

Genetic Scheduler Development Systems and their Application

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Abstract

In the steel industry, there are many scheduling tasks that determine the order of processes for each product and their timing in consideration of evaluation indicators such as quality, cost, and delivery. To assist with these scheduling tasks, we developed genetic scheduler development systems for developing schedulers without programming.

1. Introduction

The manufacturing industry uses various resources in various manufacturing processes to manufacture various types of products from raw materials or assembles parts to produce products. To effectively use such resources and carry out production so as to satisfy evaluation indicators, such as quality, cost, and delivery, each product's processing timing in each manufacturing process and the order of processes need to be appropriately determined. However, actual production sites involve many raw materials, intermediate products, and products and also the resources for processing and transferring them are complicatedly related to each other. Accordingly, constraints to be considered are complicated, which makes it difficult to form schedules such that the evaluation indicators become optimal.

Under such circumstances, Nippon Steel Corporation, as a means to resolve such scheduling problems mathematically, has been developing techniques to form production plans and schedules using mathematical optimization.¹⁾ Mathematical optimization is a technique to obtain optimal solutions, using mathematical calculation techniques, for issues in various fields by expressing target problems in numerical formulas. In recent years, calculator performance has been enhanced and various computational algorithms, which are represented by mathematical optimization solvers, have also been advancing significantly. These factors are making it possible to form schedules such that evaluation indicators, such as quality, cost, and delivery, become optimal even for scheduling problems for which forming schedules used to be difficult.

Meanwhile, to apply mathematical optimization to scheduling problems at actual manufacturing sites, expertise on mathematics and programming is required. Steel production processes involve a wide variety of product types and manufacturing processes and thereby scheduling tasks vary. It is not practical for experts in mathematical optimization to improve all such tasks. In addition, scheduler development demands high-level system implementation technologies and thereby whenever operations or equipment are changed

after production systems have been started up, system maintenance by experts is required. This makes it impossible to implement the PDCA cycle for improvement quickly, tending to render schedulers obsolete.

Under such circumstances, we developed, in cooperation with Nippon Steel Texeng Co., Ltd., a genetic scheduler development system that makes it possible to create, execute, and evaluate mathematical optimization models on a graphical user interface (GUI) without involving programming. Our aims are to allow users who do not have expertise in mathematical optimization and programming to resolve scheduling problems at actual production sites on their own using mathematical optimization; and to continuously improve scheduling based on changes in operations and equipment. Chapter 2 of this paper introduces the mechanism of the genetic scheduler development system and Chapter 3 introduces the development case of a scheduler considering the balance between productivity and costs (costs increased by temperature rises due to heat radiation) targeting steelmaking mills. Chapter 4 introduces the development case of a scheduler that realizes appropriate allocation of equipment, storage spaces, and work crews for refractory construction plans at steelmaking mills.

2. Genetic Scheduler Development System

In production scheduler development, it is important to make implementation and maintenance easy. However, formularization of mathematical models requires knowledge of mathematics and the loads to implement models are also high (software consists of several tens of thousands of lines). Because humans create programs, they include bugs and debugging takes an enormous amount of time, which creates the following two issues: (1) It takes time to implement programs in actual machines and (2) the loads of maintenance after their introduction are high and thereby they cannot be revised in a timely manner. To resolve these issues, Nippon Steel developed its proprietary optimization technique²⁾ in cooperation

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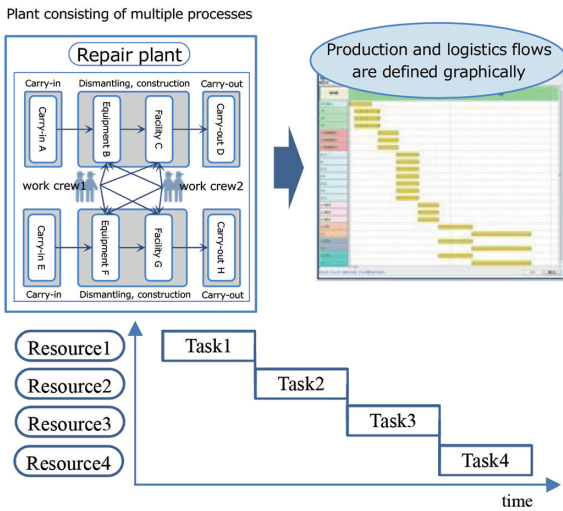


Fig. 1 Definition of production and logistics flows

with Nippon Steel Texeng. This technique makes it possible for people who do not have expertise in optimization and programming to automatically create mathematical optimization models for typical scheduling problems only through simple input on screens without programming.

Our optimization tool (FitOptimizer) that utilizes this technique defines a series of flows, such as transfer and processing, as tasks for each order that becomes the main element in the processing of products and intermediate products; and defines work crews, equipment/facilities, and storage spaces that are used in the course as resources. This generalizes scheduling problems, which enables graphical registration of production and logistics flows. **Figure 1** illustrates a series of tasks for each order and a screen used to register resources required to carry out those tasks. The registered production and logistics flows are saved to an individual database and the data is used to create mathematical optimization models automatically. This enables users who do not have knowledge of mathematical optimization to easily form schedules.

Formulas (1) and (2) below express a simple case. The formulas express the relations listed below.

- Formula (1) expresses the relation between the task start time $T_{s_{o,p}}$ and end time $T_{e_{o,p}}$ where the processing time when each order is $o \in O$ and each task is $p \in P$ is $PT_{o,p}$.
- Formula (2) expresses the processing of task $p2$ begins after task $p1$ has ended.

$$T_{e_{o,p}} - T_{s_{o,p}} = PT_{o,p} \quad \forall o \in O, \forall p \in P \quad (1)$$

$$T_{e_{o,p1}} \leq T_{s_{o,p2}} \quad \forall o \in O \quad (2)$$

In addition, constraints and objective functions in production and logistics processes can be registered on screens and mathematical optimization models can be automatically created based on the data. Formulas (3), (4), and (5) below express a simple case.

- Formulas (3) and (4) express the constraint that the order $o1$ and order $o2$ cannot use the same resource $r \in R$.
- Formula (5) expresses an objective function to minimize the total sum of the dwell time ($= T_{e_{o,p}} - T_{s_{o,p}}$) from the start of each order $o \in O$ and each task $p \in P$ to the end and to minimize the total sum of the end time $T_{e_{o,p}}$.

$$T_{e_{o1,p}} - M(1 - \delta_{o1,o2,p,r}) \leq T_{s_{o2,p}} \quad \forall p \in P, \forall r \in R \quad (3)$$

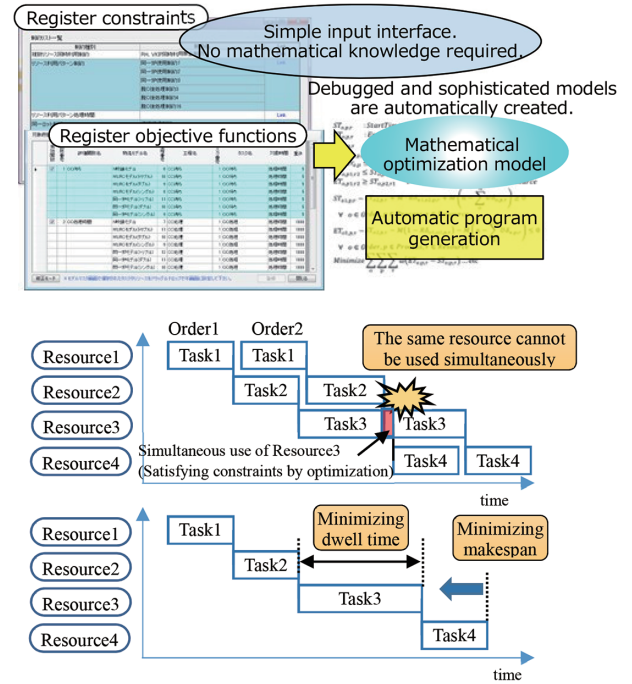


Fig. 2 Definition of constraints and objective functions

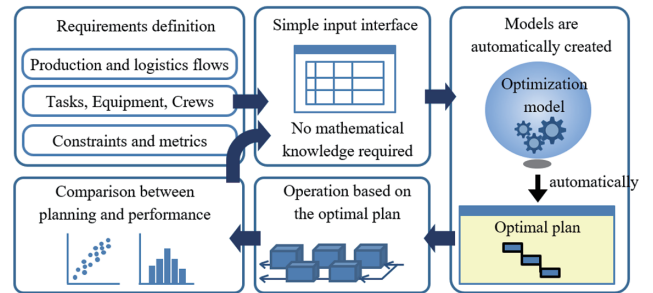


Fig. 3 Consistent optimization system

$$T_{s_{o1,p}} + M(1 - \delta_{o1,o2,p,r}) \geq T_{e_{o2,p}} \quad \forall p \in P, \forall r \in R \quad (4)$$

$$\text{minimize } W_1 \sum_o \sum_p (T_{e_{o,p}} - T_{s_{o,p}}) + W_2 \sum_o \sum_p T_{e_{o,p}} \quad (5)$$

Where, $\delta_{o1,o2,p,r}$ is a binary variable that can be only 0 or 1. W_1 and W_2 are weighing parameters for the evaluation indicators and users can enter them on screens (**Fig. 2**).

As described above, debugged, sophisticated optimization models are automatically created including the aforementioned production and logistics flows and they enable establishing high-productivity and high-quality systems. In addition, even if schedules need to be promptly changed due to equipment failures and production problems, users can easily revise the schedules on screens. By providing a function for fixing some solutions and obtaining solutions for the remaining parts using optimization models, humans can form schedules in cooperation with systems. Furthermore, a mechanism that can automatically extract differences between planning and performance and that can perform quantitative evaluations has also been established. This consistent optimization system can continuously improve the capabilities at actual sites by quickly incorporating changes in the operation environments into subsequent actions (**Fig. 3**). The next chapter describes cases where the aforementioned optimization tool was applied.

3. Application Case 1: Steelmaking Scheduler

In the steelmaking processes, for the pig iron produced in blast furnaces, impurities are removed and components are adjusted in converters (CVs) and secondary refining equipments (RH: Ruhrstahl-Heraeus); then continuous-casting (CC) machines are used to manufacture cast steel, which is an intermediate material. Molten steel for which the components were adjusted in the converter process is charged into containers called ladles and sent to RH units; then it is transferred to continuous-casting machines and continuously cooled to turn it into solid steel. Molten steel for one ladle is called charge and a group of multiple charges that are cast in a continuous-casting machine is called cast. In the steelmaking processes, it is important to shorten the idle time of equipment from the viewpoint of productivity; and it is also important to aim at reducing costs due to temperature rises and extending the service life of refractories by lowering the converters' blowout temperature through the suppression of heat radiation from molten steel during the waiting time. The section below describes Nippon Steel's work on a technique to form schedules considering an increase in the productivity and reduction of temperature rise costs.

As steelmaking scheduling problems, given charge configuration of cast (charges) for continuous-casting machines and casting orders, operation schedules of converters, RH units, and continuous-casting machines are determined such that the objective functions become optimal while satisfying constraints on the manufacturing and logistics at steelmaking mills. There are several types of constraints: Constraint on the processing flow where each charge advances the predetermined manufacturing processes one by one; constraint of interference that prohibits the processing time of different charges from overlapping in each manufacturing process; and constraint of sequentially continuous casting to cast multiple charges in the same cast without interruption. In addition, as representative evaluation indicators that form objective functions, dwell time and casting completion time are used. Dwell time refers to the time period from when molten steel is discharged from a converter to when its casting begins. With regard to dwell time, the aim is to minimize the costs related to temperature rises of molten steel by suppressing temperature decrease of the molten steel as much as possible. Casting completion time is an indicator showing the productivity and is used with the aim of maximizing the continuous-casting machines' operating rates.

In this case, for such steelmaking scheduling problems, we developed a scheduler involving FitOptimizer. FitOptimizer, by registering the aforementioned constraints and objective functions for steelmaking scheduling problems, automatically creates mathematical optimization models that include 0-1 variables that express the selection of manufacturing facilities (furnace numbers) and continuous variables that express the manufacturing time. Thus, it can form optimal schedules (Fig. 4).

However, as an issue, the number of combinations of 0-1 variables is increasing due to the increase in the number of patterns of molten steel tapping from converters, a more complicated RH process, and increase in the number of charges requiring scheduling due to increase in the production. For example, when 60 charges are processed with two converters, the number of combinations of the charge processing order and allocation of the charges to the converters are approximately 10^{100} . To resolve this issue, we developed a technique that enables scheduling in practical time (approximately five minutes for scheduling for one day). In this technique, target charges are extracted in the order where the CC processing start

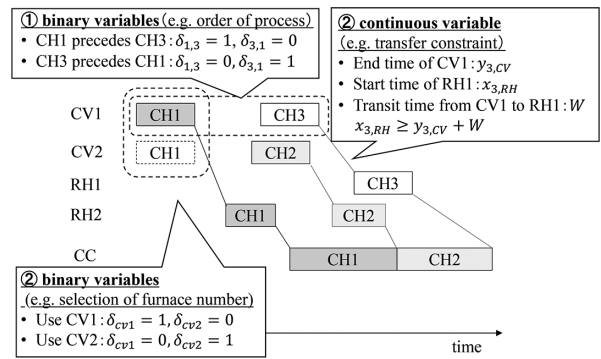


Fig. 4 Example of constraints formulation

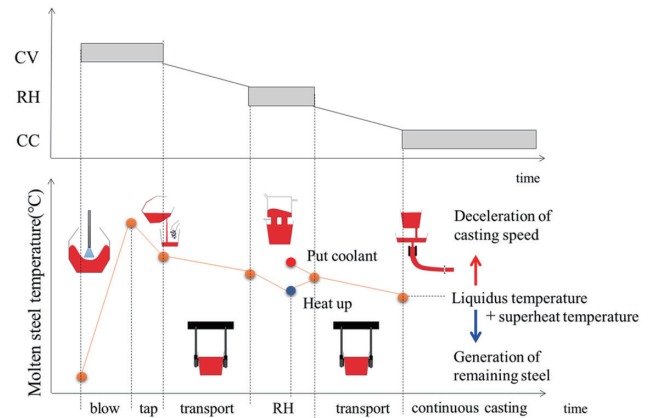


Fig. 5 Model for molten steel temperature and schedule

Table 1 Effect of optimization

	Manual	Optimize
Waiting time at CC	1.00	0.94

time is earlier, the scheduling problem is resolved for the extracted charges, and then these steps are repeated.

To control the molten steel temperature in casting appropriately, we also have developed an optimization technique considering molten steel temperature. Formerly, in molten steel temperature control, the target temperature in each manufacturing process was calculated with the processing time of each charge in the formed steelmaking schedule as a precondition. However, in this method, to secure the temperature adjustment time required to achieve the target temperature specified in the schedule, the steelmaking schedule needs to be reviewed. To resolve this problem, we created a model to represent the temperature change of molten steel during transferring and processing, and developed a simultaneous optimization model in which the molten steel temperature changes and the schedule are united (Fig. 5). This technique makes it possible to calculate an operation schedule such that the molten steel temperature fits in the range (upper and lower limits) determined for each manufacturing process.

The introduction of the developed scheduler succeeded in reducing the CC waiting time by 6%, compared with the time before the introduction as shown in Table 1. As a result, the converter blowout temperature can be reduced, which increases expectations for a reduction of temperature rise costs and longer service life of refractories. This scheduler has reduced costs of several tens of millions per year.

4. Application Case 2: Refractory Repair Scheduler

Refractories used in the steel industry come into direct contact with hot metal and molten steel and thereby they quickly wear. For stable operation, they are periodically repaired and replaced with new ones. To make such repair efficient and smooth, forming high-accuracy plans is important. At refractory repairing yards, as common resources (places, crews, and repair equipment) are used to repair multiple furnace facilities and thereby to improve the accuracy of scheduling, plans need to be formed beyond the boundaries of the facilities in charge. In addition, for emergent repairs that are suddenly required, optimal schedules need to be promptly formed. However, because adjustment of entire plans considering the constraints of resources demands high levels of skills, even experienced workers in charge of scheduling sometimes form schedules that demand work on holidays and overtime by construction crews.

The case below describes, among facilities with refractories, application to a Ruhrstahl-Heraeus (RH) construction plan as shown in **Fig. 6**. The vacuum chambers of RH units are used to decarbonize, degas (hydrogen and nitrogen), and deoxidate molten steel that was primarily refined in converters. This secondary refining unit refluxes molten steel between the vacuum chamber and the ladle to make the degassing highly efficient.

The objective functions and constraints in the RH construction plan are described as follows.

- (1) Objective functions
 - (a) Minimize the overtime.
 - (b) Minimize increase in the number of construction crews.
 - (c) Minimize the transfer time and loads (relocation).
- (2) Constraints
 - (a) It needs to secure time required based on the necessary repair operations for each type of repair.
 - (b) It needs to secure work spaces required for each type of repair (**Fig. 7**).
 - (c) Construction crews with the requisite skills are needed for each type of repair (**Table 2**).
 - (d) The delivery schedule must be met.

By registering constraints and objective functions in the construction plan, FitOptimizer creates a mathematical optimization model automatically and then forms an optimal plan automatically. Using an optimal plan enabled allocating equipment, storage spaces, and construction crews appropriately. The obtained results were excellent and equal to or higher than the plans formed by skilled persons in charge of scheduling; for example, all delivery schedules have been met without fail and work on holidays by construction crews was reduced (**Fig. 8**).

5. Conclusion

This paper introduced FitOptimizer—a genetic scheduler development system—that can create, execute, and evaluate mathematical optimization models for production and logistics scheduling problems using a GUI without programming, along with its application cases. In the first application case, we developed a steelmaking scheduler that considers heat balance and productivity. This scheduler works to lower converter blowout temperature in the steelmak-

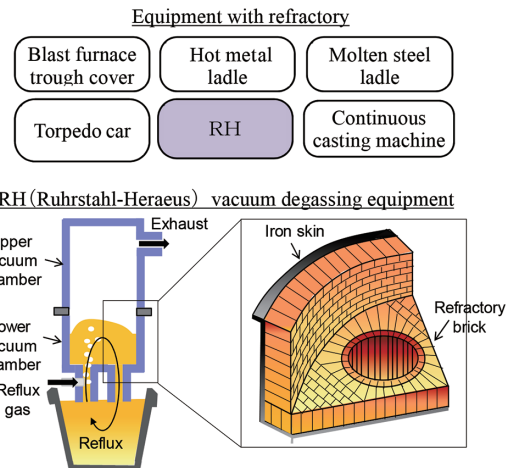


Fig. 6 Equipment with refractory and the target of this scheduler

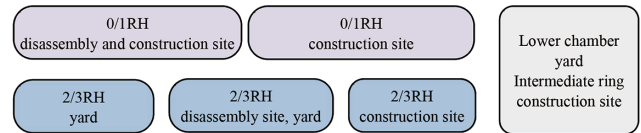


Fig. 7 Example of RH lower vacuum chamber repair place

Table 2 Example of work skills

Repair target	Work skills			
	Loading and unloading	Disassembly	Construction	Inspection
Refractory	2 persons	2 persons	4 persons	1 person
Iron skin	2 persons		3 persons	1 person

ing processes, thus contributing to saving energy. In the second application case, FitOptimizer was applied to a refractory repair plan. This application has confirmed that plans can be automatically formed so as to make work on holidays by construction crews zero while the delivery schedules are satisfied without fail. In addition, these schedulers implemented by FitOptimizer are in use at Nippon Steel’s steelworks as actual systems. Although there have been many requests for revising them due to changes in operations and equipment after they were incorporated as actual systems, the introduction of FitOptimizer has enhanced the maintainability and thereby system maintenance has been completed in a short period of time at low costs.

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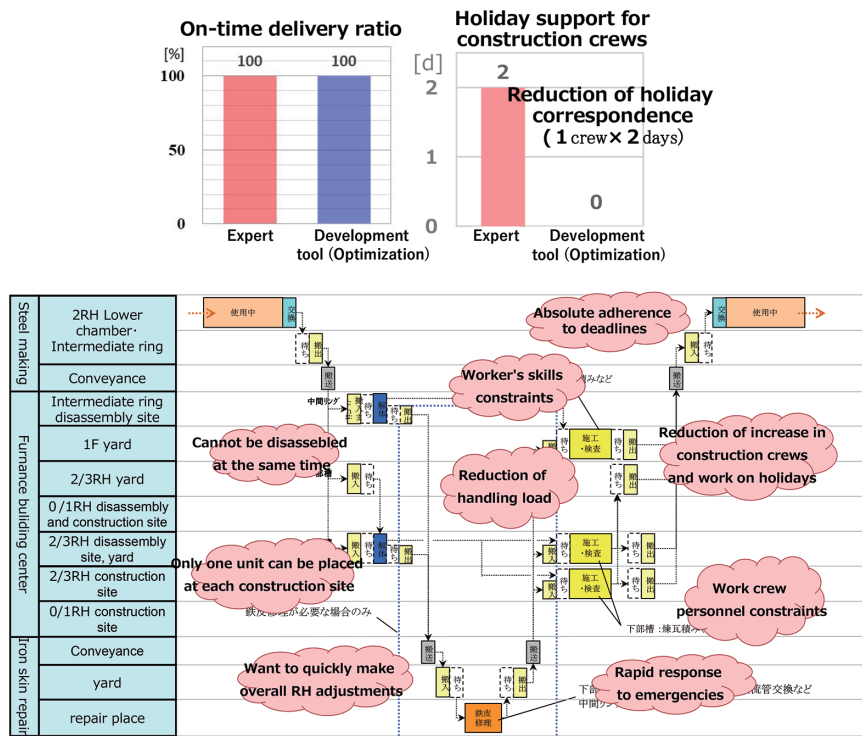


Fig. 8 Example of construction plan result



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