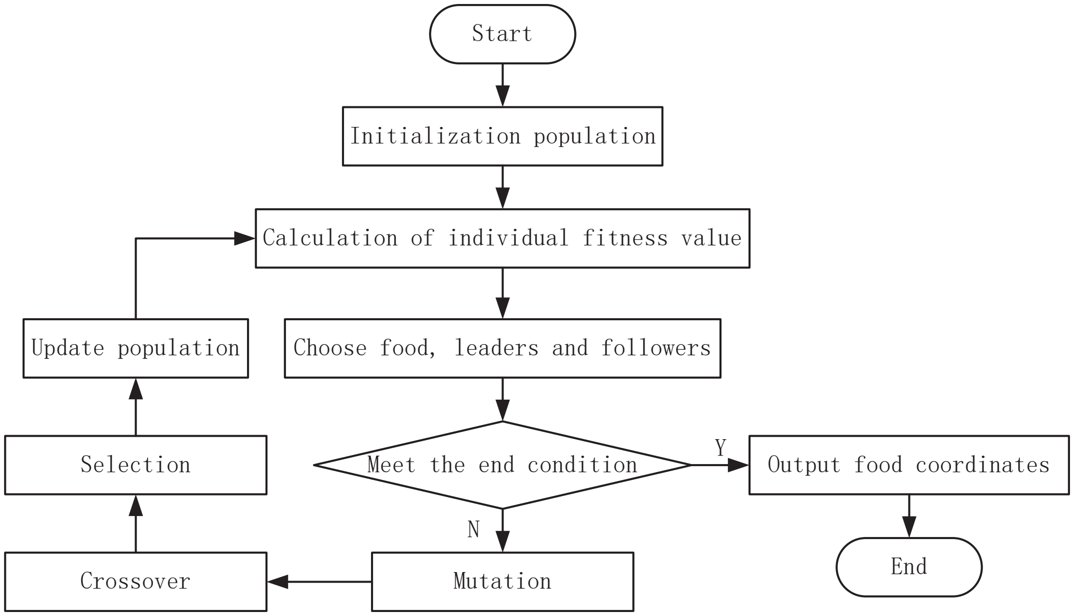

Fig. 4. Flow chart of salp swarm algorithm based on differential evolution.

is only related to its initial location, velocity and acceleration. The movement mode conforms to Newton law of motion, so follower's moving distance R can be expressed as follows.

$$R=\frac{1}{2}at^2+v_0t=\frac{1}{2}\left(X_d^{m-1}-X_d^m\right) \tag{14}$$

Where, t is the D-value of iterations, that is $t=1$; v_0 is the initial velocity of followers, that is $v_0=0$; a is the acceleration from the beginning to the end of the iteration, that is $a=(v_{final}-v_0)/t$ because the follower follows only the movement of the previous salp next to himself, its velocity is $v_{final}=(X_d^{m-1}-X_d^m)/t$'s location update is shown as follows.

$$X_d^{m'}=X_d^m+R=\frac{1}{2}\left(X_d^m+X_d^{m-1}\right) \tag{15}$$

Where X_d^m and $X_d^{m'}$ are the location of m followers in the d-dimension before and after updating respectively.

In solving the optimization problem of the coal supply chain network, the search scope is large. In order to make pre-search process of SSA more global and random, this paper chooses half of the salps as the leader to take into account the randomness and stability of SSA. In addition, this paper combines the strategy of differential evolution (DE) to mutate, cross and select the leaders generated by each iteration, which avoids the danger of SSA falling into local optimum and further increases the diversity of salps.

Differential evolution (DE) algorithm is a simple and effective uncertainty search algorithm proposed by Rainer Storn and Kenneth Price in 1995 (Fan et al., 2018). DE algorithm generates new individuals by randomly selecting two dissimilar leaders in SSA, scaling their difference vectors and performing vector operations with other individuals to be mutated as follows.

$$V_i(l+1)=X_{r_1}(l)+F\times(X_{r_2}(l)-X_{r_3}(l)) \tag{16}$$

Where $i\neq r_1\neq r_2\neq r_3$, $i=1,2,\cdots,N/2$, r_1, r_2, r_3 are all random integers between $[1,N/2]$; l is the current number of iterations; $X_i(l)$ is the leader i in the number of iterations l. F is a scaling factor. In order to prevent premature convergence and ensure faster convergence speed, this paper uses adaptive mechanism to assign F as follows.

$$F=F_{\max}-(F_{\max}-F_{\min})\times\frac{l}{l_{\max}} \tag{17}$$

Where $F_{\max}$ and $F_{\min}$ are the upper and lower limits of F respectively.

Crossover between individuals of the population $\{X_i(l),i=1,2,\cdots,N/2\}$ and the variant intermediate population $\{V_i(l+1),i=1,2,\cdots,N/2\}$ is shown as follows.

$$u_{ij}(l+1)=\begin{cases}v_{ij}(l+1), rand(0,1)\leq CR \ \ or \ \ j=rand(1,D)\\ x_{ij}(l), \quad rand(0,1)>CR \ \ or \ \ j\neq rand(1,D)\end{cases} \tag{18}$$

Where $i=1,2,\cdots,N/2, j=1,2,\cdots,D$; $U_i(l+1)=[u_{i1},u_{i2},\cdots,u_{iD}]$ is the new leader i in the number of iterations $l+1$; $u_{ij}(l+1)$ and $v_{ij}(l+1)$ are the component j in $U_i(l+1)$ and $V_i(l+1)$ respectively. CR is the crossover probability. This paper also uses adaptive mechanism to assign CR as follows.

$$CR=CR_{\min}+(CR_{\max}-CR_{\min})\times\frac{l}{l_{\max}} \tag{19}$$

Where $CR_{\max}$ and $CR_{\min}$ are the upper and lower limits of CR respectively.

DE algorithm uses greedy strategy to select new individuals into the population based on the size of the objective function:

$$X_i(l+1)=\begin{cases}U_i(l+1), f(U_i(l+1))\leq f(X_i(l))\\ X_i(l), \quad f(U_i(l+1))>f(X_i(l))\end{cases} \tag{20}$$

In summary, this paper can get the flow chart of salp swarm algorithms based on differential evolution as shown in Fig. 4.

In order to ensure the rationality of proposed algorithm, this paper takes $f(x)=\sum_{i=1}^{10}x_i^2, -100\leq x_i\leq 100$ as the test function, and selects improved particle swarm optimization (IPSO) and traditional SSA as the comparison model to verify the optimization performance of proposed algorithm. The convergence curves of the

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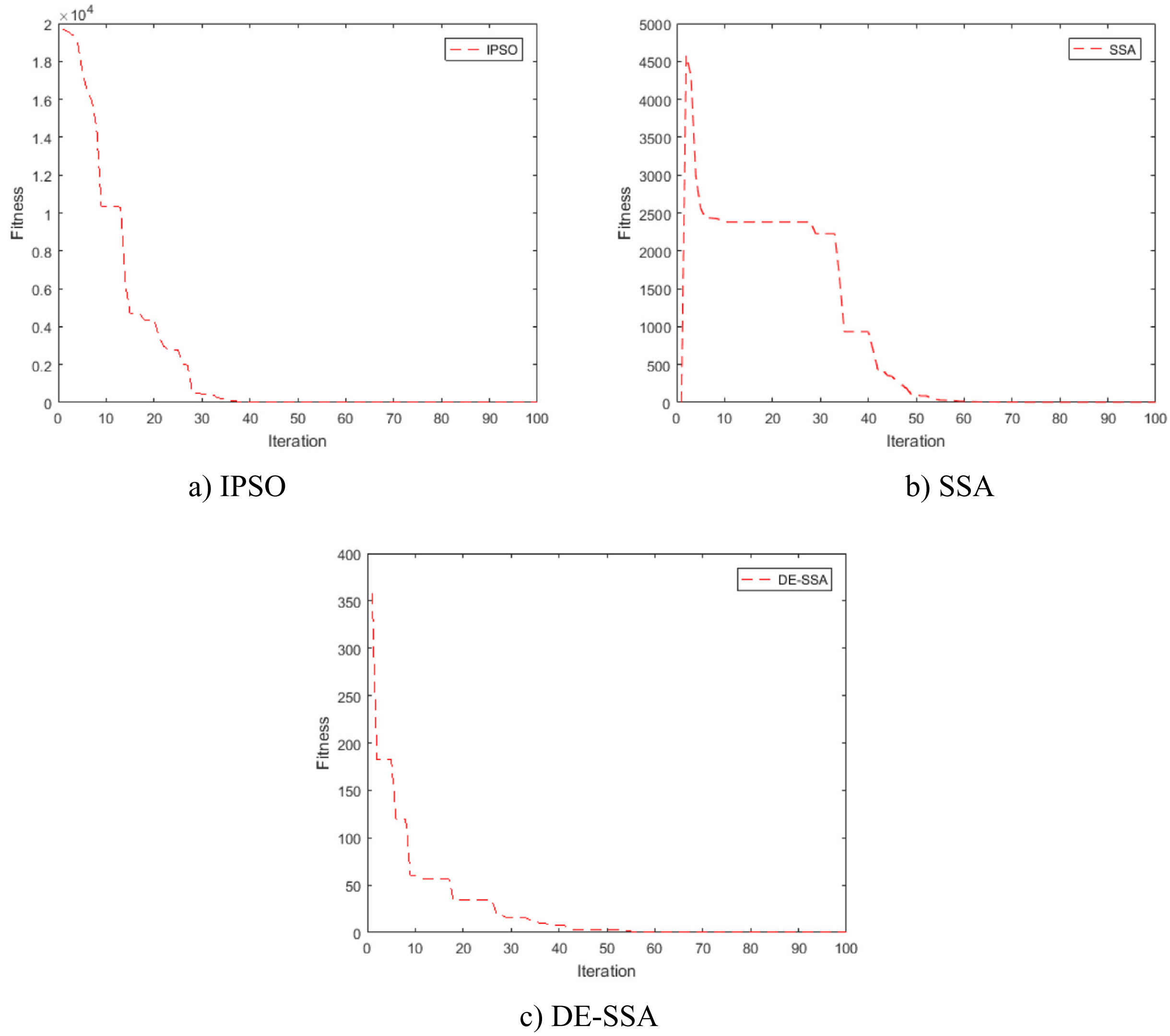

Fig. 5. Convergence curves of three algorithms.

Table 3
Optimal results obtained by three algorithms.

	Ideal situation	IPSO	SSA	DE-SSA
Result	0	9.2029×10^{-9}	1.1409×10^{-15}	2.3806×10^{-17}

three algorithms are shown in Fig. 5.

Meanwhile, the optimal results obtained by three algorithms are shown in Table 3.

In Table 3, the ideal state represents the minimum value of formula $f(x) = \sum_{i=1}^{10} x_i^2, -100 \le x_i \le 100$, which can be known as 0 (Sayed et al., 2018). The ideal values and the convergence accuracy of IPSO, SSA and DESSA are 0, 9.2029 × 10−9, 1.1409 × 10−15 and 2.3806 × 10−17, respectively. Where, the ideal state represents the minimum value of the formula, which can be known as 0.

It can be seen that all three algorithms can converge successfully in 100 iterations, the convergence speeds of IPSO and SSA in the pre-stage are obviously faster than that of DE-SSA, but the fitness value of DE-SSA in the post-stage is obviously lower than that of IPSO and SSA from Fig. 5 and Table 3. In addition, IPSO and SSA may not converge due to the control of motion or velocity parameters during the testing process. Therefore, this paper uses proposed DE-SSA to solve the optimization problem of coal supply chain network.

4. Case study

In order to analyze the impact of carbon emission policies on the optimization of coal supply chain network, this paper takes the coal supply chain network in X corporation as a case study. The coal supply chain network consists of 2 coal mines, 3 coal washery, 3 coal distribution centers and 2 power plants. On the basis of obtaining the relevant parameters, the optimization model proposed in this paper is applied to calculate and analysis, and the results are shown in Fig. 6.

The supply chain model values calculated by the above algorithm under the carbon emission cap policy were selected from five of them and obtained as figure a). The results showed that the government can guide coal enterprises to effectively reduce carbon emissions by formulating reasonable emission cap policies, without significantly increasing the total cost of coal enterprises. When the emission cap $L > 7.50 \times 10^{10} kg$, the economic cost and carbon emissions of the coal supply chain network will be a certain value, so the emission cap $L > 7.50 \times 10^{10} kg$ will not affect the

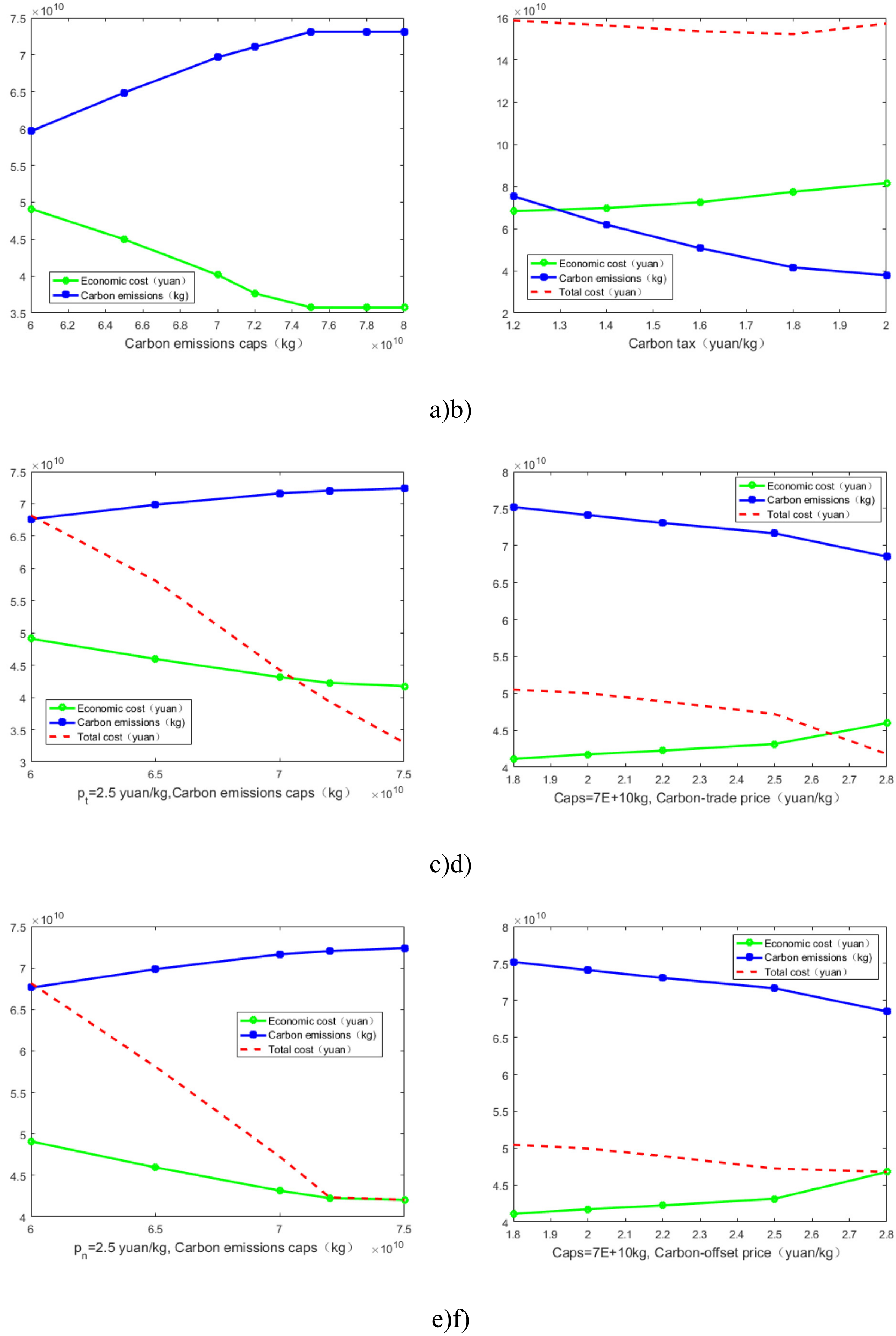

Fig. 6. Optimization results of coal supply chain network under different carbon emission policies.

optimization results of the coal supply chain network. Meanwhile, when the emission cap $L < 7.50 \times 10^{10} kg$, it can be seen that when $L = 7.20 \times 10^{10} kg$, the slope of economic cost reduction of coal supply chain is the largest by calculating the slope of economic cost change, which is 1.25. Therefore, $L = 7.20 \times 10^{10} kg$ is the most reasonable emission cap. The supply chain model values calculated by the above algorithm under the carbon tax policy are selected and five of them are given in figure b). Figure b) can be seen that the "Trade-off" phenomenon exists in the economic cost and environmental cost of the coal supply chain network. In order to find a balance, when carbon tax $\alpha = 1.8\ yuan/kg$, the total cost of coal supply chain is the smallest, so the most reasonable carbon tax price is $\alpha = 1.8\ yuan/kg$. Similarly, model values under the carbon trading policy were calculated, and figures c and d were obtained. Figure c) can be seen that when the carbon emission cap $L = 7 \times 10^{10} kg$ is fixed, with the gradual rise of carbon trade price, coal enterprises will pay more attention to the carbon trade cost, so the total cost shows a gradual downward trend. Figure d) shows that when carbon trade price $p_t = 2.5 yuan/kg$ is fixed, with the gradual rise of emission cap, coal enterprises can make profits through carbon trade, so the total cost shows a gradual downward trend. Similar to carbon trade policy, the values calculated under the carbon offset policy are shown in figure e) and figure f). Figure e) and Figure f) shows that the total cost under carbon offset policy also shows a gradual downward trend. However, the reduction of carbon emissions under carbon offset is not as obvious as the result under carbon trade, because there is no reward for coal enterprises under the carbon offset policy.

5. Results and discussion

Under the background of more and more attention paid to environmental issues in various countries, this paper studies the impact of different carbon emission policies on the optimization of coal supply chain network, and establishes the optimization model of coal supply chain network based on carbon emission policies. By comparing the effects of four different carbon emission policies on the optimization of coal supply chain network, it is found that the government can guide enterprises to reduce carbon emissions effectively by formulating reasonable emission policies, so as to achieve the optimal cost of coal enterprises under different carbon emission policies.

Meanwhile, it can be seen that these carbon emission policies can all make coal enterprises reduce carbon emissions. Apart from carbon emissions cap is a complete policy means, the other three policies can stimulate coal enterprises to reduce carbon emissions from an economic perspective. So this paper will compare these three policies from the perspective of carbon emissions and total cost. The comparison of carbon tax policy and carbon trade policy shows that when $\alpha = p_t, L = 0$, carbon tax policy and carbon trade policy are equivalent. In addition, comparing the carbon trade policy and carbon offset policy, it can be seen that if the carbon emission cap L is less than the minimum emissions of coal enterprises, enterprises can only purchase carbon credits, so the effects of the carbon trade policy and carbon offset policy are equivalent. However, with the increase of L, coal enterprises' emissions will continue to increase under the carbon offset policy due to the inability to sell extra emission credits. So it can be seen that the carbon trade policy is more effective than the carbon offset policy. From the perspective of total cost, it can be found that when $\alpha = p_t$, $L > 0$, the total cost of coal enterprises under carbon trade policy is lower than that under carbon tax policy. Meanwhile, under the carbon trade policy, coal enterprises can make profits through selling the emission credits. Therefore, compared with other policies, carbon trade policy is easier to promote. This means carbon trading policies can make enterprises in minimizing the cost of carbon emissions is minimum at the same time, the pressure on the environment caused by the minimum, to make the business enterprise to protect the environment, reduce carbon emissions low carbon policy applied to the whole process in reducing carbon emissions to the environment pressure makes the enterprise operation cost minimum at the same time, it also conforms to the clean production should not only meet the people in the rational use of natural resources, energy and the production methods of protecting the environment.

In terms of production practice, this paper combines carbon emission with enterprise cost to minimize carbon emission and minimize enterprise cost. This is not only in line with the policy of sustainable development, to minimize the pressure on the environment, but also conducive to the development of enterprises, thus promoting the overall economic development.

6. Conclusions and suggestions

By studying the sustainable design of coal supply chain network under the new background, it is found that the government can effectively guide enterprises to reduce carbon emissions by formulating reasonable emission policies, so as to achieve the optimal cost of coal enterprises under the condition of low carbon. At the same time, carbon trade policies have the best effect on the emission reduction of coal enterprises. So as to achieve the optimal cost of coal enterprises under low carbon.

This applies not only to the optimization of the coal supply chain network, but also to other enterprises that generate carbon emissions and costs. Also that said, for most enterprises to produce carbon, especially in process industry, this paper studies process method (DE - SSA) and research conclusion (under the carbon trading policies, the coal enterprise best reduction effect, and the lowest cost), and the research methods of this article overcomes the drawback of SSA easy to fall into local optimum, DE - SSA model is established, and that the SSA and search process with overall importance and randomness, lay a foundation for later research on SSA. However, the research in this paper also has some limitations. This paper studies the carbon emission policy under the joint action of economic benefits and environmental benefits. Although it has a certain emission reduction effect, it does not research from the level of production technology to make enterprises reduce carbon emissions in the production process. In addition, this paper only optimizes the carbon emission policy and the cost of coal enterprises, but there is still a lack of supply chain optimization. Reducing carbon emissions is not a difficult task for coal companies, which can strike a balance between cost and environmental protection. The following three suggestions can be put forward for low-carbon coal supply chain in the future:

(1) Low-carbon technology development. With the development of the economy, technology is the core issue of low-carbon development and the biggest constraint for the transformation of the coal enterprises from "high-carbon" to "low-carbon". Coal enterprises focus on developing low-carbon mining technology, low-carbon transportation technology and clean coal combustion technology to train high-end technical personnel, which effectively promotes the construction of low carbonization in the coal supply chain. Enterprises should strengthen the close cooperation with colleges and universities, realize the school-enterprise cooperation, form the situation of combining production, education and research, and accelerate the research and development of low-carbon technology. A combination of short-term low-carbon project training and long-term

education could also be considered to improve the skills of practitioners matched with the supply chain low-carbon. Actively participate in low-carbon knowledge lectures and technical exchanges organized by industry associations to create a low-carbon talent cultivation environment. The independent innovation ability of low-carbon technology is also very important. Enterprises should invest research and development costs and actively improve the innovation management mechanism of enterprises. At the national level, they should also provide financial and policy support for the development of low-carbon technologies to provide a good environment for the development of low-carbon technologies

(2) Rational optimization of supply chain path. It can be found that the economic cost and carbon emissions involved in the process of coal transportation have the greatest impact on establishing the optimization model of coal supply chain network under carbon emission policies. Therefore, it is necessary to rationally arrange the number of coal transportation, optimize the transportation path and scientifically establish the coal supply chain market under the carbon emission policy. It can greatly reduce the operating costs of enterprises. Enterprises should strengthen the close cooperation with colleges and universities, realize the school-enterprise cooperation, and accelerate the research and development of low-carbon technology. At the national level, it is also necessary to provide financial and policy support for the development of low-carbon technologies, and provide financial support for enterprises that control carbon emissions to develop clean technologies, so as to provide a good environment for the development of low-carbon technologies.

(3) Implement carbon trading policy. The implementation of carbon trading policies can be promoted in the coal supply chain industry or even the whole coal industry. Because of carbon emission reduction policies can reduce the pressure on the environment and promote sustainable development. Companies want to make money by cutting costs. Under the influence of carbon trading policy, the environmental pressure can be reduced to the greatest extent and the profits of enterprises can be maximized. We should accelerate the improvement of the construction of a national carbon trading market and the construction of supporting facilities for the market, do a good job in connecting the pilot projects of carbon trading with the national carbon trading, give full play to the function of the market in allocating resources, and guide enterprises to implement carbon trading policies. At the same time, legislation on carbon trading should be accelerated to provide legal support for the implementation of carbon trading policies. We will accelerate the improvement of the construction of a national carbon trading market and the construction of supporting facilities for the market, do a good job in connecting the pilot projects of carbon trading with the national carbon trading, give full play to the function of the market in allocating resources, and guide enterprises to implement carbon trading policies. At the same time, legislation on carbon trading should be accelerated to provide legal support for the implementation of carbon trading policies.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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Appendix

The scholar interviewed in this paper is professor ci, department of mechanics, north China electric power university.

Q:Hello, Professor ci, we have recently in the study about the influence factors of the coal industry to implement low carbonization, and to determine the influence of 12 factors, including (1) incentive and guiding policy (2) regulatory constraints (3) plan and standard low carbon (4) environmental preferences of consumers (5) low carbon consciousness (6) high quality human resources support (7) information level (8) organization and management of the coal supply chain (9) low carbon environmental protection technology (10) cost of low carbon production (11) and utilization of green energy (12) energy efficiency level, etc. According to your experience, whether these influencing factors are reasonable.

Answer: In you sure 12 factors are very reasonable. Low-carbon awareness is the awareness that the whole society should establish. Consumers should not only have low-carbon consumption awareness, but also supply chain practitioners should establish awareness. The low-carbon consciousness of practitioners is extremely important to the low-carbon development of enterprises, and the low-carbon consciousness of managers can play a role of benchmarking in enterprises. Strengthening the transformation motivation of enterprises in a low-carbon environment will make enterprises show more practical and purposeful low-carbon behaviors, which is also an important condition for equipment low-carbon. Professional talents are not only the core link for enterprises to compete in low-carbon competition, but also an important human resource reserve for enterprises to improve their own low-carbon management ability. Shortage of human resources will limit an important aspect of low-carbon supply chain. When enterprises have related talents with low carbon, they will have low carbon technology, green energy utilization and energy efficiency level. These factors can not only enhance the independent innovation ability of enterprises but also improve their own low-carbon management ability. The investment in the early stage of low carbonization will increase the cost of the enterprise compared with the traditional development mode and delay the profit of the enterprise. However, enterprises aim at making profits. If the country does not have corresponding policies, laws and regulations, and corresponding low-carbon standards to compensate and regulate enterprises, enterprises will lose the motivation of low-carbon. A series of government policies and regulations can make up for the lack of market regulation. From incentive and guide policy, the influence factors of coal supply chain through the investment of manpower to reduce carbon emissions, has made a contribution to the social and public environment, but this is not reflected in profits from the enterprise, the longer it will reassure the enthusiasm of enterprises, which requires policy incentives and low carbon subsidies. At the same time, the government should also incorporate low-carbon factors into the development planning of the national supply chain, determine the position of low-carbon supply chain at the macro level, organize and manage the coal supply chain, and integrate resources. The purpose of formulating relevant laws and regulations for the development of low-carbon supply chain is to restrict enterprises' behaviors of high carbon emission from the system. The coal supply chain organized and managed is to reduce carbon emission through the standardized construction system of low carbon. In the market economy, enterprises in the supply chain should strengthen the connection, pay attention to the information communication between each other and improve the information level. Based on the above analysis, I think the factors you have chosen are reasonable.

Q: What other factors do you think affect the thermal coal supply chain under the low-carbon policy?

A: I think the factors you chose are reasonable and there is nothing to add.

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