

Development of Fuel Supply and Demand Planning Simulator at Kobe Power Plant

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Abstract

This study focuses on the logistics planning of fuel for thermal-power generation from its unloading to being supplied for boilers. A new concept simulation system has been developed and implemented, which utilizes both logistics models and human judgment bidirectionally. This system utilizes diverse historical and planned information such as ship allocation, silo inventory, power generation, fuel composition, and process data. Its core is a simulator that calculates the logistics of storage from ships to silos, transportation from silos to boilers, and circulation among silos in a time series manner. Additionally, this system can incorporate human judgment in switching logistics during simulation. Furthermore, it is possible to backtrack to any chosen point in time after execution and modify or add judgments for switching, enabling re-simulation. These capabilities allow for the seamless incorporation of irregular operations that are difficult to model, while basing logistics planning on standard conditions derived from data and models.

Introduction

Following the 1995 amendment to the Electricity Business Act, Kobe Steel built a coal-fired power plant to make maximum use of our existing infrastructure and in-house power generation expertise in the ironmaking business. The plant has two 700,000 kW power generation units. Unit 1 began operation in April 2002, and Unit 2 in April 2004.

Following the suspension of upstream operations at Kobe Works in 2017, we constructed a power plant with two 650,000 kW units on the former site of a blast furnace - Unit 3 began commercial operation in February 2022, and Unit 4 in February 2023.

During capital expenditure planning for Units 3 and 4, we recognized that our procurement of coal, the fuel for power generation, would nearly double. We leveraged our knowledge in ironmaking logistics¹⁾ to develop a simulator²⁾ designed specifically for power plant coal logistics. We used the simulator to study coal carrier configurations and the number of additional coal storage silos required.

Maintaining our manual supply and demand

planning process, which requires in-depth experience, would be challenging because of the increase in complexity of logistics between the loading port and the berths, silos, and boilers in the power plant.

This challenge drove us to leverage our experience using simulators for production planning and similar operations.^{3), 4)} Using the simulator for Units 3 and 4 capital expenditure planning as a foundation, we developed a support system for coal logistics supply and demand planning on the scale of several days to months.

This system supports supply and demand planning given the increased coal volume and complexity in coal logistics following the introduction of Units 3 and 4. Its output is implemented directly into live operations, including for irregular conditions.

As such, we focused on not only the accuracy of the simulator's logic, but also on linking it seamlessly and efficiently with human judgment.

This paper describes the configuration and features of the simulation system developed to address these issues.

1. Overview of target processes and operations

1.1 Power plant coal logistics

Fig. 1 shows an overview of the logistics at Kobe Power Plant. Coal for power generation comes from Australia, Indonesia, and other foreign countries by

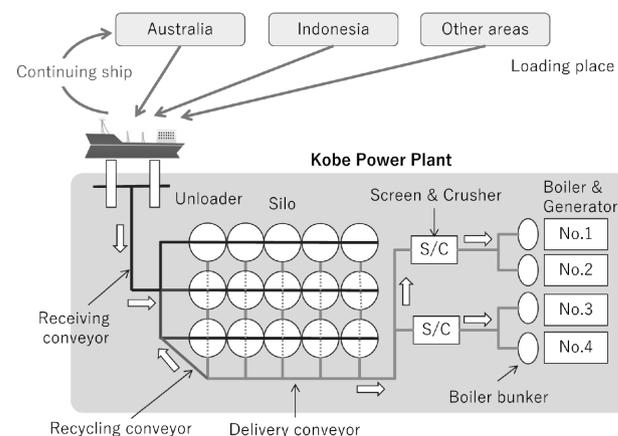


Fig. 1 Outline of Kobe Power Plant logistics

ships with capacities in the tens of thousands of tons. Unloaders at the plant's dedicated wharf unload the coal for storage in 15 silos with an approximate capacity of 30,000 tons.

Because coal composition varies by place of origin and because different brands are procured, each incoming lot is allocated to a designated silo. Four steam turbines are each connected directly to a generator, each of which has a boiler to supply steam. Coal from the silos is pulverized and prepared in the screens and crushers, sent to the bunkers upstream of the four boilers, and then fed into the boilers. Coal transport handling downstream of the unloader is performed by a conveyor. All unloaders and conveyors are sealed for environmental health and safety.

The flow described to this point represents the basic transport path; described next are the logistical factors of coal for power generation.

- (1) It is common practice to mix coal brands with different compositions to satisfy various parameters such as combustibility in the boiler, the control of soot after combustion, and the quality assurance of by-products such as ash and gypsum (for reuse as raw materials, e.g., in cement). This practice, called "coal mixing," involves adjusting ratios adjusted based on operating conditions and brands.
- (2) Exposure to air activates some of the coal while in storage, generating heat. Coal can ignite if stored for a long time, so it is moved to another empty silo depending on the gas concentration inside the silo, the temperature of the stored coal, how long the coal has been stored, and brand-specific heat generation characteristics. This practice, called "recycling," interferes with regular coal logistics because it uses the same conveyors and pathways.
- (3) Long-term coal storage is undesirable from the perspective of disaster prevention, as described above. Additionally, sufficient coal storage capacity is a challenge due to space constraints at urban power plants. Therefore, it is not at all implausible to have no silos available for unloading, creating delays for coal carriers (demurrage and detention).

1.2 Supply and demand planning operations

Coal supply and demand planning in a power plant involves determining the rate and route of coal transport from unloading to storage and to the boiler, as described above. An appropriate route must be selected from the many possibilities based on silo inventory and the status of coal carriers.

Transport rates depend on coal consumption at the boiler (i.e., the end of the route) as well as the capacities of the equipment and conveyors. Therefore, the key to coal supply and demand planning is to set the routes based on a timeline, which can be thought of as a task of deciding when and how to switch logistics operations. Detailed below are the three logistics switching functions.

- (1) Unloading: Decide when to start unloading and which silo to unload to based on coal carriers' voyage information and the maintenance schedules of the unloaders and conveyors.
- (2) Coal mixing: Determine brands (1 to 3 types), brand ratios (coal mix ratio), and silos based on the power generation schedule of each boiler. Switching to coal mixing usually occurs when the silo is emptied.
- (3) Recycling: The start time of coal transfer, supplying silo, and empty receiving silo are based on the number of days the coal has been stored, the temperature of the stored coal, and forecast silo availability. This process is also used to move coal to another silo in preparation for silo servicing.

Real-world coal logistics switching requires consideration of many different conditions, posing the challenges below.

- i) Recycling uses conveyors on both the receiving and delivery sides of the silos, which can interfere with unloading and with feeding coal to the boiler. Prioritizing recycling to prevent ignition could interrupt or delay unloading or restrict the routes available for feeding coal to the boilers.
- ii) There is an abundance of possibilities in coal logistics switching, each of which has spatial and temporal ripple effects; it is very difficult to accurately predict the effects of switching at the time of switching. Logistics planning hence, ultimately involves a degree of trial and error.
- iii) Supply and demand plans must be revised daily to compensate for variables unknown during planning, such as the arrival times of coal carriers, temperatures of stored coal, and equipment malfunctions. Moreover, the entire plan must be evaluated, not just a part of the plan created the previous day (see the logistics propagation in reference ii).
- iv) While there are standard logistics switching rules and constraints, circumstances may require irregular operations that run counter to these. For example, when running trials with new brands, switching processes involving coal mixing may be performed many times before a silo is empty. As another example, when a particular coal type

must be prioritized, coal carriers may have to wait for coal carriers that arrived later to unload.

A simulation model based on parameters, rules, and logic is effective for factors through i) to iii), which are within the standard scope of logistical control (regular operation).

Factor iv), however, falls outside this scope (i.e., irregular operation) and is difficult to model logically. As such, human judgment is required. Because regular and irregular operations are temporally linked, one challenge in developing a system for supply and demand planning is to support bidirectional interaction between the simulation model and human judgment.

2. Coal logistics simulation model

2.1 Components

Fig. 2 shows the configuration of the simulation system for supply and demand planning. This system can compute coal movement in a power plant given varying conditions and assumptions by incorporating information such as historical data, plans, and constraint parameters. Below is an overview of the system's components.

-Logistics elements model:

There are three types of elements, the equipment and facilities that form the basis of logistics: buffers, equipment, and transportation. Buffers hold a volume, equipment and transportation elements have capacity in terms of the weight they can handle per unit time, and transportation elements have routes with buffers or equipment as endpoints.

-Actual data:

Actual data on silo inventory and ship allocation link the plan with actual results. Further data

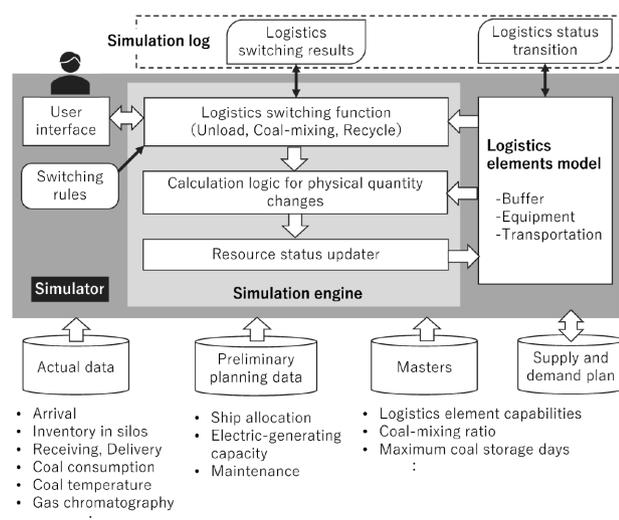


Fig. 2 System configuration

points include composition inspection information for each coal lot, which is used for coal mixing calculations, and coal storage temperature and gas chromatography data, which are used to determine when recycling should occur.

-Preliminary planning data:

Information on ship allocation, power generation, equipment maintenance, etc. is entered for preliminary supply and demand planning.

-Masters:

Parameters for standard constraints are established, including capacities of logistics components, brand combinations, and coal mixing ratios, and the maximum number of storage days per brand.

-Simulation engine:

This simulator calculates changes in the logistics status at regular intervals. It has a component that determines whether logistics switching is necessary upon each update and a component that calculates changes in physical quantities over the interval. The system has a user interface to reflect human judgment in logistics switching.

-Simulation log:

Logistics switching operations and transition times of each element's status are stored as data for the simulation process. The former is output at the time of switching and the latter at regular intervals. These are used for backward re-simulation, a feature that will be described later.

2.2 Simulator operation

This section covers the operational features of the simulator based on the simulator's operational flow shown in Fig. 3.

- Since the system operates in conjunction with updates to the time, the time updates at regular intervals (ΔT : variable), with changes in physical quantities over an interval being calculated to provide discrete updates to the quantity. The smaller the ΔT is set, the greater the resolution of calculated changes; however, this increases the calculation time, so we set it to one hour based on preliminary testing.
- The simulator decides whether to switch logistics at each point in time and calculates the change in physical quantities based on the result of the decision. There are two modes of logistics switching decisions: a mode based on the standard rules of the simulator and a mode that can reflect user judgment. The next section covers the latter.
- To reuse user decisions upon the next day's simulations or backward re-simulation, the

previous logistics switching decision is retrieved at each point in time and adopted if possible.

2.3 Verification of accuracy

Although the simulator is characterized by its ability to reflect user judgment in the simulation process, it must be able to accurately reproduce realistic logistics operations using standard simulation logic as a foundation for supply and

demand planning. Therefore, we compared historical logistics results with the simulator's logistics calculations, with the conditions below set for the simulator.

- Ship allocation information: coal brands, weights, and port arrival times of coal carriers
- Inventory information: brands and inventories in each silo on the first day
- Coal demand: coal consumption per boiler per day
- Number of coal storage days: coal storage days of each silo as of the first day

In addition, standard operating conditions were established for coal mixing and recycling rules.

Fig. 4 shows a comparison between the actual and simulated change in silo inventory over three months, with the simulator being provided the parameters above.

This figure reflects the composition of the inventory when brands are classified into one of four coal types based on their characteristics. Although there are idiosyncrasies in the simulator's decisions regarding logistics switching, it clearly reproduces actual changes in the composition of the inventory over time well. The difference in the total inventory in the first month is due to unloader issues.

We also confirmed that the amount of coal transferred by recycling and the average coal carrier waiting time differed from actual results by only a few percent, leading to our decision to use this simulator as the basis for supply and demand planning.

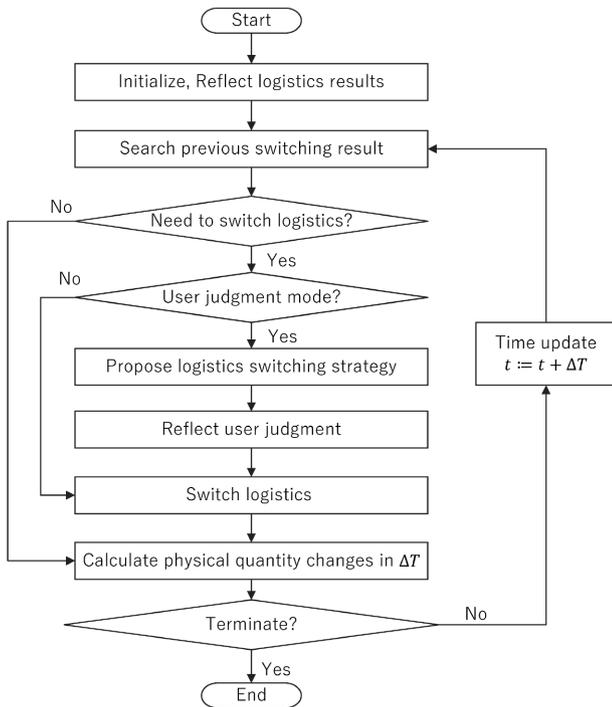


Fig. 3 Simulation flow

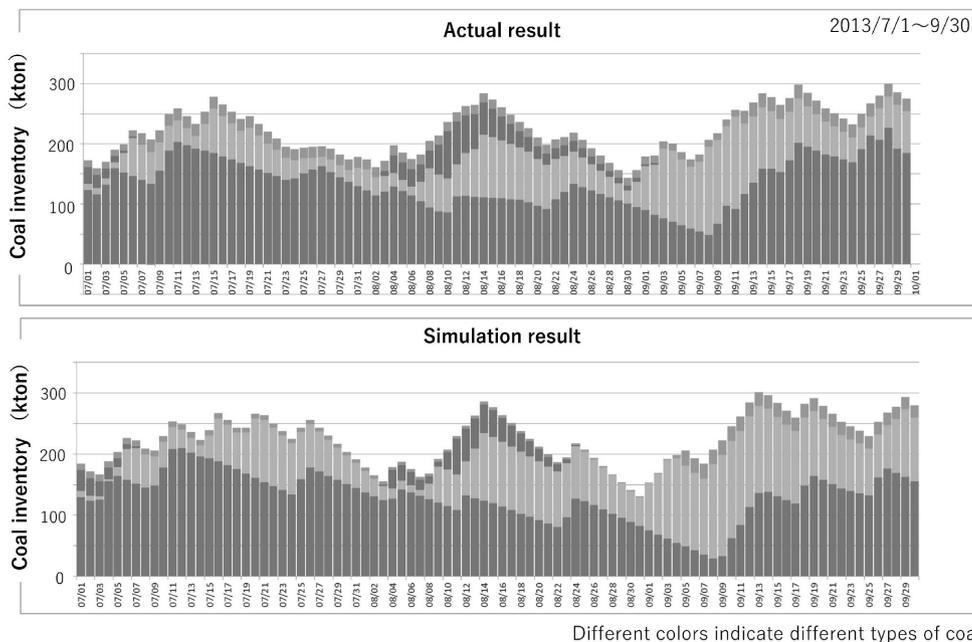


Fig. 4 Comparison between simulation results and actual results (changes in coal inventory)

3. Linking human judgment

3.1 Interactive execution mode

As described above, this simulation system features the ability to reflect user judgment in terms of logistics switching in the simulation process. An execution mode enables the user to override a decision the simulator makes based on standard rules, add a new decision, or change the time of execution of a decision. The characteristics of this feature are as follows.

- When the simulator deems logistics switching necessary, it stops and presents the decision. The user can confirm or change the decision. For example, the user can change the silo used for coal mixing, the coal mixing ratio, or the silo used for recycling or unloading.
- The user can push back the simulator's suggested timing for a logistics switching operation. It might be necessary, for example, to postpone unloading to change the unloading sequence of coal carriers, or to postpone recycling in a silo that is currently being unloaded.
- By combining this feature with the backward re-simulation function (next section), the user can set a new logistics switching process for any time during the execution period after running a simulation once. For example, logistics switching can be set for a time at which it would not occur under standard rules, such as switching the coal mixture before the silo is emptied or starting recycling early.

All logistics switching decisions are saved to a decision log with timestamps that can be read and reused in the next execution. This way, the user does not have to repeatedly enter the same inputs. Additionally, the previous input can be modified to set a different logistics switching operation. **Fig. 5** shows an example of a case in which re-simulation

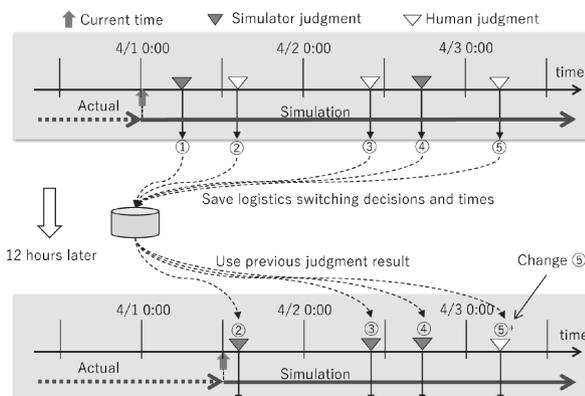


Fig. 5 Simulation using results of previous logistics switching decision

is performed using the results of an earlier logistics switching decision. The first simulation was started at 0:00 on April 1, after which five logistics switching operations were performed (numbered (1) to (5)). Three of the five switching operations ((2), (3), and (5)) were user decisions. The five logistics switching decisions and their time stamps were saved to a log.

Upon re-simulation 12 hours later (12:00 on 4/1), the previous user decisions are reflected by retrieving logistics switching decisions (2) to (5) from the log. In this example, the logistics plan changes starting on 4/3 following a modification to the original logistics switching decision number (5).

3.2 Backward re-simulation function

The simulation is run and modified (logistics switching modifications) several times to arrive at a more suitable supply and demand plan. As mentioned in the previous section, a requirement for this process is the ability to revert the simulation status to that of any given time and add or change logistics switching decisions. One method for returning to any given time is to reverse the logistics operation log and stop it at a specified time⁵. Another is to save the logistics status (silo and bunker inventories, coal destinations, postponement decisions, etc.) at each point in time and replace the logistics status at a specified time. Both methods are impracticable. The reverse playback for the first method consumes the same amount of time as the forward simulation. In the second method, the state must be saved for every time interval, amounting to thousands to tens of thousands of data points for supply and demand planning.

Therefore, we developed a function for this system to save the logistics status at a coarse interval (e.g., daily) and perform pre-simulation from a given save time to a specified backtracking time. This function enables the system to quickly return to any specified time. **Fig. 6** depicts an example of returning to a backtracking time. In this example, the logistics status is stored every two days, and a pre-simulation of 39 hours is performed by resetting to the logistics status at 0:00 on 4/5 (the most recent save before 15:00 on 4/6). The logistics switching decision from the previous execution during this period at 12:00 on 4/5 is retrieved, making it possible to accurately reproduce the logistics status even if a user decision is made.

The simulator pauses when the scheduled time is reached. A new logistics switching decision can be set or the previous decision can be changed, making it possible to simulate different conditions from any point as many times as desired.

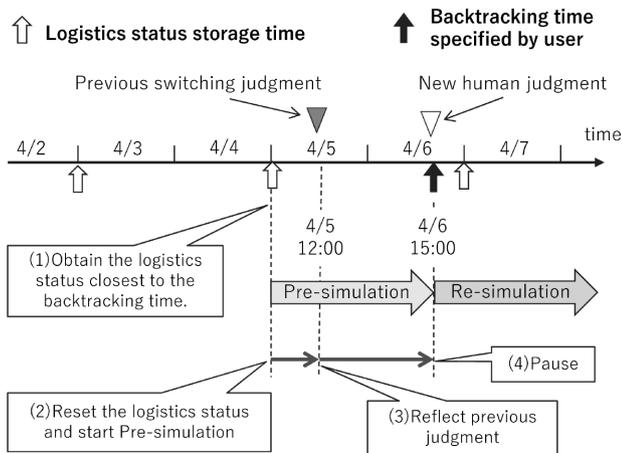


Fig. 6 Return to backtracking time and reproduction of logistics status

3.3 Execution example

We prepared data replicating actual conditions and used the backward re-simulation function described above to simulate planning operations. Figs. 7 and 8 show the resulting supply and demand planning screens, which show the daily inventory (across the table) for each silo (top to bottom). The top row shows the voyage number of the coal carrier on the start date of unloading. A-L indicates the coal brand. The numbers below each of these letters indicate the inventory in the silo in kton.

Fig. 7 shows the daily supply and demand planning screen simulated based on the rules for unloading and recycling set in the master, with only the coal mixing set by the user. In this simulation, the inventory in Silo 2 reaches the coal storage deadline at 16:00 on 11/1. Therefore, recycling was started using Silo 12, which was empty. A coal carrier (indicated by ★) arrives during the recycling process on 11/2. Because recycling has priority and the carrier cannot enter the port at night, unloading begins at 8:00 on 11/4, when the carrier can enter the port after recycling is complete.

Fig. 8 shows the supply and demand planning screen after re-simulation. To start recycling earlier, the user set the recycling of Silo 2 to occur at 0:00 on 10/31 and the simulator's decisions to occur thereafter. As a result, the coal carrier that arrived on 11/2 could start unloading on 11/2, without waiting for recycling to finish as had occurred in Fig. 7. The coal mix switching operation on 11/4 and 11/5 is the same in Figs. 7 and 8, indicating that the original logistics switching decision was reused. It would be challenging to execute a plan such as the one presented, in which the timing of logistics switching had to be moved earlier than standard, using the simulator alone. As such, the incorporation

Fig. 7 Example of supply and demand planning screen (unloading and silo inventory)

Fig. 8 Backward re-simulation example (case of starting recycling 40 hours earlier)

of human judgment and the backward re-simulation functions are critical.

4. Application to operations

We linked our simulator to power plant operating and process data, ran trials in tandem with supply and demand planning operations, and made improvements to functionality and operability. In doing so, we confirmed that the system can create plans that can be used in actual operations. Following are specific details regarding use of the system.

- For the approximately one-month period after ship allocation is almost finalized, a detailed plan that incorporates human judgment and irregular operations is created. The results are incorporated into coal logistics operating instructions, and plans are revised daily to reflect changes in operations and coal carrier movement.
- After a detailed one-month plan is developed, the simulator's automatic decision mode automatically generates a plan for the subsequent five months based on ship allocation and maintenance schedules, yielding a six-month forecast. The simulated plan is linked to the most recent plan to reflect the effects of plan modifications. The results are used to adapt ship allocation (procurement).
- The amount of ash and gypsum generated by combustion is predicted based on the coal mixing plan for each boiler, in turn based on supply and demand planning. This information is used for inventory management and to plan shipping operations for reusing these materials.

Below are some of the long-term accomplishments we achieved through this system.

- The project's initial objective was met, which was to enable supply and demand planning that accommodates the additional coal volume and additional logistical complexity associated with increasing the number of boilers from two to four.
- An accelerated planning process makes it possible to compare scenarios with different coal mixes, unloading and recycling times, etc., in turn reducing vessel delays and stabilizing operations.
- The ability to simulate changes in ship allocation enables the power plant to request ship allocation and coal procurement changes at an early stage, thereby reducing operational risk by stabilizing inventories.
- Planning know-how that has been hidden in the minds of skilled employees can be visualized and shared, expanding the pool of experts capable of supply and demand planning.

Conclusions

Kobe Steel has applied its simulation technology to numerous in-house manufacturing and logistics processes. Application has been especially strong in the materials business (e.g., steel and nonferrous metals), which is responsible for an increasingly wide variety of products, to enhance and expand the simulation models' functionality and expressive power. These systems were offline, operating

independently from actual operations. In tasks such as comparing production patterns or researching capacities to support capital expenditure decisions for equipment or logistics, results were not reflected directly in live operations. Therefore, a certain degree of inaccuracy was acceptable. However, if this simulator is connected directly to live operations, a level of accuracy that can faithfully reproduce actual operations would clearly be necessary. Real-world operations, however, are always subject to anomalies involving information a simulator cannot be cognizant of. We achieved a level of accuracy sufficient for connection to live operation by developing a new guiding model based on data- and logic-driven simulation technology that incorporates human judgment at logistics switching points.

Continued, reliable use in day-to-day operations requires a mechanism to continually update master settings to reflect changes in coal procurement and operating methods. This can be achieved by detecting inconsistencies between actual data and master settings and issuing alarms. Another opportunity for improvement is a more intuitive user interface for enhanced operability. In support of comprehensive coal logistics, we will link supply and demand planning at the power plant with ship allocation planning in the coal procurement department to achieve integrated supply and demand planning for power generation from the loading area to the boilers.

The simulator's distinctive technologies, such as interactive execution mode and backward re-simulation can be applied broadly not only to power plant logistics but also to simulations of production and transport operations even outside of the factory. We intend to solve a wide range of logistical challenges throughout our group using this technology.

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