Research on Carbon Emissions Reduction of Iron and Steel Remanufacturing Industry Supply Chain

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Abstract. The steel industry occupies an important position in China’s economic development, but it also consumes a lot of energy and produces CO2. Iron and steel remanufacturing can recycle scrap iron as raw materials for crude steel smelting and reduce energy consumption. However, different raw materials in the supply chain will result in different steel plants’ choice of supplier, purchase volume, and production volume. These choices will affect the economic cost and carbon emissions of the entire system. This paper establishes a model to simulate the economic cost and carbon emissions of the supply chain system. Under various constraints, the carbon emissions are set at 95% and 90% of the previous year’s carbon emissions as constraints to solve the system’s impact on suppliers selection and processing distribution of steel plants. The results show that as carbon emission constraints become more stringent, steel plants will choose suppliers with better quality raw materials, and processing production will shift to steel plants with lower carbon emission factors. It is worth noting that with the strict carbon emission restrictions, at 90%, the economic cost will rise rapidly, so too strict carbon emission restrictions should be carefully considered.

1. Introduction

With the rapid industrialization and urbanization, China’s steel industry has developed rapidly. Since 1996, China has been the world’s largest steel producer[1]. In 2014, China’s crude steel production reached its peak, with a total output of approximately 822.68 million tons, accounting for almost 50% of the world’s total production[2]. The steel industry has brought huge economic benefits to China, but at the same time, it has produced quite high energy consumption and carbon emissions. China’s steel industry accounts for 16.5% of total energy consumption, and CO2 emissions account for the country’s total emissions more than 10% of the amount[3][4].

Gutowski et al.[5] pointed out that steel is the main industry for energy use and carbon emissions. In order to reduce pollution and carbon emissions, material recycling is one of the important ways. Steel remanufacturing is a mode of production in the steel industry, which can alleviate energy consumption. Scrap iron can replace part of iron ore as raw material for steel production. Existing scrap iron is mainly divided into household scrap iron, steel processing and scrap steel products (cars, buildings, machinery, etc.). Among them, the proportion of household scrap iron has increased year by year, from 13.3mt (32%) in 2001 to 36.5mt (43%) in 2012[6], the total amount of scrap iron increased from 42.1mt in 2001 to 84.4mt in 2012, a double increase.

Considering the huge energy consumption and carbon emissions of the steel industry, it still has the possibility of energy saving and carbon emission reduction. Although scrap iron recycling can reduce energy consumption, CO2 emissions have always been there. China has tried to implement carbon trading policies in the power generation industry. However, Wu et al. [7] used the Shanghai area as the...
research area and found through the establishment of a CGE model analysis that, by 2030, the reduction of carbon emissions may affect 2.3% of GDP [8]. China is on the verge of a middle-income trap, to reduce carbon emissions or to maintain economic growth is a problem.

In the process of reducing carbon emissions, we are confronted with the competition for the interests of enterprises and the environment. For steel plants, reducing emissions means higher production requirements and higher production costs. The steel recycling industry itself is energy-saving and environmentally friendly, but in the production process, carbon emissions are inevitable. In the supply chain of steel remanufacturing, taking the optimal system cost as the constraint, we explored how to limit the appropriate degree of emission reduction to protect the economy and the environment at the same time.

2. Problem Description

In the entire supply chain of steel remanufacturing, costs are mainly generated in the four notes of procurement, transportation, inventory, and production, and carbon emissions are generated in the transportation and production. In the system, different types of raw materials (scrap iron) supplied by different suppliers affect the cost of the procurement process. The purchase price of high-quality raw materials is high, and the processing methods of different raw materials will also lead to different production costs. The number of purchases, batches, and the number of raw materials consumed simultaneously affect the cost of transportation and inventory. The carbon emissions in the transportation are determined by the purchase volume, while the carbon emissions in the production are affected by the quality of raw materials, processing methods, and steel plant technology.

By simulating steel remanufacturing supply chain, this paper discusses the process of the system from scrap iron suppliers to steel plants, taking the optimal economic cost as the constraint, and discussing under different carbon emission constraints, the optimal selection that different steel plants make.

3. Model construction

The total economic cost includes the costs of purchase, transportation, inventory and production in four process:

$$TC = \sum_{i} \sum_{j} \sum_{t} PC_{ij} * Q_{ijt} + \sum_{i} \sum_{j} \sum_{t} TRC_{ij} * Q_{ijt} + \sum_{j} \sum_{i} IC_{ij} * IP_{j(t-1)} + \sum_{i} \sum_{j} \sum_{t} R_{ij} * Y_{ijt} * SC_{ij}$$

Among them, TC is the total cost of the system, PC_{ij} is the unit cost of raw materials provided by supplier i to steel plant j (RMB/t), Q_{ijt} is the quantity of raw materials provided by supplier i to steel plant j at t (t), and D_{ij} is the transportation distance between supplier i and steel plant j (km), TRC_{ij} is the unit raw material cost between supplier i and steel plant j (RMB/(t*km)), and IC_{ij} is the unit cost of steel plant j inventory (RMB/t), IP_{j(t-1)} is the raw material i provided to steel plant j at the end of t-1 period (t), IP_{j(t)} is the raw material i provided to steel plant j at time t Inventory at the end of the period (t), Y_{ijt} is the amount of raw material used by supplier i during the t period of steel plant j (t), R_{ij} is the raw material steelmaking conversion rate of supplier i used by steel plant j (no unit), SC_{ij} is The cost of steel plant j’s production of steel using scrap iron from supplier i (RMB/t).

Carbon emissions are the total amount of transportation and production:

$$TE = \sum_{i} \sum_{j} \sum_{t} D_{ij} * TRE_{ij} * Q_{ijt} + \sum_{i} \sum_{j} \sum_{t} Y_{ijt} * R_{ij} * SE_{ij}$$

Among them, TRE_{ij} is the carbon emissions per unit of scrap steel and distance between supplier i and steel plant j (kg/t*km), and SE_{ij} is the carbon emissions per unit of steel produced by supplier i’s raw materials in steel plant j. (Kg/t).

On basis, the supplier will have a maximum supply limit (3), the inventory needs to meet the purchase and production restrictions (4), at the same time, it needs to be larger than the minimum inventory for normal production (5), each steel plant has the largest production capacity restrictions (6), and the total production volume of the steel plant needs to be greater than customer demand (7).
\[ \sum_{j} Q_{ij} < X_{i} \cdot SM_{i} \quad (\forall i, \forall t) \tag{3} \]
\[ IP_{ij(t-1)} + Q_{ijt} - Y_{ijt} = IP_{ijt} \quad (\forall i, \forall j) \tag{4} \]
\[ IP_{jt} \geq IP_{jt \min} \tag{5} \]
\[ \sum_{i} Y_{ijt} \cdot R_{ijt} \leq QM_{jt} \quad (\forall j, \forall t) \tag{6} \]
\[ \sum_{i} \sum_{j} Y_{ijt} \cdot R_{ij} \geq DE_{t} \tag{7} \]

Among them, Xi is 0-1 variable, 1 means that supplier i is selected, and 0 means no; SMit is the maximum supply capacity of supplier i in period t (t); IPjtmin is the normal state of steel plant j in period t. The minimum processing inventory (t); QMjt is the maximum processing capacity of steel plant j in period t (t), and DEt is the customer demand in period t (t).

Xi, Qjit, Yijt are the variables to be solved.

4. Numerical Experiment

Now suppose there are four suppliers and two steel plants. Among them, Supplier 2 provides raw materials with the smallest carbon emission factor, but relatively more expensive. The raw materials provided by Supplier 1 and Supplier 3 have medium carbon emission factors and relatively low prices. Supplier 4 provides the raw materials with the largest carbon emission factor and the lowest price. The processing technology of Steel Plant 1 is mature and the carbon emission factor is relatively low, while Steel Plant 2 is the opposite.

Now, taking the lowest economic cost as the constraint, we can solve the problem of the selection of suppliers in the supply chain system and the selection of steel plants' purchase and processing quantities. Table 1 shows the solution results. It can be seen from the table that the system now selects 3 suppliers, which are Supplier 1, Supplier 3, and Supplier 4. Steel Plant 1 tends to choose Supplier 3, and Steel Plant 2 tends to choose Supplier 4.

| Supplier  | Steel Plant 1 (kt) | Steel Plant 2 (kt) |
|-----------|--------------------|--------------------|
|           | T=1 | T=2 | T=3 | T=4 | T=1 | T=2 | T=3 | T=4 |
| Q(I,J,T)  |     |     |     |     |     |     |     |     |
| Supplier 1 | 27.58 | 11.57 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Supplier 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Supplier 3 | 37.30 | 38.00 | 35.29 | 27.74 | 0.00 | 0.00 | 0.00 | 0.00 |
| Supplier 4 | 0.00 | 0.00 | 0.00 | 0.00 | 36.00 | 40.00 | 37.00 | 38.00 |

When the carbon emissions are restricted to 95% of the carbon emissions with the smallest economic cost, the solution results are shown in Table 2. It can be seen from the table that the system now selects four suppliers, and Steel Plant 1 starts to select Supplier 2, but relatively few. Most of the raw materials of the steel plant 2 are changed from the original Supplier 4 to the Supplier 3 because the raw materials of the Supplier 3 have relatively low carbon emissions. It is worth noting that the production volume of Steel Plant 2 is transferred to Steel Plant 1, Steel Plant 2 has lost its competitive advantage in the market.

| Supplier  | Steel Plant 1 (kt) | Steel Plant 2 (kt) |
|-----------|--------------------|--------------------|
|           | T=1 | T=2 | T=3 | T=4 | T=1 | T=2 | T=3 | T=4 |
| Q(I,J,T)  |     |     |     |     |     |     |     |     |
| Supplier 1 | 40.00 | 38.00 | 31.27 | 26.71 | 0.00 | 0.00 | 0.00 | 0.00 |
| Supplier 2 | 0.00 | 0.00 | 0.00 | 0.00 | 25.00 | 39.00 | 39.00 | 48.00 |
When the carbon emissions are restricted to 90% of the carbon emissions with the least economic cost, the solution results are shown in Table 3. It can be seen from the table that the system has selected three suppliers, namely Supplier 1, Supplier 2, and Supplier 3. Supplier 4 is eliminated when carbon emissions constraints became stricter. It can be seen from the table that Steel Plant 1 prefers the raw materials provided by Supplier 2, which can prove that when carbon emission constraints become stricter, the system's choice of suppliers gradually shifts from suppliers with high carbon emission factors and low prices. Transfer to suppliers with low carbon emission factors and high prices.

Table 3 Total carbon emissions constraint 90% solution

| Supplier  | Q(I,J,T) | T=1    | T=2    | T=3    | T=4    | T=1    | T=2    | T=3    | T=4    |
|-----------|----------|--------|--------|--------|--------|--------|--------|--------|--------|
| Supplier 1| 28.55    | 24.05  | 36.77  | 24.94  | 9.45   | 13.95  | 4.23   | 14.06  |
| Supplier 2| 0.00     | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| Supplier 3| 15.78    | 36.82  | 26.77  | 15.54  | 9.45   | 13.63  | 0.00   | 18.29  |
| Supplier 4| 0.00     | 0.00   | 0.00   | 0.00   | 28.21  | 0.00   | 0.00   | 0.00   |

It can be seen from Table 4 that when carbon emission constraints are strict, the total economic cost increases. When the carbon emission limit is 95%, the total economic cost has a small increase, and when the carbon emission limit is 90%, the total economic cost has a large increase.

Table 4 List of total economic costs and total carbon emissions

|                  | Steel Plant 1 (kt) | Steel Plant 2 (kt) |
|------------------|--------------------|--------------------|
| Q(I,J,T)         | T=1    | T=2    | T=3    | T=4    | T=1    | T=2    | T=3    | T=4    |
| Supplier 1       | 30.08  | 9.43   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| Supplier 2       | 35.00  | 40.00  | 30.66  | 28.02  | 0.00   | 0.00   | 0.00   | 0.00   |
| Supplier 3       | 0.00   | 24.47  | 36.80  | 23.15  | 38.00  | 13.53  | 4.23   | 14.03  |
| Supplier 4       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| Y(I,J,T)         | T=1    | T=2    | T=3    | T=4    | T=1    | T=2    | T=3    | T=4    |
| Supplier 1       | 26.29  | 48.71  | 30.66  | 28.02  | 0.00   | 0.00   | 0.00   | 0.00   |
| Supplier 2       | 26.29  | 48.71  | 30.66  | 28.02  | 0.00   | 0.00   | 0.00   | 0.00   |
| Supplier 3       | 0.00   | 24.47  | 26.80  | 33.15  | 25.58  | 13.95  | 6.20   | 24.03  |
| Supplier 4       | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |

5. Conclusion

From numerical experiments, it can be concluded that in the absence of carbon emission constraints, the output of the two steel plants is basically the same, and both will choose suppliers that are more favourable for their own cost control to provide raw materials. When it has carbon emission constraints, Steel Plant 1 begins to show its competitive advantage because it has a relatively low carbon emission factor and is more in line with the environmental requirements of carbon emission. At the same time, the system selection of suppliers has shifted from suppliers with low prices and high carbon emission factors to suppliers with high prices and low carbon emission factors.

In terms of total economic cost, when the total carbon emission constraint is less than 90%, the total economic cost rises slightly, but when the carbon emission constraint is less than 90%, the total economic cost of the system rises more. China already has a carbon trading mechanism, but the steel industry has not been included. With the development of economy and society, the public began to pay attention to the environment. In order to allow more companies to conduct low-carbon production, gradient prices can be set in the carbon trading mechanism, and higher economic subsidies can be provided to companies with more emission reductions.
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