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Technical Report

Production Planning and Scheduling Technology for Steel Manufacturing Process

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Abstract

The steel manufacturing process is a V-type production process that separates products from natural raw materials so as to satisfy product quality and delivery times of each order while orienting large lot variety of small lot orders, making large lots from each process. Because of the large-scale and complicated production process, the burden of production planning and scheduling work is high, and support needs by system technology are strong. In this paper, we describe the development status and future prospects of optimization algorithms to support decision making in our production planning and scheduling tasks.

1. Introduction

In steel manufacturing processes, various types of steel products are manufactured from iron ore, coal, and other raw materials imported from overseas based on requests by customers in various industries (e.g., automobiles, shipbuilding, bridges, and home appliances) through processes from blast furnace to converter, continuous casting, rolling, annealing, and surface treatment. The production pattern is V-type (branching) flow shop. Product specifications include various requirements based on the application of products such as quality of materials (e.g., strength and toughness), grades of the inside and surface of slabs, and size (e.g., thickness and width). Specifications range in number from several thousands to tens of thousands although this varies depending on the product type. In addition, their manufacturing conditions consist of a combination of various factors such as molten steel components, rolling size, annealing temperature, and plating type. The variety of manufacturing conditions is equivalent to that of product specifications.

Production planning and scheduling determine processing timing and sequence in each manufacturing process for each order while manufacturing conditions and delivery date in each process are satisfied. Comprehensive judgment in consideration of quality, costs, delivery dates, and other various performance indexes is required. In the steel manufacturing processes, in particular, large lot production in which products with the same manufacturing conditions are continuously manufactured is advantageous from the aspects of quality and costs (including profitability) and thereby such production has been targeted. However, as explained above, conditions for manufacturing products vary from process to process and delivery dates are also different. Therefore, it is difficult to plan a single production schedule throughout all manufacturing processes while balancing the quality, costs, and delivery dates, so such work depends on the expertise of experienced workers.

Meanwhile, technologies for supporting production planning and scheduling from the aspect of systems are being increasingly demanded because one generation of experienced planners has been giving way to another recently, manufacturing conditions are becoming more difficult due to a shift to high-grade steel, and workloads need to be reduced toward work-style reform. In addition, regarding computer technologies, in addition to the enhanced performance of computers themselves, various algorithms represented by mathematical optimization solvers have been advanced and they have enabled support by systems in domains for which practical use used to be difficult.

Against such a background, Nippon Steel & Sumitomo Metal Corporation has been developing technologies for supporting production planning and scheduling in various manufacturing processes such as raw materials, steelmaking, hot rolling, and logistics. Chapter 2 introduces cases in which Nippon Steel & Sumitomo Metal worked to optimize production and logistics simultaneously from raw material transportation to their physical logistics schedules at steelworks. Chapter 3 introduces the development of a scheduler considering the balance between productivity and cost (temperature)

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targeted at steel mills. Chapter 4 shows a case in which an explicit solution technique in mathematical programming was applied to a problem involving complicated manufacturing conditions (constraints) targeted at hot rolling mills.

Recently, support for planning production schedules throughout multiple manufacturing processes is highly desirable in addition to schedules of individual manufacturing processes. As explained above, production lot conditions vary from manufacturing process to process, so increasing the size of individual lots in each manufacturing process hinders the synchronization of the production timing between upstream and downstream processes, which increases workpieces and varies production periods. Chapter 5 introduces a technology for estimating standard production periods throughout multiple manufacturing processes highly accurately by machine learning targeted at steel plate mills. Chapter 6 introduces a technology in which such standard production periods are used to support planning weekly schedules for manufacturing steel plates in consideration of the balance between larger lot size at steel mills and levelling of loads in the refining process that follows the rolling process while aiming at starting just-in-time production according to delivery dates.

To regulate production and logistics throughout manufacturing processes, logistics between manufacturing processes needs to be regulated in addition to that in mills. Chapter 7 introduces the development of a discrete event simulator that is a base for estimating and controlling logistics. Chapter 8 introduces a case in which a mathematical optimization technique was applied to the instruction of logistics of slabs (half-finished goods) between steel mills and hot rolling mills.

Meanwhile, there are cases, depending on application targets, in which all conditions cannot be modelled on a computer and in which the presentation of grounds for planned schedules that is difficult for computers to achieve is required. Section 2.2 and Chapter 9 introduce the development of a human cooperative scheduler as a solution for such problems that are often seen in steel production planning and scheduling involving complicated work adjustment.

2. Simultaneous Optimization of Production and Distribution for Raw Materials

The quantity of iron ore and coal (raw materials) consumed by the entire Japanese steel industry per year is several hundreds of million tons. Coal baked in a large furnace called a coke oven turns to coke. Coke is put into a blast furnace with iron ore; they are melted at high temperatures and they chemically react. Through such processes, iron oxide contained in the iron ore is reduced by coke and it turns to iron containing carbon of slightly less than 5% (pig iron). This pig iron is processed by adjusting the components in various ways to make end products, such as sheets, plates, and billets.[1] As explained above, the steel industry handles large quantities of raw materials, pig iron, half-finished goods, and products, so an enormous quantity of goods is distributed every day and the logistics cost is very high.[2] Therefore, in addition to regulating the logistics of goods to stabilize operation and reduce costs, adjusting the components of slabs is essential to satisfy customer requirements and maintain the high quality of products. To achieve these, planning schedules for transporting raw materials and planning production and logistics schedules in manufacturing processes are important.

Against such a background, Nippon Steel & Sumitomo Metal has been working to optimize production and logistics for raw materials simultaneously aiming at streamlining and advancing the production and logistics related to raw materials throughout the company. Specific optimization targets are assigned to the Head Office and steelworks at each region (**Fig. 1**). The Head Office determines the outline of annual and termly schedules for multiple steelworks in consideration of advantages for the entire company. Steelworks plan daily schedules based on such schedules determined by the Head Office so that they can carry out daily operations within the outline. Specifically, the Head Office plans the following schedules: (1) Ship chartering schedules to secure ships to transport raw materials considering the tapping quantity (outputs of pig iron) and outputs of coke at the entire company, (2) ship load-schedules to determine which ships are assigned to which loading place (mine and coal mine) considering purchased quantity, (3) ship unloaded- schedules to determine which ship that took in raw materials at a loading place is assigned to which steelworks, and (4) blending schedules of raw materials to determine the ratio of raw materials to be used considering the transported raw materials and tapping quantity and coke outputs.

On the other hand, steelworks determine the following schedules based on the schedules for ships and blending raw materials determined by the Head Office such that they can carry out daily opera-

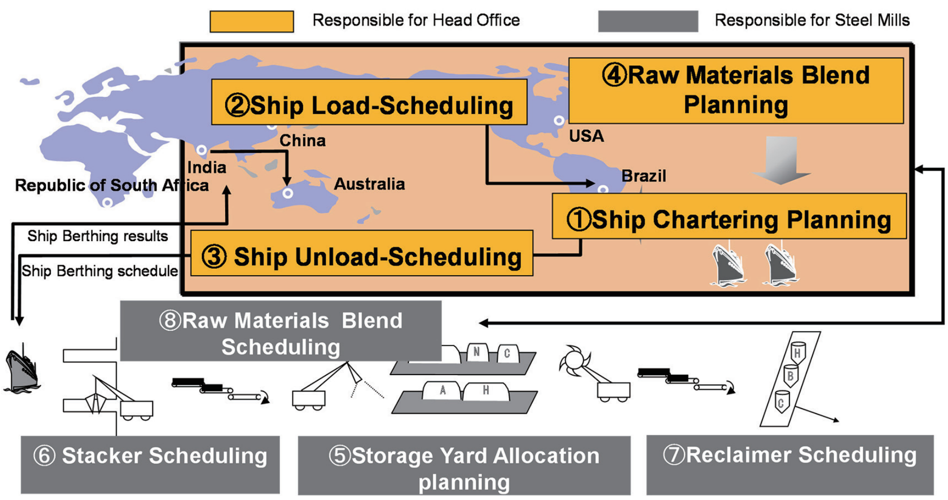

Fig. 1 Target of planning, scheduling and logistics related to raw material

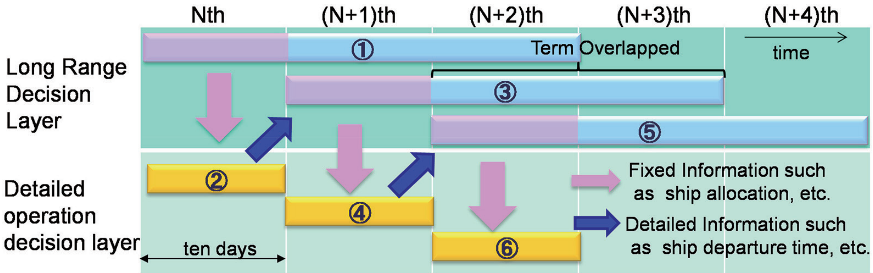

Fig. 2 Overview of the hierarchical dividing term and moving horizon algorithm[4)]

tions: (5) Storage yard allocation schedules to determine places to receive raw materials at yards and discharge them, (6) stacker schedules to determine the operation time of transportation systems to receive raw materials at the receiving places determined in the storage yard allocation schedules, (7) reclaimer schedules to determine the operation time of transportation systems to deliver raw materials to the discharging places determined in the storage yard allocation schedules and determine storage tanks such as silos that store discharged raw materials temporarily, and (8) blending schedules of raw materials to adjust the termly and monthly blend schedules determined by the Head Office such that they match actual daily operations. Nippon Steel & Sumitomo Metal has developed a system that allows the Head Office and steelworks to manage information on the supply and demand of raw materials in an integrated way for the targets listed above and has introduced an optimization technology for each target.[3)]

This chapter describes, as one example, the raw material transportation and ship allocation optimization system as work at the Head Office[4)] and raw material yard allocation optimization system as work at steelworks.[5)]

2.1 Raw material transportation and ship allocation optimization system

2.1.1 Details of work

In this work, schedules for chartering ships and allocating each ship to loading and unloading places are determined based on information on the allocation of signed ships (ship types, quantity, and current locations), available ships, purchased quantity under contracts, and raw materials to be used at each steelworks while constraints to secure the stock at each steelworks are met. The transportation fee varies depending on the type of ships to be signed, contract form, and port call patterns, so optimizing the configuration of ships to be chartered and transportation routes can reduce the costs.

However, ships' transportation conditions vary, for example, between China from which the transportation time to Japan is short and Brazil from which it is long. Therefore, it is difficult to optimize ship allocation schedules half a year in advance considering the movements of each ship at an unloading berth in the accuracy of one-hour units while avoiding out-of-stock at each steelworks.[6, 7)]

2.1.2 Configuration of the scheduling function

Considering factors to be combined in long-term schedules and quantity determining factors simultaneously was difficult from the aspects of calculation scale and time. In the developed system, to consider such extensive conditions, two layers are provided: One to determine a long-term broad outline and the other to optimize arrival and departure timing and other factors in detail using such determined outline as fixed information. In addition, we have developed an original technology in which the total period for each layer is divided into a time line and hierarchical time sharing where mathematical programming is linked to the simulator in each divided period is repeated. This has made it possible to obtain solutions that can be used for actual operation for problems that used to be impossible to solve (**Fig. 2**).

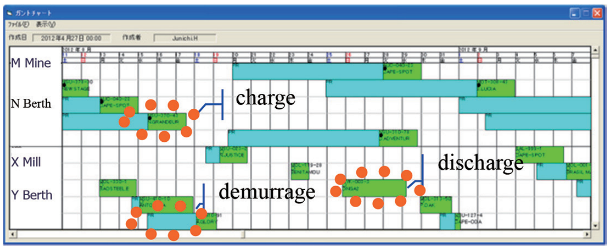

Fig. 3 Example Gantt chart of a scheduling result

2.1.3 Scheduling result

Figure 3 is a Gantt chart as an example schedule. The schedule shows that the overstays of the ships at unloading places are reduced and the entry to ports becomes smooth (demurrage at the loading places is a given condition). In addition, increase in the ratio of unloading at a single port by Cape size or larger ships reduces extra charges for unloading at multiple ports, which can reduce the total transportation cost.

2.2 Raw material yard allocation optimization system

2.2.1 Details of work

This work determines charge positions (piles) required to stack multiple types (several tens) of raw materials transported by ships at empty spaces in yards and determines discharge positions to supply raw materials in accordance with the usage schedules for blast furnaces and coke ovens along with their amounts. In these operations, 1) stacking raw materials in many small piles creates dead spaces, which reduces the yard efficiency, so the number of small piles needs to be reduced and 2) securing a large empty space in a yard in advance can reduce the time from when ships enter a port to when they depart, which can reduce the cost of the ships' waiting at anchor offshore, thus enabling efficient yard use.

However, the relationship between the length of a yard and tonnage capacity is not linear and thus it requires complicated calculation. In addition, many factors need to be considered: e.g., significant changes in the real yard capacity as a result of stacking the same brand by overlapping and securing of a space between a pile and an adjacent pile in a different brand; and constraints on storage spaces vary from brand to brand. Therefore, staff used to plan such schedules based on their experience and intuition, so planning a long-term schedule in a short period was impossible, which posed problems, for example, planning schedules looking ahead to future delivery of goods was impossible.

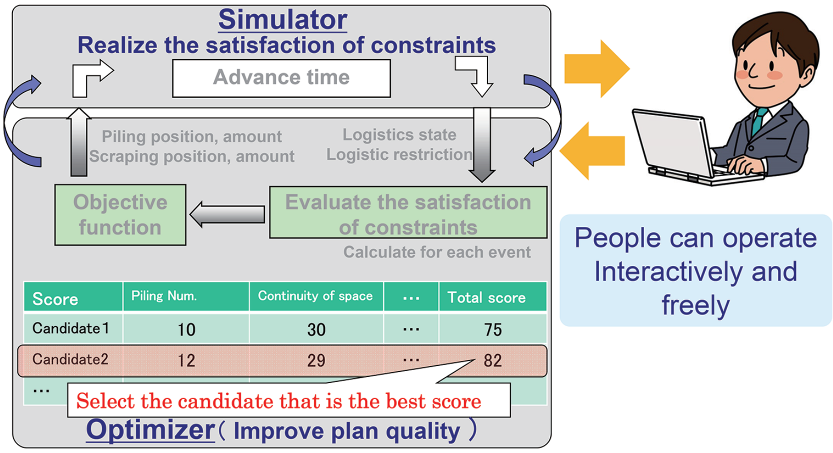

Fig. 4 Human cooperative optimization algorithm

2.2.2 Configuration of the scheduling function

When optimization technologies were applied to production and logistics schedules, planning was regarded as a mathematical programming problem and Nippon Steel & Sumitomo Metal focused on mathematical optimization technologies and technologies to use rule-based techniques, etc. for optimization, which allowed Nippon Steel & Sumitomo Metal to significantly advance such technologies. Meanwhile, it was revealed that it needed to address cases that were difficult to model into formulas and thereby that required high-level judgment by humans, and cases where know-how that had not turned to explicit knowledge was secured by experienced workers and to address gradually changing operation conditions to allow systems to be continuously used in actual operation.[8]

Therefore, this system was aimed at fully utilizing human knowledge and addressing operation flexibly by creating a scheme that cooperates with humans. Specifically, this system has enabled 1) planning an initial schedule that satisfies constraints quickly by a simulator that simulates actual operations finely and the greedy algorithm, 2) planning a schedule that satisfies constraints by allowing humans to revise schedules freely and interactively and by using such details to operate the simulator, 3) storing details that humans planned or revised one by one and allowing humans to revise each detail freely, and 4) allowing humans to revise parameters (e.g., constraints and performance) freely and storing changed details one by one to allow humans to revise each detail freely (**Fig. 4**).

2.2.3 Scheduling result

Figure 5 is a ship schedule planned using the developed raw material yard allocation optimization system. In the schedule, the ships can leave the ports earlier than the target arrival and departure time given by the Head Office, which can reduce the costs of the ships' waiting at anchor offshore.

2.3 Summary

This chapter described our work aiming at simultaneous optimization of production and logistics for raw materials. As explained above, we have developed an optimization technology that can be applied to large-scale planning problems by combining hierarchical division consisting of a long-range decision layer and detailed operation decision layer with time sharing. This technology was used to develop the raw material transportation and ship allocation optimization system that could plan schedules that were accurate enough to be used for actual operations and the results were favorable. In addition, it was found through the development that flexibly addressing changes in operation and requirements is essential for the system to be used for a long period of time. Therefore, we have developed a new scheme that cooperates with humans to support planning by providing functions for planning initial schedules, changing such schedules interactively, and storing revision history. This technology has been contributing to reduction of the costs of ships' waiting at anchor offshore.

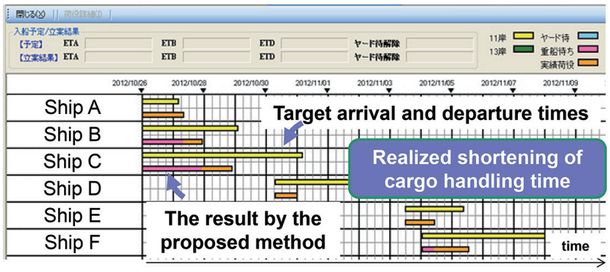

Fig. 5 Result example of ship scheduling

3. Development of a Steelmaking Scheduling Technology

In the steelmaking process, the components of molten iron supplied from a blast furnace are adjusted in a converter and secondary refining equipment manufactures slabs (half-finished goods) by a continuous-casting machine. Molten steel for which the components were adjusted in a converter is poured into a ladle (transportation container) and then transported to a continuous-casting machine through the secondary refining process. Molten steel in a single ladle is called a charge. Multiple charges to be continuously casted in a continuous-casting machine are called a cast. One characteristic in the steelmaking process is that the production target is a high-temperature liquid called molten steel. The temperature of molten steel gradually decreases as time passes. When the waiting time between manufacturing processes is too long, the molten steel in the ladle solidifies, which hinders the productivity significantly. Therefore, it is impossible to manufacture extra molten steel in advance and store it in a buffer. In the converter and secondary refining process, molten steel for which the temperature was appropriately adjusted needs to be supplied to the continuous-casting machine according to the casting timing.

In addition recently, the processing flow in the refining process has become complicated to satisfy the needs for high-quality products. Several methods have been developed as molten iron pretreatment methods using converters; such as the LD converter-optimized refining process (LD-ORP) method that achieves desiliconization and dephosphorization at the same time and a multi-refining converter (MURC) method that enables a single converter to continuously process dephosphorization and decarbonization interrupted by the discharge of dregs in between. Such methods have been applied to actual equipment.[9] The processing flow and time in the secondary refining process also differ for each steel type. Therefore, it is becoming difficult to plan a schedule in which various indexes, such as high productivity, minimum cost, and strict adherence to delivery dates, are satisfied in the entire steelmaking process while the peak of the processing load in each manufacturing process is reduced.

3.1 Problem with steelmaking scheduling

One problem with steelmaking scheduling is to determine operation schedules of converters, secondary refining, and continuous-casting machines such that the objective functions become optimum while constraints on manufacturing and logistics at steelworks are met with charge configuration of casts for the continuous-casting machines and casting sequence given. As constraints, there is a constraint on the processing flow according to which each charge moves on through the predetermined manufacturing processes successively and another one on interference that prohibits the processing time of one charge from overlapping with that of another one in a manufacturing process.

In addition to those constraints, there is also a constraint regarding the consecutive continuous casting of casts to allow multiple charges to be casted without interruption in the same cast. As representative performance indexes included in objective functions, residence time and casting completion time are used. The residence time refers to the time from when molten steel is tapped from a converter to when casting begins. The objective is to reduce the decrease in the temperature of molten steel to the extent possible to minimize the cost generated as a result of the temperature increase of molten steel. The casting completion time refers to an index indicating the productivity that is used to maximize the operation rate of a continuous-casting machine. We have developed algorithms for which mathematical optimization techniques are applied to solve the afore-mentioned problem with steelmaking scheduling.

3.2 Example of optimization of the problem with steelmaking scheduling

Planning steelmaking schedules manually took time and labor and the optimality and feasibility of operations of obtained schedules were not always satisfactory, so we have developed an algorithm based on a mathematical optimization technique.[10] All operational constraints were considered to be difficult as the calculation would take time. Therefore, the main operational constraints and performance indexes only were considered in the mathematical optimization technique and other specific constraints were described in the logistics simulator. Combining the two has enabled planning of a schedule in a few minutes that is optimum to a level equal to or higher than those planned by experienced workers. In addition, because the converter operation procedures were changed and new equipment was added, it needed to handle various factors: Increase in the number of combinations in the sequence of tapping of molten steel from a converter; the performance of cranes and other transportation systems becoming an obstacle; and increase in the number of charges to be included in schedules due to increase in the output. Therefore, we have developed another new algorithm in which constraint logic programming is combined with the technique described above.[11] The new algorithm has made it possible to model operational constraints flexibly and plan schedules within a practical time (approximately one minute for a schedule for three days) by narrowing down the range for searching for a solution during scheduling only to feasible solutions (**Fig. 6**).

Furthermore, we have developed an optimization technique in which the temperature of molten steel is considered to control its temperature appropriately during casting. As molten steel temperature control, the target temperature in each manufacturing process used to be calculated separately with the planned operation schedule as preconditions. However, the schedule needed to be readjusted because the temperature of molten steel decreased as time passed and the processing time had to be changed to secure the time required to adjust the temperature in the schedule. We have developed a simultaneous optimization model in which variation in the temperature of molten steel during transportation and processing is modelled and such variation is linked to a schedule (**Fig. 7**).[12] This technique allows the temperature of molten steel when it arrives at a continuous-casting machine to match the target temperature and an operation schedule to be calculated such that the temperature of the molten steel in each manufacturing process is within the upper and lower limits. In addition, we have been studying a robust scheduling tech-

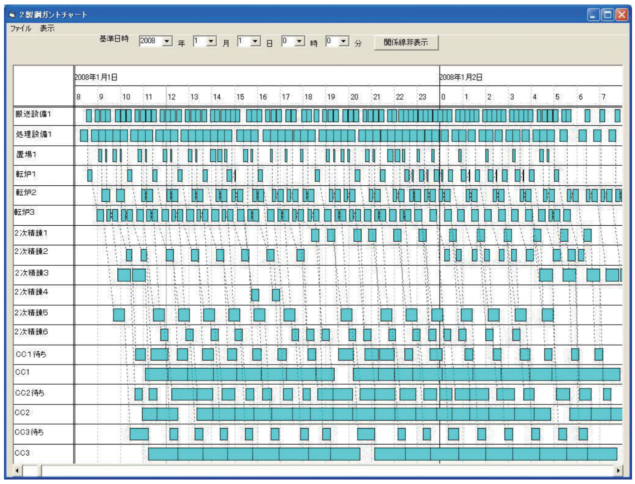

Fig. 6 Gantt chart of scheduling result[11]

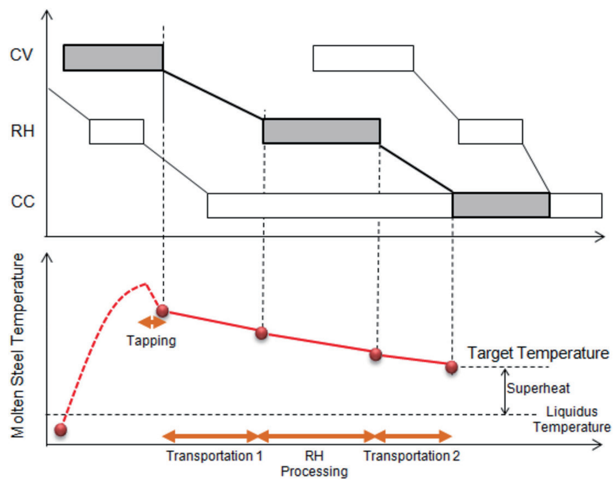

Fig. 7 Model for molten steel temperature and schedule[12]

nology that includes the appropriate temperature control time in the secondary refining process to reduce variation in the temperature of molten steel caused by changes in operational conditions in order to make casting stable.[13)]

3.3 Summary

Almost all molten iron is processed at steel mills following the blast furnace process and it is turned into sheets, plates, and other various end products, so it is an important process from all aspects of quality, cost, and delivery dates. To continue manufacturing high-quality products while keeping the productivity high by maximizing the operation rate of equipment owned, planning more accurate steelmaking schedules is required. To that end, processing and transportation conditions in steel mills need to be more specific and integrated optimization for the entire steelworks even considering production and logistics schedules for upstream and downstream processes is important. To achieve this, development of modelling technology for large-scale optimization problems and technologies for speeding up calculation is expected through the development of algorithms and parallelization.

4. Development of a Hot-rolling Scheduling Technology

4.1 Problem with hot-rolling scheduling

In the hot-rolling process (hot strip mill), usually slabs reheated in multiple heating furnaces (three or four units) are extracted one by one in accordance with the predetermined sequence of extraction furnaces and rolled by a roller. Therefore, scheduling needs to determine distribution to heating furnaces and the charging sequence for each furnace such that heating constraints are met and it needs to determine the rolling sequence appropriately such that rolling constraints are met.

As a heating constraint, there is a constraint on the heat change that the charging temperature, target extraction temperature, and heating characteristics should be at the same level between neighboring slabs (in three to five meters) in the same furnace because the furnace temperature is equally controlled for them due to the furnace's thermal inertia. As typical constraints on rolling, there is a coffin constraint that in a single rolling chance (one schedule), wider slabs should be processed first because controlling such shape is easier and then the width should be gradually reduced; and another constraint on the changes in the width and thickness that demands that differences in the thickness and width of the coils of two slabs to be rolled successively should be small and thereby the change should be smooth.

Meanwhile, for the problem with hot-rolling scheduling, several performance indexes are used to minimize the changes in temperature, width, and thickness to the extent possible, reduce the quantity of fuel consumed by heating furnaces, and enhance the productivity by shortening the total extraction time from the first extraction to the last in a schedule although they overlap with the constraints. In addition, as described later, regarding the relation with yards, the charge sequence needs to be adjusted in some cases such that the number of re-staking becomes the smallest possible with stacking conditions in yards as preconditions.

Regarding methods to solve the problem with hot-rolling scheduling using mathematical programming, some researchers have studied heuristics methods such as methods using genetic algorithms (GA)[14, 15)] and another method in which assignment problem formularization is combined with a local search[16)] because the scale of the problems is large and too many constraints need to be met. This chapter introduces solutions using the explicit solution technique.

4.2 Technology for optimizing charging and rolling sequences (extraction sequence) simaltaneously[17)]

To maintain the temperature when slabs are charged high into a hot-rolling heating furnace, hot-rolling yards usually have equipment for keeping slabs warm recently. Under such a circumstance, consideration on the charging schedule side is also required to avoid the rearrangement of piles at the time of charging into a heating furnace. This demands consideration of the charging sequence in a hot-rolling schedule for which the original requirement is to make the rolling sequence (sequence of extraction from a heating furnace) appropriate.

4.2.1 Relation between the rolling sequence (extraction sequence) and charging sequence

When the ratio of the numbers of slabs to be extracted from multiple furnaces is different, the time during which slabs stay in the high-ratio furnace is shorter than that in the low-ratio furnace. Therefore, the charging sequence is relatively late comparting to the extraction sequence. A charging event occurs when an empty space is formed on the charging side after an extraction event. Therefore, based on the relationship between the width of a slab extracted and the width of a slab to be charged, there are three charging cases after a single slab was extracted: (1) No slab can be charged (width of the extracted slab < width of the slab to be charged), (2) a single slab can be charged (width of the extracted slab ≥ width of the slab to be charged), and (3) two slabs can be charged (width of the extracted slab ≥ total width of the two slabs to be charged). The charging sequence differs depending on which case occurs. That is to say, the charging sequence depends on the rolling sequence (extraction sequence) and it can be uniquely determined, but its formularization is difficult and charging and extraction simulations are required for such determination.

4.2.2 Simultaneous optimization of charging and rolling sequences

When considering re-stacking at yards, the schedule should be determined such that slabs can be charged from the top of piles for both rolling and charging sequences to the extent possible. If the functional relation between the rolling and charging sequences can be formulated, simultaneous optimization of the rolling and charging sequences is possible using such relation as a constraint. However, as explained above, the functional relation between the rolling and charging sequences can be identified only by charging and extraction simulations. Therefore, we have determined to solve such problem by convergent calculation where the relation between the rolling and charging sequences is calculated through simulations; such relation is used as a constraint in the calculation; and these procedures are repeated until the relation between the rolling and charging sequences for the obtained solution matches the hypothesis. At this time, the determination of the rolling and charging sequences was formulated as a 0/1 integer programming problem where slabs are assigned to the charging and rolling sequences as a double assignment problem.

4.2.3 Procedures for formulating a double assignment problem of charging and extraction sequences

Decision variables:

$x_c[i][j_c]$ (charging sequence assignment variable):
0/1 variable where when slab i is charged in charging sequence j_c, it is 1, and when not, it is 0

$x_e[i][j_e]$ (rolling sequence assignment variable):
0/1 variable where when slab i is rolled in rolling sequence j_e, it is 1, and when not, it is 0

Table 1 Effect of optimization

	Load of pile (ave.)
Manual	112
Optimize	72 (−40)

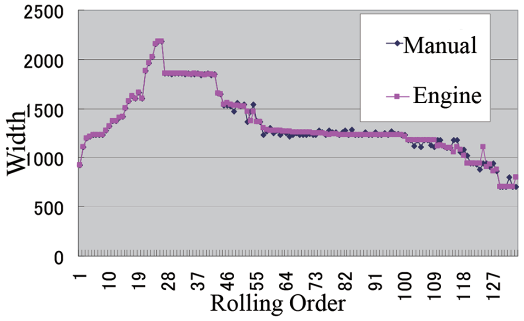

Fig. 8 Width change with rolling order[17)]

Constraint formulas:

Charging sequence constraints:

Constraint on the pile sequence at a yard and constraint on the relation between the rolling and charging sequences

Rolling sequence constraints:

Constraint on the changes in the width, thickness, and temperature, constraint on the input position, constraint on charging regulation for each furnace, etc.

Objective functions:

Objective function for the charging sequence:

Minimizing the number of pile rearrangements

Objective function for the rolling sequence:

Minimizing the amounts of the changes in the width, thickness, and temperature, minimizing fuel for a heating furnace, etc.

4.2.4 Results of the application of the technology for optimizing charging and rolling sequences (extraction sequence) simultaneously

It has been found that simultaneous optimization of the charging and rolling sequences can reduce the total number of pile rearrangements per schedule by 30% or more as shown in **Table 1** and the changes in the width and thickness do not break as a result. **Figure 8** shows example width changes.

4.3 Future prospect

This chapter described a problem with scheduling when the extraction ratio is fixed (the extraction furnace sequence is fixed). However, it is ideal to handle the extraction ratio as a variable that relies on slabs to be charged into each furnace, so such solution is expected.

In addition, schedules for charging slabs into heating furnaces and extracting them are closely related to the combustion control in the heating furnaces. Some researchers have been working on simultaneous optimization of schedules and combustion control.[18–20)] Such technologies may be realized soon thanks to the future advancement in computer technologies. Some researchers have also reported expansion to integrated scheduling of steelmaking and rolling[21)] and practical use of such technology in the future is expected.

5. Development of Technology for Designing Standard Plate Production Periods

In the steel industry where products are manufactured based on orders received, products with specifications demanded by customers should be delivered by designated delivery dates. Staff in charge of production control always monitor the progress of the production of each order so that the delivery dates can be met. The most important thing in production control is to determine an appropriate date on which the production of each order begins. The reason is that if the date is too late, the delivery date cannot be met and if it is too early, the yards and warehouses become full, which stops the manufacturing lines. However, production periods for steel products vary significantly; the production periods of product types that pass through many refining lines vary even more, in particular, so managing their production is difficult.

A standard production period refers to the standard value of production periods used to calculate the production start date. Staff in charge of production control calculate a standard production period based on the specifications of an order. They plan a rolling schedule and cast formation such that the rolling can be performed on the date and time that are calculated by deducting the standard production period from the delivery date. When there is no pile of workpieces in each manufacturing process and manufacturing processes through which products pass are known, the production period can be calculated by adding the processing time in each manufacturing process and transportation time.[22)] However, in plate manufacturing processes (as is the case with steel sheets and pipes), there is a large pile of workpieces before each manufacturing process and there are some stochastic processes (e.g., conditioning and leveler process) for which whether products should pass through the processes is determined in the middle of manufacturing (whether products pass through such processes is determined only after the production begins), so estimating production periods accurately is difficult.

This chapter describes the procedures for calculating standard production periods of plates for which estimating production periods is difficult. The next section introduces the plate production flow and conventional procedures for calculating standard production periods first. Then the newly developed procedures for calculating standard production periods using decision trees and the maximum likelihood estimation are described. Lastly, effects of the application of such procedures to actual equipment are shown.

5.1 Plate manufacturing process and conventional procedures for calculating standard production periods

Figure 9 illustrates the plate production flow. Slabs heated in reheating furnaces are rolled into a designated size at the roughing and finishing mills. Then they are water-cooled by an accelerated cooling device such that designated crystal structure is obtained and they are cooled at room temperature at a cooling bed. The processes following the cooling bed are referred to as refining processes: They are divided into normal processes (e.g., heat treatment and coating) for which whether products pass through the processes is determined based on the production specifications of an order; and stochastic processes (e.g., conditioning and leveler process) for which whether products pass through the process is determined based on the quality in the middle of the production. In Fig. 9, the processes enclosed with the solid lines are normal processes and those enclosed with the dashed lines are stochastic processes. The ultrasonic test equipment (UST) is a process having both characteristics. A production period in this paper refers to the number of days from rolling to when preparation for shipment (or certificate test) has become complete, that is to say, the period during which products remain in a plate mill.

A conventional standard production period used to be managed

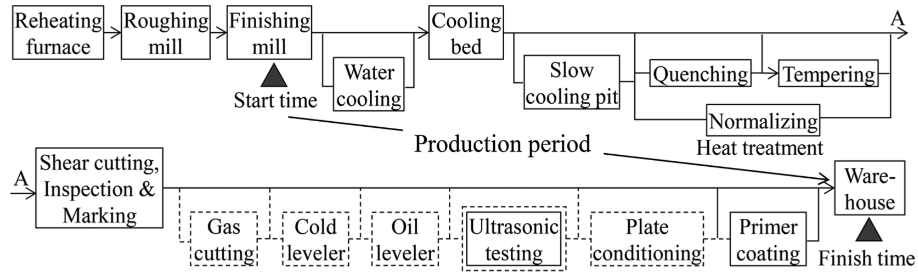

Fig. 9 Manufacturing process of steel plate (solid line: normal processes, dash line: stochastic processes)[23, 27]

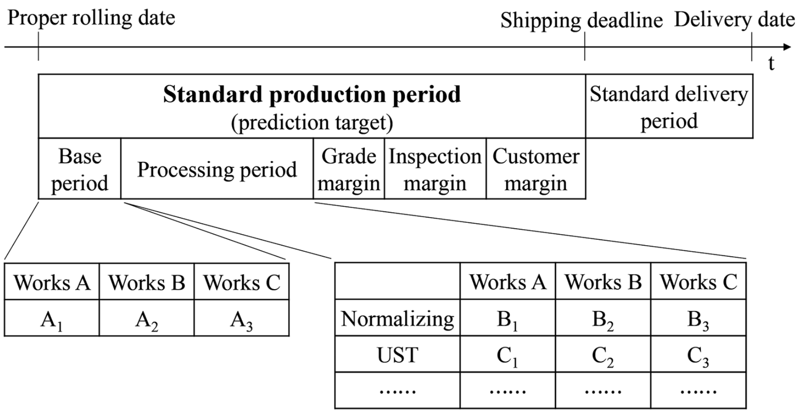

Fig. 10 Tables of old standard production period[27]

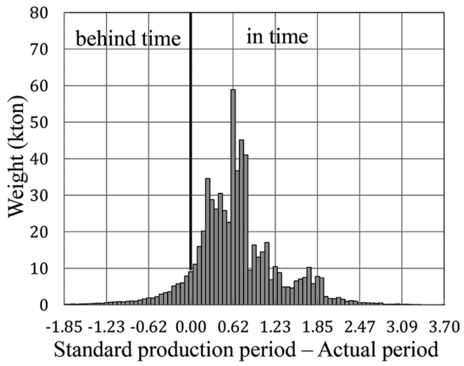

Fig. 11 Margin of old standard production period[27]

using tables as shown in **Fig. 10**. The period is broadly divided into the base period, processing period, grade margin, inspection margin, and customer margin: They are further divided into small categories. The value in each table refers to the days based on the quality specifications of the order and such values are added to obtain the standard production period. However, only normal processes for which whether products pass through can be determined based on the order specifications are included in the processing period and stochastic process periods are included in the grade margin and other margins. Therefore, the margins that are differences between the standard production periods and actual periods spread horizontally in a histogram as shown in **Fig. 11**. The proper production completion rate defined by the percentage of production completion within the standard production period (ratio of "actual period ≤ standard production period") remained at 91.5% (the periods have been normalized with reference to a certain value).

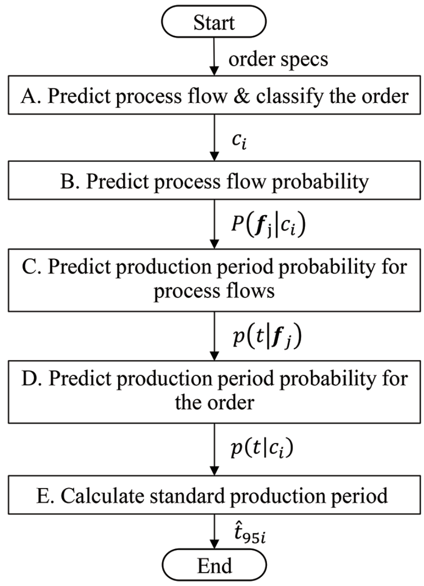

Fig. 12 Calculation algorithm of new standard production period[23]

5.2 New procedures for calculating standard production periods

Analyzing actual production periods, the production periods highly correlated with processes through which products pass (hereinafter, "transit processes"). Therefore, we devised the procedures for calculating standard production periods after estimating transit processes. **Figure 12** shows a new algorithm for calculating standard production periods.[23] Details of the processing in each step in the algorithm are explained below.

A. Determination of a production class to be manufactured

If the transit processes and production class of orders are both the same, it is considered that the probability distribution of the production periods must be the same. Decision trees[24] are used to estimate the transit processes through which the product would pass based on the production specifications of the order as shown in **Fig. 13** and 0 or 1 that indicated whether the product passes through each process is arranged in a line to form a process flow. The order class was added before the process flow as shown in Formula (1) to determine a code. This code is called production class c_i (i is the index of the production class).[25]

$$\text{Production class } (c_i) \overset{\text{def}}{=} \text{order class\_process flow} \tag{1}$$

B. Calculation of the probability distribution of the transit processes

Plates in the same production class c_i are extracted from past operation data, and the occurrence rates (empirical distribution) of actual process flow $\boldsymbol{f}_j = (f_1, f_2, \cdots, f_M)$ are calculated as shown in Formula (2). This is an occurrence probability model of production class c_i.

$$P(\boldsymbol{f}_j|c_i) = \frac{\text{Number of } c_i \;\&\; \boldsymbol{f}_j \text{ plates}}{\text{Number of } c_i \text{ plates}} \tag{2}$$

C. Calculation of the production periods for each process flow

On the assumption that when an order is manufactured in certain process flow $\boldsymbol{f}_j$, the probability distribution of the production periods can be calculated by the summation of the processing periods of the manufacturing processes through which the order has passed (including waiting time to be processed). Specifically, if the processing periods are assumed to be a normal distribution, the probability density function of the production period (t) of actual process flow $\boldsymbol{f}_j$ is expressed as Formulas (3) and (4). The average (μ_m) and variance (v_m) are calculated such that the likelihood function of actual period t_n shown as Formula (5) becomes the maximum (maximum likelihood estimation[26]). Where, $\tilde{\boldsymbol{f}}_n$ is the actual process flow of the nth plate, and $\tilde{\mu}_n$ and $\tilde{v}_n$ are the average and variance of the production period, respectively.

$$p(t|\boldsymbol{f}_j) = N(t|\tilde{\mu}_j, \tilde{v}_j) = \frac{1}{\sqrt{2\pi\tilde{v}_j}} \exp\left\{-\frac{(t-\tilde{\mu}_j)^2}{2\tilde{v}_j}\right\} \tag{3}$$

$$\begin{gathered} \tilde{\mu}_j = \boldsymbol{f}_j \boldsymbol{\mu}^{\mathrm{T}}, \quad \tilde{v}_j = \boldsymbol{f}_j \boldsymbol{v}^{\mathrm{T}} \\ \boldsymbol{\mu} = (\mu_1, \mu_2, \cdots, \mu_M) \geq 0, \quad \boldsymbol{v} = (v_1, v_2, \cdots, v_M) \geq 0 \end{gathered} \tag{4}$$

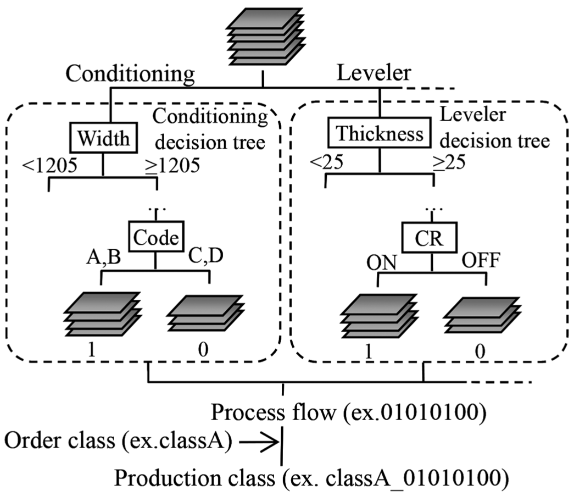

Fig. 13 Decision trees to decide production class[23, 27]

$$\begin{aligned} \mathrm{J} &= \sum_{n=1}^{N} \ln p(t_n|\tilde{\boldsymbol{f}}_n) \\ &= -\frac{1}{2}\sum_{n=1}^{N}\left[\ln(2\pi) + \ln(\tilde{v}_n) + \frac{(t_n-\tilde{\mu}_n)^2}{\tilde{v}_n}\right] \to \text{Max} \end{aligned} \tag{5}$$

N in Formula (5) is the number of plates in learning data. It is desirable to use the number of plates for half a year to one year during which all production classes are manufactured for the time. The value of N becomes several hundreds of thousands. Therefore, when Formula (5) is used as it is, the scale of the optimization problem becomes very large. However, fortunately, Formula (5) can be grouped by the process flow type and the scale of the problem is reduced to the number of the types (L) (several hundreds), which makes the calculation easy.[27]

D. Estimation of production periods for the production class

The occurrence probability model ($P(\boldsymbol{f}_j|c_i)$) of the process flow for the production class calculated in step B is combined with the probability density function ($p(t|\boldsymbol{f}_j)$) of the production periods for the process flow calculated in step C as shown in Formula (6) to calculate the production period ($p(t|c_i)$) of the production class.

$$p(t|c_i) = \sum_{j=1}^{L} p(t|\boldsymbol{f}_j, c_i)\, P(\boldsymbol{f}_j|c_i) \approx \sum_{j=1}^{L} p(t|\boldsymbol{f}_j)\, P(\boldsymbol{f}_j|c_i) \tag{6}$$

E. Calculation of the standard production period

When the cumulative distribution function of the probability density function ($p(t|c_i)$ in Formula (6) is determined as $F(t|c_i)$, standard production period $\hat{t}_{95i}$ can be calculated using Formula (7). Where, 0.95 is the designed value for the proper production completion rate.

$$\hat{t}_{95i} = F^{-1}(0.95|c_i) \tag{7}$$

5.3 Effects of new standard production periods

Standard production periods were designed using actual data on plates manufactured at a steelworks during a certain period. The margins of the standard production periods in another period are shown as a histogram in **Fig. 14**. Compared to Fig. 11, the new standard production periods were steeply distributed with a higher peak. The average of the new standard production periods was almost the same as that of the conventional production periods, but the proper production completion rate can be improved by 3.2% (91.5 → 94.7%).

Next, **Fig. 15** shows changes in actual proper production completion rates at three steelworks before and after switching from conventional standard production periods to new standard production periods. These actual proper production completion rates are not the margin of "standard production period ≥ actual period."

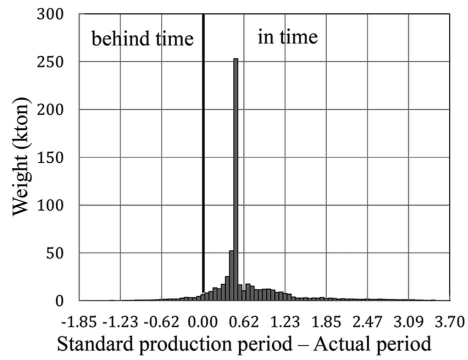

Fig. 14 Margin of new standard production period[27]

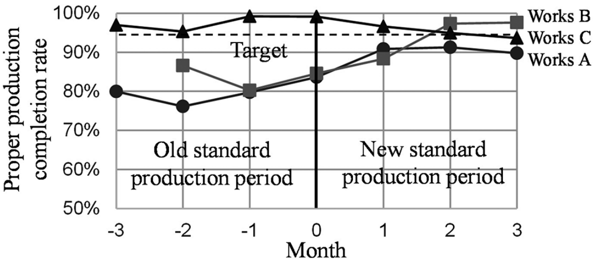

Fig. 15 Changes in proper production completion rate[30)]

They are the rates of production completion by shipping deadlines. That is to say, they are management indexes used in actual production control work including the differences between actual rolling dates and appropriate rolling dates. When the conventional standard production periods were used, the actual proper production completion rates largely varied from steelworks to steelworks and dropped lower than 80% in some cases. After the use of the new standard production periods began, the actual proper production completion rates remained at a high level. The new standard production periods designed using this algorithm were shorter than conventional ones by one to three days on average, so this algorithm has made it possible to shorten production periods and improved the actual proper production completion rate at the same time. In addition, the new standard production periods designed using the proposed technique have been used for some scheduling systems at steelworks,[28, 29)] contributing to improving the accuracy of production control at steelworks.

5.4 Summary

This chapter described the procedures for designing the standard production periods for plates. In the proposed technique, decision trees are used to estimate transit processes because production periods relate to the transit processes; then, the maximum likelihood estimation is used to estimate the probability density function of the production periods; and the production period that satisfies the designated proper production completion rate is determined as the standard production period. The new technique for designing standard production periods is used in the order entry system (OES) that issues production instructions for received orders,[30)] contributing to maintaining the high production completion rates at each steelworks and reducing the stock.

6. Development of a Technology for Optimizing Weekly Plate Output Schedules[28, 29)]

Appropriate weekly plate output schedules need to be quickly planned in consideration of various performance indexes, such as improvement in the productivity (maximization of the sequential number of continuous casting), levelling of processing loads, and adherence to delivery dates, while operational constraints (production capacity and storage capacity) are met. The parameters for planning schedules, such as processing loads and production periods, vary depending on the order specifications and operation change. In addition, it is difficult to solve large-scale and complicated optimization problems within a practical time if each order is directly modelled. Therefore, we have developed an optimization algorithm that can consider production class models that can be used throughout processes from parameter estimation to schedule planning by learning of actual results and that can consider complicated constraints and performance indexes.

6.1 Output schedule optimization problem

Orders to steelworks are grouped by steel type and processing route pattern. The output weight for each grouped order is determined using mixed integer programming under various constraints (e.g., production capacity) such that the evaluation value of Formula (8) for the increase in the output lot, adherence to output deadlines, and levelling of processing loads becomes optimal. An estimation model that was obtained by statistical analysis of actual data was used to estimate processing loads.

Constants:

$\hat{x}_{j,t}$: Order weight for grouped order j and output deadline t

$\hat{y}_{k,t}$: Processing capacity for manufacturing processes k and date t

Decision variable:

$x_{j,t}$: Output weight for grouped order j and planned output date t

Intermediate variables:

$\delta_{i,t}$: 0/1 variable. When steel type i is output on planned output date t, it is 1. When not, it is 0.

$y_{k,t} = \sum_j f_k(\cdot) x_{j,t}$: Weight of the processing load for manufacturing process k and planned output date t

Note: $f_k(\cdot)$ is a function that estimates the occurrence rate of the processing load in manufacturing process k from the production specifications.

Performance indexes:

$$\text{Minimization } J = W_1 J_1 + W_2 J_2 + W_3 J_3 \qquad (8)$$

$J_1 = \sum_i \sum_t \delta_{i,t}$: Number of seams of different steel types

$J_2 = \sum_j \sum_p \left| \sum_{t=0}^{p} \hat{x}_{j,t} - \sum_{t=0}^{p} x_{j,t} \right|$: Delivery schedule delay

$J_3 = \sum_k \sum_t \left| \hat{y}_{k,t} - y_{k,t} \right|$: Amount exceeding the processing capacity

Where, W_1, W_2, and W_3 are weighting factors.

Constraint formulas:

Steelmaking constraint, processing and storage space constraint, etc.

6.2 Optimization algorithm

A mathematical optimization technique is used to calculate the output weight (output schedule) for each production class such that performance indexes (e.g., increase in the productivity, levelling of processing loads, and adherence to delivery dates) become optimal under various constraints (e.g., production capacity). As the optimization technique, basically mixed integer programming is used. However, some cast formation constraints (e.g., constraints on charge locations in casts) to be considered when output schedules are planned are complicated and thereby modelling is difficult by mixed integer programming alone. Therefore, we have developed a multistep solution in which a tentative output schedule for which only linear constraints are taken into account is planned by mixed integer programming; the charge quotas are formulated for the obtained output schedule for each continuous-casting machine; a search technique is used to rearrange the charge quotas in consideration of all constraints including those indicated in the non-linear or If-then rule; and linear programming is used to assign a production class to each of all the obtained casts and charge quotas (**Fig. 16**).

6.3 Example schedule

Table 2 compares a schedule planned using this technique and another schedule manually planned for actual manufacturing data for eight days. The table shows that this new technique can increase the output lot size and reduce variation in delivery dates while the constraints are met. Where, the seam length refers to the performance index value for the length of waste of seams and the variation of delivery dates refers to the standard deviation of differences between the output deadlines and planned output dates.

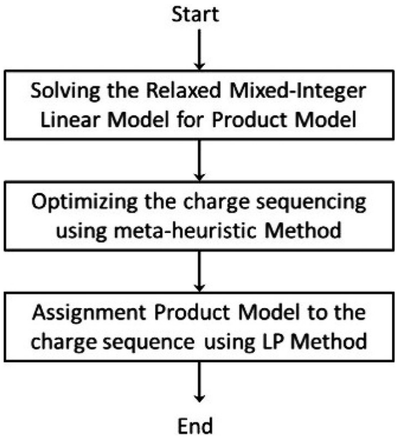

Fig. 16 Optimization algorithm[29)]

Table 2 Effect of optimization

	Proposal	Manual
Number of the violation of the restrictions [-]	0	0
Amount of the waste of the steel [-]	16	26
Standard deviation of the due date [day]	14.17	15.04

6.4 Summary

This chapter described the optimization algorithm that supports planning output schedules that balance the production in larger output lot size, levelling of loads in the processing process, and reduction of variation of delivery dates in the plate production. Trade-off adjustment between the production in larger output lot size and reduction of variation of delivery dates is a task common in steel production. Application of the algorithm to product types other than plates is expected.

7. Development of General-purpose Colored Petri Net Simulator

Many heavy objects are transported at steelworks, so reducing the logistics costs is an important task. Therefore, logistics control that allocates transportation equipment to objects to be transported properly is important to transport more objects with fewer numbers of transportation equipment to deliver products to destinations as scheduled. Nippon Steel & Sumitomo Metal has developed a real-time advanced simulator tool for colored Petri Net (TrasCPN) as a logistics simulation tool that can handle entire processes from analysis of logistics to control in order to improve the efficiency of logistics control. The simulator can cover complicated logistics conditions, perform fast calculations, and can make simulations linked to the optimization algorithm. Nippon Steel & Sumitomo Metal has been using the simulator to solve various problems with logistics at steelworks.[31)] This chapter describes the functions of TrasCPN.

7.1 Formats in the colored Petri Net simulator

Figure 17 illustrates an example of colored Petri Net created using this simulator. The thin rectangle in Fig. 17 indicates a transition, the square containing a circle indicates a place, and the small circle in a circle indicates a token. A firing condition can be given to the arc connecting a place to a transition. Token conditions required for firing can be given to the input arc to a transition (input arc expression) and conditions of a token generated after firing can be given to the output arc of a transition (output arc expression). This in-

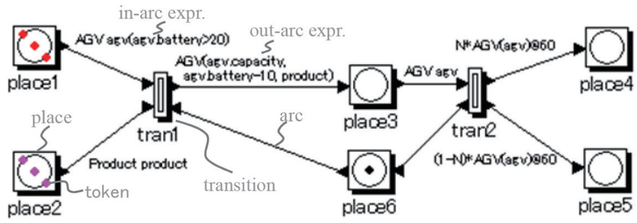

Fig. 17 Example of colored Petri Net[31)]

put arc expression is a rule required for firing for a single token. Firing conditions in which multiple tokens' attributes are combined can be described in a dialog shown by double-clicking a transition.

In this simulator, a Petri Net can be input using a mouse and keyboard, and a simulation can be executed immediately to see the network behavior. At the beginning of a simulation, compilation is performed in the background and the behavior of the tokens can be seen immediately on the graphical user interface (GUI), so debugging the simulator is inherently easy.

In this colored Petri Net simulator, tokens' attributes can be defined. List 1 shows examples of attribute definition. In **List 1**, a Product token and Automated guided vehicle (AGV) token are defined: The weight (product weight) and deadline (delivery time) are defined as attributes of the Product token, and the capacity (maximum authorized payload), battery (battery capacity), and product (product loaded) are defined as attributes of the AGV token.

List 1 Examples of token definition

```
Product(double weight, double deadline);
AGV(double capacity, double battery, Product product);
```

The locations of tokens at the beginning of a simulation (initial markings) are described in a dialog shown by double-clicking a place as shown in **List 2**. Setting specific value(s) as attribute(s) creates a token instance.

List 2 Examples of initial marking

```
Product(20, 800);
AGV(50, 80, Product(0,0));
```

An input arc expression that is a token condition that enables a transition to fire can be given to the input arc of the transition. **List 3** shows such examples. The upper row in List 3 means that when a Product token is present in the place, the transition can fire. The term "product" is the name of the token instance variable and is referred to in the transition's firing conditions and output arc expressions to be described later. Meanwhile, the lower row in List 3 means that when an AGV token for which the battery capacity is 20 % or more is present in the place, the transition can fire.

List 3 Examples of input arc expression

```
Product product
AGV agv(agv.battery>20)
```

As an input arc expression, conditions in which multiple tokens' attributes are combined cannot be described. To define this firing condition, a transition setting dialog is used. **List 4** shows an example of firing conditions. As shown in List 4, the C++ language is used to describe firing conditions. Once the processing completes, firing is enabled and when zero is returned in the middle of processing, firing is disabled. In List 4, when the maximum authorized payload of the AGV is smaller than the product weight, firing is disabled. Together with multiple token combinations that enable firing are provided, the keyword "fire_priority" can be used to designate the priority of firing. In List 4, the priority of a token with closer delivery time is set to higher. In addition, the keyword "fire_delay" can be used to specify a delay time in which a token created after a transition fired becomes ready to fire next.

List 4 Example of transition firing conditions 1

```
if (agv.capacity < product.weight) return 0;
fire_priority = 1.0/product.deadline;
fire_delay = 60;
```

In addition, a new variable can be created in a firing condition as shown in **List 5** and it can be used in an output arc expression to be described later. Complicated logistics events can be easily described, for example, the calculation result of a designated function can be set as the attribute of a transition that is created after another transition fired.

List 5 Example of transition firing condition 2

```
int N = agv.product.weight<50? 1: 0;
```

List 6 shows example output arc expressions that are the condition of a token to be created after a transition has fired. In the upper row in List 6, the AGV and product token instance variables in the input arc expressions in List 3 are used; the maximum authorized payload is the same and the battery capacity is reduced by 10% to create an AGV with product. Meanwhile, in the lower row in List 6, variable N described in List 5 is used to create no (0) or one AGV token. Such case is useful to select an output place depending on the token attribute. In addition, the term "@60" means the delay time from when a token is created to when the next firing is enabled as is the case with the keyword "fire_delay."

List 6 Examples of output arc expressions

```
AGV(agv.capacity, agv.battery-10, product)
N*AGV(agv)@60
```

7.2 Colored Petri Net GUI

Providing easy-to-use GUI is important when creating a large-scale complicated simulator. In this simulator, Petri Nets can be easily created with a mouse and keyboard. Part of a Petri Net can be divided into some modules to improve the readability and reusability of complicated Petri Nets as is the case with other tools[32], which allows hierarchical Petri Nets to be created. In this tool, two methods are provided to reuse modules and users can select whichever they require. **Figure 18** is an example of a simple hierarchical Petri Net. The double-lined blocks are modules having lower-layer Petri Nets.

Two methods are available to copy and reuse modules: Complete copy and reference copy. In complete copy, the original module and copied module become different objects and all the lower-layer Petri Nets are copied, so a change to a lower-layer Petri Net in one side does not affect the other one. On the other hand, in reference copy, lower-layer Petri Nets are not copied and only the information relationship with the original is copied. Therefore, when one side is modified, the other side is also changed. The middle module in Fig. 18 is a module created by copying the relationship with the top module and the bottom module is one created by complete copy.

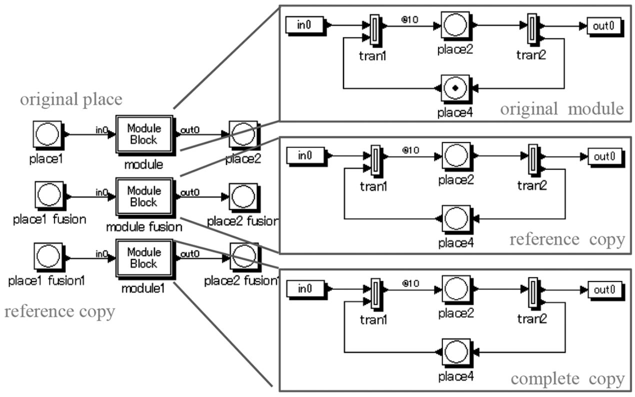

Fig. 18 Example of hierarchical colored Petri Net

The lower-layer Petri Net of the module created by the reference copy is the same as the original before the simulation begins. At the beginning of the simulation, the lower-layer module is copied and it becomes an instance different from the original, turning into another lower-layer Petri Net for which the locations of the tokens are different from those in the original.

In addition, regarding places, complete copy and reference copy are available. Complete copy is to create instances different from those in the original. Reference copy means creating and displaying a place the same as that in the original in a different location. This function eliminates the use of a long arc to connect a place to a far transition, allowing complicated Petri Nets with good readability to be created.

7.3 Summary

This chapter described the colored Petri Net tool developed to solve the problem with logistics control. In this simulator, multiple tokens with different attributes can be defined to make it possible to simulate complicated logistics flow freely and such attributes can be used to describe complicated firing logic. In addition, the hierarchical structure makes it possible to create Petri Nets with good inherent reusability even for large-scale logistics.

This colored Petri Net tool has been used to solve many problems with logistics control in the steelmaking process, such as AGV allocation control,[33] molten iron control system,[34] molten steel output schedule planning support system,[10, 11] and yard control scheduler.[35]

8. Development of a Technology for Optimizing Logistics at Slab Yards

8.1 Problems with slab yard control optimization

When steel materials (slabs) are supplied from the steelmaking process to the rolling process, slabs are once placed in temporary storage spaces called slab yards (hereinafter "yards") and then transported in accordance with the processing time at heating furnaces. Yards are intermediate storage spaces working as buffers between different manufacturing processes. That is to say, they work to adjust the manufacturing sequences between different manufacturing processes of steelmaking and rolling and to supply materials to the rolling process without hindrance. Lately, with the increasing demands for CO_2 emissions reduction, needs for control optimization at yards are increasing because preventing decrease in the temperature of slabs at yards is expected to reduce fuel consumed by heating furnaces. In yard control, items ① to ④ in **Fig. 19** need to be determined.

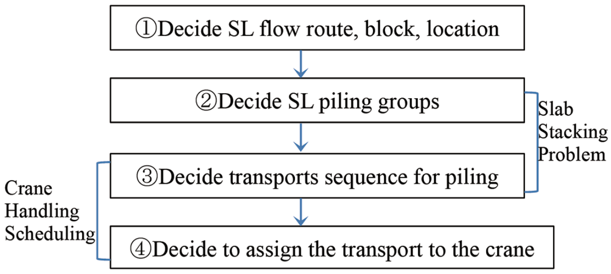

Fig. 19 Slab yard control decision flow

Items ① to ④ are related, so they cannot be determined separately. However, determining all the factors at the same time is also difficult because the scale is large. Therefore, control staff usually determine them in the following sequence: Target slabs are allocated to one of multiple buildings (①); the slabs allocated to each building are further divided into piles (unit) because approximately 10 slabs are stacked in each building for storage (②); the transportation sequence is determined to stack the slabs efficiently by overhead cranes and other transportation equipment (③); and the transportation tasks are allocated to transportation equipment (④).

Technologies for using mathematical optimization techniques and simulation technologies for such determination are under development. Regarding item ①, some researchers have reported technologies for formulating such determination as flow optimization problems and calculating appropriate flow routes.[36, 37] Regarding items ③ and ④, some researchers have reported techniques in which GA and simulation technologies are combined.[38] In addition, determination of piling groups in ② and determination of the transportation sequences for piling in ③ (slab stacking problem) have been studied most intensely. This is because slabs are stored in piles at yards to save space and they are rearranged at the time of the reception such that slabs to be discharged early are positioned in the upper part of a pile to allow them to be discharged quickly. Improving the efficiency of such rearrangement is a target in work at yards. There are various preceding researches on such problem including similar problems of reducing the rearrangements of containers at ports.[39]

This slab stacking problem assumes that when slabs arrive at a yard, the heating furnace schedule in the next manufacturing process has been determined. If such schedule has not been determined at the time of the arrival, different approaches are required after the schedule is determined, for example, slab rearrangement (pile rearrangement problem[40, 41]) or adjustment in the charge schedule.

The slab stacking problem is a combination optimization problem to form a pile in which slabs are stacked in the discharge sequence at small workloads to the extent possible under a pile form constraint. Some researchers regard this problem as a grouping problem and they have proposed formularization procedures using the vertex coloring method[42, 43] and those based on the set partition method.[35, 44] This chapter introduces the set partition method briefly.

8.2 Formularization of the slab stacking problem as a set partitioning problem

The slab stacking problem can be regarded as a grouping problem in which target slab set N is divided into subsets (piles). This problem can be formulated using a set partitioning problem (SPP)[45] that is a type of combination optimization problem. SPP is a problem in which the elements in N are divided into subsets $S_1, S_2, \cdots, S_j, \cdots, S_m$ without overlapping and omission so as to minimize the total cost on the assumption that any subset S_j has its cost c_j.

$$S_1 \cup S_2 \cup \cdots \cup S_j \cup \cdots \cup S_m = N, \quad S_{j1} \cap S_{j2} = \varphi \quad \forall j_1, j_2 \tag{9}$$

φ in Formula (9) is an empty set. In SPP, 0/1 decision variable $x[j]$ is provided for arbitrary subsets S_j. The variable indicates whether each subset S_j is adopted as an optimum subset for dividing universal set N. It can be formulated with Formulas (10) to (12) listed below as a 0/1 planning problem below. At this time, subset group M for universal set N needs to be listed in advance. For the slab stacking problem, feasible pile group M that meets the pile form constraint needs to be predetermined.

$$\text{SPP: Min. } \sum_{j \in M} c_j \cdot x[j] \tag{10}$$

M: Feasible pile set

$$\text{Subject to } \sum_{j \in S(i)} x[j] = 1 \quad (i \in N) \tag{11}$$

$S(i)$: Set of subsets j including slab i

$$x[j] \in \{0, 1\} \quad (\forall j \in M)$$

$$c_j = k_1 \cdot 1 + k_2 \cdot c_{j2} = k_1 + k_2 \cdot c_{j2} \quad (\forall j \in M) \tag{12}$$

c_j in Formula (10) is the evaluation value of feasible pile j and it is evaluated based on the number of piles and the number of rearrangements as shown in Formula (11). The number of piles is one for all the piles. The number of rearrangements at the time of stacking is c_{j2}, the weighting factor for the number of piles is k_1, and that for the number of rearrangements is k_2.

In SPP, the evaluation of the pile form constraint that is a constraint unique to the target problem and the evaluation of the number of rearrangements that becomes an objective function are included in the processing that lists feasible piles. Therefore, a constraint as the 0/1 planning problem is only Formula (11) requesting that the target slabs belong to any pile without omission and overlapping. As described above, constraint and evaluation formulas for which the formularization is difficult can be handled in the listing processing. It can be said that this is as an advantage in applying a set partitioning problem to an actual problem. Where, how quickly the pile form constraint and the number of temporary placed slabs are evaluated in the listing processing are important. (For the details, refer to the document 44).

8.3 Results of the application of the set partitioning problem method to the slab stacking problem

Table 3 compares the results of slab stacking planned by this method and those of stacking that humans planned. The table shows that the rates of temporary placed slabs are at the same level, but the number of piles can be reduced by approximately 25%. This method is expected to increase the charge rate to hot pits, which may increase the charge temperature.

8.4 Summary

This chapter introduced the method to solve the slab stacking problem by SPP when the discharge schedule to the following manufacturing process has been determined when slabs arrive at a yard. However, this method consumes a lot of memory and when N exceeds 50, the calculation becomes impossible in some cases. In addition, the conditions of yards change hourly, so real-time rescheduling procedures according to such condition changes are required. To this end, the pile form rearrangement problem described above needs to be addressed.

Table 3 Effect of optimize (*n*: 3 115)

	Number of Slab per one pile (piles)	Rate of temporary placed slabs
Manual	6.9 (451)	36%
Optimize	9.0 (346)	33%

9. Development of Human Cooperative Scheduler

Production planning and scheduling systems assist humans in making decisions. Normal production schedulers have no function for explaining the reason why final schedules were planned. Users may be dissatisfied with schedules planned by such systems depending on the application targets.

Many researchers have reported research outcomes for decision support systems. For example, Qian, C. et al.[46] have reported that rearranging items displayed on screens can reduce the time required to solve problems and can improve the quality of the solutions in arrangement problems including production schedules.

This chapter describes the study results of functions required as scheduling systems and of a human cooperative algorithm along with its application to cast formation when schedulers are regarded as decision-making systems.

9.1 Guidelines for designing cooperative type schedulers

To identify specific design guidelines for scheduling problems, a simple scheduling problem was used to research how means to present information and function allocation would affect decision making.[47] Results are shown below.

(1) When some attributes that a system did not use for optimization calculation were hidden from view, the speed at which people judged the system's proposals increased in some cases. However, users who referenced such hidden attributes to make judgments felt more dissatisfaction with the system.

(2) Providing functions that allowed users to select the cooperative ratio by humans and the system in a form that users could recognize increased the degree of acceptance of schedules proposed by the system: Such functions include one for displaying results in the course of optimization calculation; one for calculating the schedule by system in half and calculating by humans after that; one in which humans' calculation results are used as initial values and the following processes are calculated by the system; and one for manually revising schedules finely.

The item (1) above is common to all decision-making systems: Presenting too much information to humans decreases their cognitive capacity, so it is desired to display the minimum necessary information on decision-making systems. In steel production schedules, the amount of information required to judge whether schedules can be accepted or rejected is huge and functions for displaying as much information as possible need to be provided. However, we think that the user interface where only main items are always displayed and other necessary information is displayed based on user requests should be provided.

Regarding the item (2), providing a function that leaves a margin for humans to make judgments even in the course of calculation, in addition to judging calculation results, possibly allows humans to feel more that the final schedules are not forced by the system and they planned the schedules in cooperation with the system, which possibly makes the planned results more acceptable. We consider that in production schedulers, it is important to present a schedule gradually in multiple stages to give a margin for humans to adjust it at each stage, rather than presenting the final schedule one time.

9.2 Human cooperative cast formation system

We have developed a cast formation system that plans production schedules for continuous-casting machines based on the design guidelines determined in the previous section.[48] It was found that persons in charge of cast formation did not consider all target charges to be formed equally but they determined the positions of charges

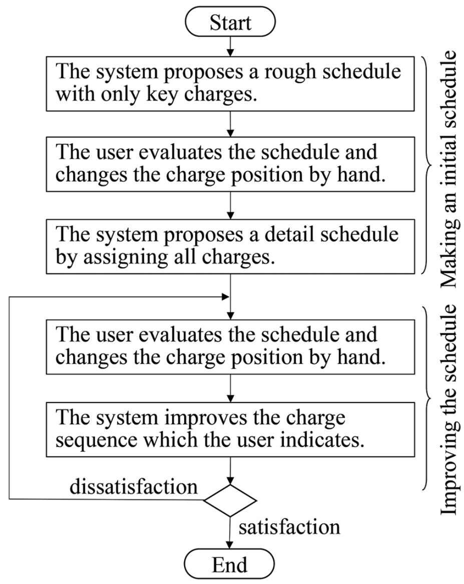

Fig. 20 Scheduling algorithm for interactive cast scheduler[48]

for which the cast position constraints were severe and thereby their production was difficult first and then planned the positions of other charges. In addition, after they planned a single cast formation schedule, they revised it repeatedly while checking the balance of the entire schedule until there were no more improvement ideas to determine it as the final schedule.

Figure 20 shows the scheduling algorithm of the cooperative cast formation system. The system loads target charges first and proposes a rough schedule to a user only showing key charges for which the position constraints are severe. Next, the user checks the proposed rough schedule and revises the cast positions of the key charges. The key charge positions that the user is more concerned about are agreed at this stage, so the system determines the positions of the remaining charges and proposes the schedule to the user. This is the detailed primary schedule including all the targets' charges. The user checks the balance of the entire detailed schedule and revises it manually, if necessary. The user also uses the system's automatic scheduling function, if necessary, to improve the production sequence in a designated range. These manual revisions and automatic improvements in a designated range by the system are repeated until the user is satisfied with the results and the final results are output as the final schedule.

In this way, providing two stages in which a rough schedule is agreed first and then a detailed schedule is proposed allows the system to propose a detailed schedule that the user can easily accept.

To allow the afore-mentioned scheduling algorithm to work as expected, an easy-to-use user interface is important. Main user interfaces realized in the cooperative cast formation system are listed below.

(1) Function for displaying evaluation values for a schedule and their details (showing grounds for the proposed schedule)

(2) Function for coloring violation of constraints, etc. (to make it easier to judge whether the schedule is acceptable or not)

(3) Charge drag-and-drop function (for improving schedules cooperatively)

(4) Function for fixing the cast positions of charges (for improving schedules cooperatively)

(5) Function for grouping multiple charges (for improving sched-

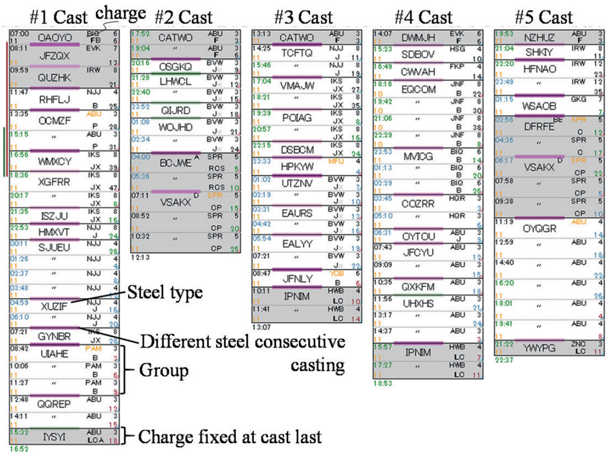

Fig. 21 User interface of interactive cast scheduler[48]

ules cooperatively)

(6) Function for designating an improvement range (for improving schedules cooperatively)

(7) Functions for enabling and disabling constraints, changing thresholds, and revising performance index weights (for adjusting the planning performance)

(8) Function for saving revision history, comparing multiple schedules, and showing their differences (for comparing multiple schedules in detail)

(9) Function for recommending positions into which targets should be put (for supporting manual planning and training to new staff)

Figure 21 shows example scheduler screens with the functions listed above.

9.3 Summary

Normal production schedulers have no function for explaining planned results, so users may not be satisfied with the results depending on the application target. Therefore, in this chapter, a scheduler was regarded as a decision support system and guidelines for designing human cooperative schedulers were proposed. These guidelines were applied to the cast formation system and the effects were verified. The developed cast formation system has been used at actual manufacturing sites and it has been confirmed that users are satisfied with the proposed schedules and excellent cast formation schedules are obtained. The system has been useful to reduce planning workloads and manufacturing costs and improve the casting quality. In addition, requirements that cooperative schedulers should have are very versatile, so they have been applied to other scheduling problems in the steelmaking process, achieving success.[49, 50]

10. Conclusions

The steelmaking process is a V-type job shop production process in which various types of steel products are manufactured in small lots using natural raw materials so as to satisfy the product specifications and delivery date for each order while aiming at increasing the size of lots in each manufacturing process (maximizing the productivity). In addition, production schedules need to be planned for each manufacturing process in consideration of the various production constraints and performance indexes from the aspects of product quality and costs. Experienced skills and know-how are required even when the scheduling unit is a manufacturing process. This paper described the development of production planning and scheduling algorithms for solving problems with raw materials, steelmaking, hot-rolling, and logistics as actual efforts for supporting such planning work. Another of our works for plates was introduced from the aspect of production planning throughout the manufacturing processes. In addition, our work for linking humans and systems at a higher level to make it possible to plan production schedules that could not be made only by humans or systems was described.

Improving the efficiency of the implementation and maintenance of the developed algorithms is also an important task. As an example of such effort, Nippon Steel & Sumitomo Metal has been developing a tool that can create mathematical optimization models automatically just by entering some data on screens without a high level of mathematical technical knowledge.[51]

As the labor population is expected to further decrease in the future, there will possibly be a need to develop technologies for supporting production planning and scheduling throughout multi-stage manufacturing processes from raw materials to production and shipment and for supporting planning schedules for multiple steelworks from the aspect of the entire company. To that end, in addition to the development of high-speed algorithms for larger-scale mathematical optimization problems, next-generation architectures (e.g., quantum computers) may need to be used.

In addition, re-planning and rescheduling performance needs to be enhanced so as to quickly cope with changes in the order configuration and operation changes as a result of changes in market needs. To detect changes promptly and cope with them quickly, technologies for analyzing order data and actual operation data will become increasingly important. Furthermore, with the remarkable advancement of AI technologies, it is important to appropriately judge how humans and systems share manufacturing process management tasks including production planning and how scheduling is desirable on a long-term basis. Designing advanced user interfaces that give awareness to humans and that can be intuitively operated is also important. Nippon Steel & Sumitomo Metal will provide these technologies as comprehensive system solutions and will work to establish general production management technologies that are linked to quality management and operation management in addition to manufacturing process management.

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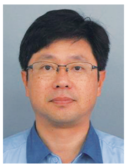
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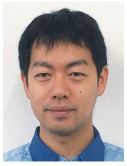
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