JFE TECHNICAL REPORT
No. 32 (Sep. 2024)

Development of Steel Works Operation Strategy Model

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Abstract:

In the steel works composed of multiple divisions, it is necessary to optimize and formulate the operation plan not for each division but for the whole steel works. JFE Steel has developed a Steel Works Operation Strategy Model for easy and accurate overall optimization, and implemented it in East Japan Works (Keihin District). The optimization target is the blast furnace process and the energy sector, which have a large impact on the production cost and carbon dioxide emissions. Main blast furnace operation conditions which satisfy the prescribed conditions are output as a guidance. It makes easy to evaluate the whole steel mill operation, and contributes to the reduction of cost and carbon dioxide emissions.

1. Introduction

In JFE Steel, operation plans are decided considering various factors such as the content of orders, manufacturing costs and carbon dioxide (CO_2) emissions. For example, production plans are determined considering the maintenance plan and the individual circumstances of each division such as iron making, steelmaking, and rolling preconditioned on the contents of orders (items, quantity, quality, delivery dates, etc.). The detailed operation plans in each division are decided so as to optimize production costs and CO_2 emissions, while also considering raw material supply-and-demand plans and supply-and-demand plans for utilities such as gas, electric power and steam.

The manufacturing cost of a steel works consists of raw material costs, utility costs, supply costs, outsourcing costs, labor costs, etc. While supply costs, outsourcing costs and labor costs generally do not affect other departments, raw material costs and utility costs have mutual effects across departments. In addition, CO_2 emissions strongly depend on the supply-and-demand situation and operation of the carbon materials mainly used as reducing agents and utilities. Therefore, optimization of production costs and CO_2 emissions requires close cooperation between the ironmaking division and steelmaking division, which use large amounts of raw material and utilities, and the energy division, which is responsible for utility supply and demand and operation. Moreover, optimization not by individual divisions, but in the steel works as a whole is necessary.

In JFE Steel East Japan Works (Keihin), an operation strategy model for optimizing the blast furnace process and the energy division was constructed as the first step of an operation plan formulation model across divisions. This paper mainly describes the contents of the operation strategy model constructed in this project, and presents a case study of operation strategy formulation utilizing the newly-developed model.

2. Summary of Steel Works Operation Strategy Model

2.1 Blast Furnace Process

In the blast furnace, molten hot metal (pig iron) is obtained by alternately charging coke and iron ore from the top of the furnace, blowing hot blast into the furnace from the tuyeres in the lower furnace, and reducing the iron ore by the reducing gas generated by the reaction of the carbon in the reductant and hot blast in the blast furnace tuyere zone. In addition to coke, inexpensive pulverized coal is widely used as a reductant, and it is known that a higher ratio of pulverized coal to the total reductant is advantageous in terms of the production cost.[1)]

In addition to the above-mentioned hot blast, the main utilities used by a blast furnace also include the fuel gas for the hot stoves (facilities used to obtain hot blast for the blast furnace by heating air to about 1 200°C), added steam used to adjust the moisture content of the hot blast, enriched oxygen used to adjust the oxygen concentration of the hot blast, fuel gas for pulverizing and drying pulverized coal, etc.

† Originally published in *JFE GIHO* No. 53 (Feb. 2024), p. 30−33

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The reducing gas generated in the tuyere zone reduces the iron ore in the process of rising through the furnace and is discharged from the furnace top. Generally, the reducing components (carbon monoxide and hydrogen) in the reducing gas are not completely consumed in the furnace, and these combustible components are discharged in the residual state. Therefore, the exhaust gas from the furnace top (called blast furnace gas; BFG) is collected for reuse in the steel works as a combustible fuel gas. Since BFG has a pressure of several 100 kPa even at the top of the furnace, electric power is also generated by a top-pressure recovery turbine (TRT).[2)]

The basic unit of the utilities used or recovered and the basic unit of the reducing agent (called the reducing agent ratio; RAR) are closely interrelated. For example, as the RAR increases, the amount of oxygen required to react with carbon also increases, and the hot blast unit tends to increase. As a result, unit consumption of hot stove fuel gas and added steam for humidity control also increases. At this time, the amount of reducing gas generated in the tuyere zone increases, and the basic units of BFG recovery and top-pressure power generation also tend to increase.

2.2 Energy Division

In the energy division of a steel works, supply and demand of each utility type are managed in order to support stable production in each production division. In addition to the above-mentioned BFG, coke oven gas (COG) is produced by the coke production process, and converter gas is produced by the steelmaking (hot metal refining) process. These by-product gases are mainly used as fuel gases in the steel works. East Japan Works (Keihin) has a private power generation facility which utilizes surplus by-product gases as fuels for generation of electric power, corresponding to electric power demand and steam demand in the works.

Thus, there is a close relationship between the supply and demand of gases, electric power and steam, but when any of these utilities are in an under- or over-supply condition, it is necessary to purchase or sell energy outside the steel works. For example, when electric power demand cannot be satisfied due to a shortage of BFG, city gas and heavy oil are purchased as fuels for the private power generation facility, or the electric power is purchased from the electric power company. Conversely, when a surplus of BFG exists and private power generation exceeds power demand, sale of that power becomes an option. Actual decisions in this regard are determined considering outside energy purchase and sale contracts, as well as costs and CO_2 emissions.

2.3 Necessity of Overall Evaluation of Steel Works

As described above, blast furnace operation has a considerable influence on utility supply and demand, which is managed by the energy division. Therefore, the results of an evaluation of costs and CO_2 emissions for the blast furnace alone and the results of an evaluation that also considers the energy division are different. **Figure 1** shows the cost evaluation results when the six different actions I to VI in **Table 1** are taken from certain operational parameters of the blast furnace. Here, “action” refers to a combination of a heat increasing operation and a heat reducing operation equivalent to a coke ratio of 2 kg/t (coke consumption per ton of hot metal production). An action causes a change in the energy balance and mass balance outside the furnace, while the heat balance inside the blast furnace is kept equal. The vertical axis in Fig. 1 represents the indexed evaluation cost. The evaluation cost was calculated as the difference in the production cost before and after taking the action, and the cost merit index was determined by defining the evaluation cost of the blast furnace process of action VI as 1. The bar graphs in the figure show the cost merit indexes for the blast furnace and energy divisions, respectively, and the line graph shows the combined (total) cost merit index for the two. Action VI is the optimum for the blast furnace alone, whereas the action V is the optimum for a total evaluation that also considers the energy division.

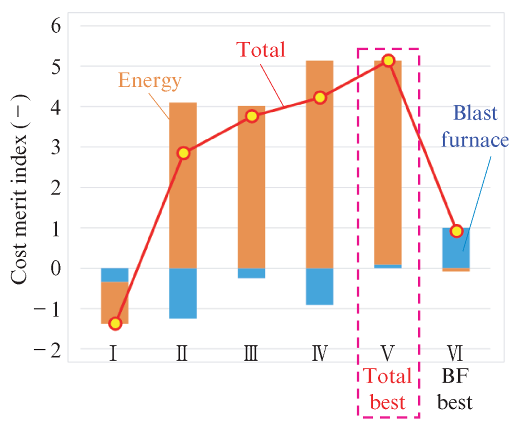

Fig. 1 Cost evaluation example

Table 1 Operational action in blast furnace (Fig. 1)

Action no.	Heating operation	Reducting operation
I	Coke ratio	Pulverized coal ratio
II	Coke ratio	Blast moisture
III	Coke ratio	Blast temperature
IV	Pulverized coal ratio	Blast moisture
V	Pulverized coal ratio	Blast temperature
VI	Blast moisture	Blast temperature

Moreover, even when the evaluation for the blast furnace is negative, there are multiple cases of a large positive evaluation for the energy division, which results in a positive total evaluation. Therefore, when formulating divisional operation plans, it is desirable to evaluate not only the individual divisions in isolation, but also the steel works as a whole.

2.4 Steel Works Operation Strategy Model

The Steel Works Operation Strategy Model is a tool that makes it possible to evaluate costs and CO_2 emissions in the entire steel works across divisions. **Figure 2** shows an outline of the strategy model. The main operational parameters of the blast furnace are set as explanatory variables, the total cost or CO_2 emission is set as the objective function, and a combination of explanatory variables under which the objective function satisfies the prescribed condition is output as the recommended operational parameters. The amounts of utilities transferred between the blast furnace process and the energy division are calculated based on the existing blast furnace model and hot stove model[3], but a data science method is applied to compensate for discrepancies between the theoretical value and the actual value, which often occur. Furthermore, when the supply-and-demand balance of each utility is changed corresponding to changes in the explanatory variable, rebalancing becomes necessary in the energy division, for example, by adjusting the amounts of in-house power generation and energy trading with outside. Therefore, a rebalancing logic for the supply and demand of utilities was incorporated in this model in advance. When multiple logics are assumed, it is possible to show the superiority or inferiority of the logics by calculating each assumed case in parallel and evaluating each objective function.

Figure 3 shows the calculation flow of the strategy model. When the production plan of each department of the steel works is input as a calculation premise, the standard operation parameters corresponding to hot metal production are automatically displayed in the blast furnace process. Similarly, in the energy division, the amount of crude steel production, the amount of hot metal, the standard supply and demand corresponding to the rolling operation schedule and the amount of private power generation are automatically displayed. These standard operating conditions are called the “base” situation. Next, the objective function is automatically evaluated according to the logic when the main blast furnace parameters, which are explanatory variables, are changed (the changed operation state is called a “case” situation). The search range of the explanatory variable is set by the user as the upper and lower limits of the action amount and the step

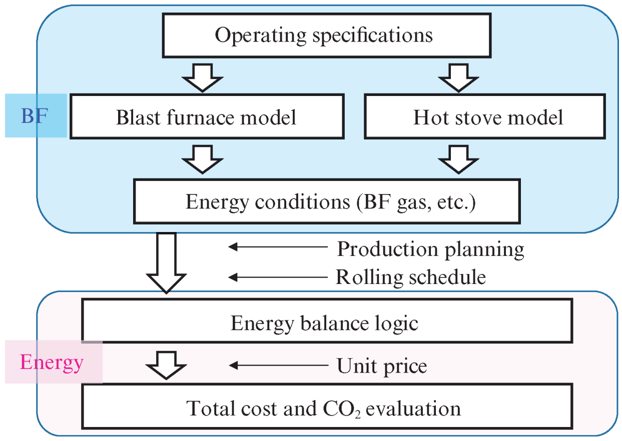

Fig. 2 Overview of strategy model

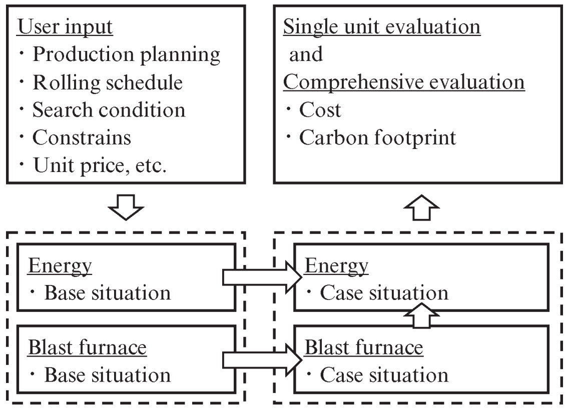

Fig. 3 Calculation flow

value. Thus, the evaluation of the objective function in this model is a relative evaluation comparing the “base” and “case” situations. The use of a relative evaluation makes it possible to calculate results in a short time by limiting the calculation range, and at the same time, because the change is expressed as a change from the standard state, recommended parameters that are realistic and have a high adoption rate can be obtained.

3. Implemented System

3.1 Overall Configuration

The system implemented in East Japan Works (Keihin) consists of three parts, including the operation planning part described in the previous chapter, an actual data accumulation part, and a previous day operation evaluation part. The actual data accumulation part and the previous day operation evaluation part are programmed to start at a fixed time every day and carry out processing automatically.

3.2 Actual Data Accumulation and Data Processing

In the actual data accumulation part, the actual daily and hourly data of each department are acquired by the system, and the hourly data are converted to daytime and nighttime data and stored. Here, "day" and "night" are defined by the time zones of the purchased power contract with the electric power company. For example, if the power contract (unit price of purchased power, etc.) changes after 20:00 on weekdays, "daytime" is defined as until 20:00 and "nighttime" is defined as times after that. If the same contract as that for weekday nights is applied throughout the whole day on a holiday, that day is defined as all-night (24-hour night).

Next, each type of actual data is divided and tallied according to the crude steel production quantity, hot metal quantity, rolling operation result, and the distinction of daytime and nighttime. This is necessary in order to automatically display the base state described in the previous chapter. It is possible to maintain the base state which matches the actual condition by adding new data for each division for which data are acquired on a daily basis.

Data processing is also carried out to correct the discrepancy between the theoretical value and the actual value calculated by the blast furnace model and the hot stove model. For example, the unit of BFG recovery can be predicted and calculated from the ratio of the reductants and the chemical composition of the reducing gas generated in the tuyere zone, but since accurate prediction of the reaction efficiency of the reducing gas is difficult, a discrepancy of a few percent is inevitable. However, in the energy division, this discrepancy of a few percent may make it impossible to accurately select the utility rebalancing logic. To address this problem, the discrepancy between the theoretical value and the actual value is monitored by data processing, and if necessary, the operator can pass the utility data to the energy division in the form of a corrected theoretical value.

3.3 Evaluation of Previous Day's Operation and Visualization of Optimum Operation

The previous day operation evaluation function is automatically executed following actual data accumulation. In this part, the optimal combination of explanatory variables, the difference of the total cost and the amount of CO_2 emissions are output in the same way as in the operation planning part, based on the previous day's actual blast furnace operation parameters and utility supply and demand. Because the optimum parameters are output together with the daily actual parameters, the operator can grasp the direction of the optimum operation, and can make adjustments in the daily detailed operation policy.

3.4 Formulation of Operation Strategy

Unlike the other parts, the operation planning part is started by the user at an arbitrary timing when necessary. Because of the characteristics of the blast furnace process, large and frequent changes in the operation policy are not desirable. Therefore, it is usually assumed that this function will be used about 1 to 3 times a month, for example, when preparing a monthly production plan, when the plan is revised during the month, or when a major process suddenly stops. For other fine adjustments of the operation plan, the optimum parameters accumulated in the previous day operation evaluation function are referenced.

Here, it should be noted that the final decision of the operation policy in the blast furnace division takes into consideration various factors such as furnace gas permeability, the balance of impurity elements such as alkali and zinc, the temperatures of the blast furnace main body and ancillary equipment, the condition of pressure control, etc., which are indispensable for maintaining the production plan, in addition to the production cost and CO_2 emissions considered in the operation strategy model. It is not possible to incorporate all these factors into the model because it would be difficult to guarantee a realistic calculation time and calculation accuracy. Therefore, the optimal parameters output from the viewpoint of cost, etc. by this model are only one candidate for the operation policy decision. Considering this, the implemented system outputs 20 sets of recommended parameters which can be said to be superior from the viewpoint of cost or CO_2 emissions or both. This broadens the range of decision-making options, and leads to an increase in the adoption rate of the output results.

A case study of experimental operation under different assumptions was conducted. The cost benefits of taking six different actions in the blast furnace process from a certain base state under six different assumptions were evaluated. The preconditions of the calculation are shown in **Table 2**, the contents of the operational actions in the blast furnace process are shown in **Table 3**, and the calculation results are shown in **Table 4**. The rolling operation plan in Table 2 shows the operation or non-operation of major mills. Due to the large power demand in the rolling process, this process has a large effect on power supply and demand. The concept of optimum operation changes depending on the combination of the unit price of coke and crude oil market conditions. For example, when coke is cheap and the price of crude oil is high, it is often optimal to

Table 2 Case study condition

	Prerequisites			
	Rolling schedule	Coke unit price	Oil market conditions	Tapping amount
Case1	Operation	Usually	Usually	Usually
Case2	Operation	Usually	Usually	High
Case3	Unattended	Usually	Usually	High
Case4	Unattended	Usually	Usually	Usually
Case5	Unattended	Usually	Soaring	Usually
Case6	Unattended	Soaring	Soaring	Usually

Table 3 Operational action in blast furnace

Action no.	Heating operation	Reducting operation
1	Pulverized coal ratio	Coke ratio
2	Coke ratio	Blast moisture
3	Coke ratio	Blast temperature
4	Pulverized coal ratio	Blast moisture
5	Pulverized coal ratio	Blast temperature
6	Blast moisture	Blast temperature

Table 4 Case study result

	Cost merit index					
	Action1	Action2	Action3	Action4	Action5	Action6
Case1	1.0	1.8	2.5	2.8	3.3	0.5
Case2	0.8	1.5	2.5	2.3	3.3	1.0
Case3	0.5	−0.3	0.5	0.3	0.8	0.8
Case4	1.0	2.0	1.3	2.8	2.3	−0.8
Case5	0.8	2.0	1.0	3.0	1.8	−1.0
Case6	2.3	0.5	−0.5	3.0	1.8	−1.0

increase gas recovery by increasing coke use (or pulverized coal use) in the blast furnace process, and to reduce the amount of city gas and heavy oil purchased in the energy division. The six actions I to VI shown in Table 3 are combinations of heat increasing and heat reducing operations with a coke ratio of 2 kg/t in the blast furnace, and the heat balance in the blast furnace is kept constant. The cost merit index in Table 4 is an index of the evaluated cost merit, and the valuation of Action I in Condition 1 is defined as 1. In Table 4, the first and second positions of the cost merit index for each condition are highlighted. It can be understood that the first-ranked actions are limited to IV and V, but the first-ranked and second-ranked combinations are different for all six preconditions. As mentioned earlier, it is not always possible to adopt the first action because the decision of the blast furnace operation policy is made considering not only the cost aspect, but also various other factors. However, since this model can easily predict and calculate the cost evaluation, etc., as shown here, it can assist in smooth reformulation of operation plans by recalculating the conditions for optimization of the total steel works in a timely manner, even if the preconditions change.

4. Conclusion

As described above, the newly-developed Steel Works Operation Strategy Model makes it easy to formulate the optimum operation strategy for the total steel works across departments. In the future, the operation strategy model will not be limited only to East Japan Works (Keihin), but will also be deployed at other steel works. The construction of a more advanced and practical strategic model which also incorporates the coke division, steelmaking division, etc. is also planned.

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