Research on Optimization of Carbon Emission Reduction of Coal Supply Chain System in Iron and Steel Industry

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Abstract: The steel industry is an important basic industry for the development of the national economy and national defense construction, but it is also a major source of energy consumption and environmental pollution. In particular, the carbon emissions in the process of coal combustion and steelmaking are huge. This situation urgently needs to be improved and optimized. Therefore, based on the perspective of the coal supply chain in the steel industry, this paper constructs a multi-objective planning model to achieve a balanced optimization of total economic costs and carbon emission reduction, and verifies the effectiveness of the model through specific case data. This paper sets three different emission reduction scenarios, discusses and analyzes the changes of economic total cost and carbon emission under different emission reduction scenarios, and finds that suppliers with good coal mining technology and low carbon emission factor have more opportunities to be selected and can obtain more coal market orders. At the same time, steel plants with mature processing technology and low carbon emission factor can further gain market competitive advantage and undertake more steelmaking tasks. Finally, based on results, management suggestions for coal suppliers and steel plants are provided.

1. Introduction
Global environmental problems represented by the greenhouse effect are becoming increasingly serious, and it has become the consensus of all countries to vigorously develop low-carbon economy. Many countries have established a benign carbon emission mechanism to regulate enterprises' short-sighted behaviors \cite{1}, forcing enterprises to reduce environmental pollution through using green raw materials, green technologies and developing green supply chain.

The annual energy consumption of the steel industry accounts for 16.5\% of total consumption, and its carbon emissions exceed 10\% of the total emissions \cite{2}, which has already brought tremendous environmental pressure to our ecosystem. The problem of carbon emission pollution is more prominent in the coal-steel supply chain. The linkage between the two types of high-pollution and high-energy-consuming industries in the supply chain poses serious challenges to environmental governance. Therefore, strengthening the carbon emission control of the steel industry has important practical significance for environmental strategic deployment, at the national level.

However, carbon emission reduction usually increases corporate costs, but the economic effects of environmental expenditures are often uncertain and lagging, which will severely reduce corporate profits. Therefore, the core issue of promoting coal suppliers and steel plants in the supply chain to actively participate in the green economy is to achieve an organic balance between social environmental effects and corporate economic costs, and to seek a sustainable development path in...
reducing carbon emissions and optimizing costs.

Previous studies have emphasized "hard means" for enterprises to reduce emissions, and explored the role of green technology and production reduction in promoting emissions reduction in the steel industry. Benjiaafar et al. (2019) discussed the impact of production cuts on economic costs and carbon emissions under the constraint of carbon emissions, and provided an integrated scheme [3]; Du et al.(2015) explored the optimization model between carbon emission permit pricing and production function of supply chain participants [4]; Liu et al.(2020) integrated service concept into green supply chain, and pointed out three kinds of contracts to improve the overall effect of supply chain [5]. However, few market players in transition economies can directly bear the huge costs of "hard tools" such as technical solutions. Therefore, many scholars have pointed out that carbon emission and cost balance in the coal supply chain of the steel industry can be analyzed from the perspective of green supply chain through model optimization and algorithm iteration, which can more effectively help the iron and steel industry to achieve a "soft landing" of green transformation [6]. However, previous studies lacked systematic exploration of the cost control and carbon emission balance optimization of the coal supply chain of the iron and steel industry, and they seldom discussed the cost control strategy in the coal supply chain of the iron and steel industry under the constraints of carbon emission reduction.

Based on the theory of green supply chain, this paper establishes a multi-objective planning model to explore the balance and optimization of the total economic cost and carbon emissions of the coal supply chain in the iron and steel industry, and enters relevant case data to verify the feasibility of the model. Further, this paper will analyze the results of the model solution, and put forward some effective management suggestions for carbon emission reduction governance and economic cost control of the coal supply chain in the steel industry.

2. Modelling and data

2.1. Objective function construction

According to the characteristics of the coal supply chain in the steel industry, the cost of the model system includes coal mining cost, transportation cost, inventory cost and coal steelmaking cost. The objective function is expressed as follows:

$$\text{Min } TC = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} Q_{ij} E \left[ \tilde{P}_{i} \right] + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} Q_{ij} I_{j} E \left[ TRC_{ij} \right] + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} IS_{ij} + IS_{ij}^{t+1} \left( IC_{ij} \right)$$

Where $TC$ is the total economic cost of the coal supply chain in the steel industry (rmb); $Q_{ij}$ is the amount of coal supplied by coal supplier $i$ to steel plant $j$ in period $t$ (t); $\tilde{P}_{i}$ is the mining cost per unit of coal mined by coal supplier $i$ in period $t$ (rmb/t); $L_{ij}$ is the transport distance from coal supplier $i$ to steel plant $j$ (km); $TRC_{ij}$ is the unit cost of transportation from coal supplier $i$ to steel plant $j$ (rmb/t•km); $IS_{ij}$ is the coal inventory cost of steel plant $j$ in period $t$ (t); $IC_{ij}$ is the unit coal inventory cost of steel plant $j$ in period $t$ (rmb/t); $q_{ij}^{c}$ is the consumption of coal burned by steel plant $j$ in period $t$ (t); $\tilde{R}_{ij}^{c}$ is the amount of steel produced by steel plant $j$ burning units of coal $i$ in period $t$ (t); $\tilde{RC}_{ij}^{c}$ is the unit operating cost required by steel plant $j$ to produce one unit of steel (rmb/t).

Similarly, the objective function of carbon emissions in the supply chain is as follows:
Where \( TE \) is the total carbon emission of coal supply chain in the steel industry (kg); \( \overline{ER}_i \) is the CH4 emission coefficient of coal mined by coal supplier \( i \) (m³/t); \( \overline{ER}_j \) is the CH4 emission factor of coal storage in steel plant \( j \) (m³/t); \( CT \) is the conversion factor from CH4 to CO₂ (44/12); \( CF \) is the density of CH4, which can be represented by the density of CH4 at 20 degrees and 1 standard atmosphere (0.67kg/m³); \( \overline{TRE}_{ij} \) is the carbon emission per unit of coal transported (kg/t•km), \( \overline{SE}_{ij} \) is the carbon emission coefficient of steel plant \( j \) burning unit coal \( i \) (kg/t).

2.2. Dynamic constraint construction

\[
\sum_{j=1}^{J} q'_{ij} E \left[ \overline{SP}_{ij} \right] X_i \leq X_i M, \quad Q'_{ij}, q'_{ij} \geq 0; X_i \in (0,1)
\]

Where \( X_i \) is 0-1 variable, 1 means choose coal supplier, 0 means don't choose; \( \overline{SP}_{ij} \) is the coal supply capacity of coal supplier \( i \) in period \( t \) (t); \( IS_{ij}^{\text{min}} \) is the minimum stock of coal \( i \) to ensure the normal operation of steel plant \( j \) in period \( t \) (t); \( PM_j \) is the steel production capacity of steel plant \( j \) in period \( t \) (t); \( DM_j \) is the total demand for steel for the whole system in period \( t \) (t); \( M \) is a very large real number, for example 1000000000. Finally, the decision variable of this paper is \( X_i, Q'_{ij}, q'_{ij} \).

2.3. Multi-objective processing

The carbon emissions of whole system in the previous production cycle were \( TE_0 \) (t); and it is assumed that local government's attitude towards CO₂ emission reduction of whole system is \( \mu \). So the objective function of total carbon emissions is converted into constraint conditions, as follows:

\[
TE \leq \mu TE_0
\]

2.4. Data collection

Now suppose there are 2 Steel Plants and 4 Coal Suppliers, and the study time is 4 periods. Among them, Supplier 1 has good coal mining technology and the smallest carbon emission factor, but relatively higher prices; Suppliers 2 and 3 have middle coal mining technology, middle carbon
emission factor, and middle price, but Supplier 2 is slightly better than Supplier 3; Supplier 4 has the worst mining technology, the highest carbon emission factor, and the lowest price. At the same time, the processing technology of Steel Plant 1 is mature and the carbon emission factor is relatively low, while Steel Plant 2 is the opposite. The input data of the model can be divided into two types: deterministic data and fuzzy random data, which will be solved by Lingo software.

3. Numerical experiment results & discussion

This paper discusses the change of optimal solution under different emission reduction scenarios (i.e. different attitudes of local governments to carbon emission reduction).

(1) When $\mu=1$, the model solution results are shown in Table 1. It can be seen from Table 1 that the system now selects 3 suppliers, namely Supplier 1, 3, and 4, among which Supplier 4 has the largest supply; at the same time, Steel Plant 2 undertakes more steelmaking tasks than Steel Plant 1.

| $Q_i^j$ | Supplier 1 | Supplier 3 | Supplier 4 |
|---------|------------|------------|------------|
| $t_{ij}Q_i^j$ | 7.54 | 8.37 | 439.95 |
| $t_{ij}q_i^j$ | 0.00 | 0.00 | 0.00 |

Table 1. The optimal solution of the model when $\mu=1$.

(2) When $\mu=95\%$, the model solution results are shown in Table 2. It can be seen from Table 2 that the system now selects 3 suppliers, namely Supplier 1, 2, and 4. Among them, the coal supply of Supplier 4 has decreased, but it is still the largest, while Supplier 3 is eliminated by the market. The remaining coal supply has been subcontracted by Supplier 1 and 2, and the coal supply of Supplier 1 has also increased compared to before. Secondly, the number of steelmaking in Steel Plant 1 has greatly exceeded that of Steel Plant 2, and Steel Plant 2 has lost its market competitive advantage.

| $Q_i^j$ | Supplier 1 | Supplier 2 | Supplier 4 |
|---------|------------|------------|------------|
| $t_{ij}Q_i^j$ | 372.78 | 394.12 | 439.95 |
| $t_{ij}q_i^j$ | 0.00 | 0.00 | 0.00 |

Table 2. The optimal solution of the model when $\mu=95\%$.

(3) When $\mu=90\%$, the model solution results are shown in Table 3. It can be seen from Table 3 that the system now selects 3 suppliers, namely Suppliers 1, 2, and 3. Among them, Supplier 2 has the largest supply, followed by Supplier 1, while Supplier 3 has a relatively small supply, and Supplier 4 is eliminated by the market. Secondly, the number of steelmaking in Steel Plant 1 increases again and occupies a dominant position in the market.

| $Q_i^j$ | Supplier 1 | Supplier 2 | Supplier 3 |
|---------|------------|------------|------------|
| $t_{ij}Q_i^j$ | 372.78 | 394.12 | 8.37 |
| $t_{ij}q_i^j$ | 315.64 | 367.28 | 0.00 |

Table 3. The optimal solution of the model when $\mu=90\%$. 
Supplier 2  386.17  366.48  436.05  345.41  0.00  0.00  0.00  0.00
Supplier 3  0.00  0.67  0.00  1.51  262.30  181.17  117.23  247.46

(4) Summarize the total economic costs and total carbon emissions under the three emission reduction scenarios, as shown in Table 4. It can be seen from Table 4 that when $\mu=95\%$, the total economic cost has a small increase of about 0.23%; when $\mu=90\%$, the total economic cost has a large increase of about 1.55%. It can be found that as carbon emission reduction constraints become stricter, the total economic cost has risen more and more.

Table 4. List of total economic costs and total carbon emissions.

|       | $\mu=1$ | $\mu=95\%$ | $\mu=90\%$ |
|-------|---------|-------------|-------------|
| $TE$  | 84913232290 | 79542907872 | 72290784637 |
| $TC$  | 40140551750 | 40231781474 | 40854904745 |

4. Conclusions
From numerical experiments, it can be found that Supplier 1 and 2 with good coal mining technology and low carbon emission factors have begun to be selected more, while Supplier 3 and 4 are either eliminated or their supply is drastically reduced. Therefore, coal suppliers should continuously optimize their mining technology and reduce carbon emissions during the mining process, instead of being eliminated in future market competition. In addition, Steel Plant 1 with mature processing technology and relatively low carbon emission factors has begun to undertake more and more steelmaking tasks, while steelmaking tasks in Steel Plant 2 are gradually decreasing. Therefore, steel plants should strictly control high-carbon emission steelmaking tasks, and adopt green production technology to reduce the carbon emission, and obtain more steel supply tasks in the future.

Further research finds that as carbon emission reduction constraints become more stringent, the total economic cost has risen more and more. Therefore, the government should not only blindly increase carbon emission reduction constraints, but should also take the cost pressures of coal suppliers and steel plants into account, and ultimately achieve the balance and optimization of the two.

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