# Development of Macro Simulation Model to Support Multi-product, Mixed Flow Production of Aluminum Rolling

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*The manufacturing processes for the sheets, plates, and strips of steel, aluminum, and copper that are Kobe Steel's main material products are characterized by the mixed production of a great variety of products. Hence, for the sake of productivity and quality, a plurality of workpieces processed by an identical type of method are aggregated together as one lot on the basis of the operating conditions specific to each apparatus. A simulation model has been developed to support production planning and to help in considering operational rules as well as the capital investment policy involved in such processes. The model has a hierarchical queue structure to flexibly express various lot-making operations. The model further incorporates a mechanism for estimating the time it takes before the minimum number of workpieces required to organize a lot become available in order to reduce the unwanted stagnation of jobs in the process. The effectiveness of the proposed model has been demonstrated by numerical experiments, while its accuracy and applicability in the macro evaluation of material flow have been verified using actual plant data on aluminum rolling.*

## Introduction

Recently, in material processing plants that manufacture, among others, ferrous and non-ferrous rolled products, an increasing variety of products are being produced in variable quantities, inevitably making the production flow more and more complicated. Furthermore, strong requirements for reducing lead-time and work-in-process (WIP) are making it difficult to properly control the production flow through an entire plant by the mere experience and intuition of experts. Hence, there is a strong desire for a system that supports determinations and decisions for advanced production management on the basis of objective data and evaluation by theoretical modelling.

Approaches to systematization include a scheduling system that calculates the detailed work sequence of apparatuses to support daily to weekly planning. Also included is a simulation for computing the macroscopic production flow in a plant to devise the operational guidelines for the resources in the plant for production planning on a monthly to yearly basis. These all play important roles in modelling production processes,[1)-3)] and some are reported to have been applied to job-shop type processes, in which the process steps vary depending on the products.[4)-6)]

Meanwhile, for a simulation that is usable in real operational investigations of the production steps in material processing, which requires the reduction of setup time and cost as well as stable quality in its complexity, a modelling of "lot aggregation and sequencing" is essential so that similar types of jobs (various processes involved in manufacturing final products from raw materials) are performed continuously under process-specific conditions.

For the problems of lot aggregation and sequencing in situations involving changeover time between lots, several approaches based on optimum solution searching have been reported.[7)-11)] However, the scale of the material manufacturing process (several tens of steps) and the number of workpieces (several thousand/month) covered by this paper require enormous calculation time, making it difficult to adapt these approaches in daily practice.

Hence, this paper proposes a simulation model for executing lot aggregation efficiently with practical accuracy for the material manufacturing process in multi-product, mixed-flow job shops involving lot aggregation at each step. The present model is based on a queue structure, which has a two-layer hierarchy with a first layer for aggregating lots and a second layer for rearranging the aggregated lots under predetermined conditions. In addition, this model is combined with a function of forecasting the arrival of workpieces to each apparatus with the renewal of the simulation time, thus, to forecast the time when each lot of a preset size is completed, so as to suppress the unwanted stagnation time of jobs associated with lot organization. As a result, it has become possible to convert the huge amount of production data into information on realistic production flows of the entire process. This has enabled forecasting the production and logistics situations on a monthly to yearly basis in the large-scale material manufacturing process.

This paper outlines these characteristic functions and introduces the verification results confirming the validity of the proposed model, giving the test data and verification examples along with the actual data of an aluminum rolling plant.

## 1. Lot organization in material manufacturing process

In a material manufacturing plant that produces a wide variety of products, there are very many types of jobs involved, and the production is carried out via job-shop-type production lines, in which each line varies depending on the job specifications. At each step, an operation is generally performed with "aggregated lots," in which a plurality of workpieces with identical processing specifications are grouped and processed together in order to improve productivity and to reduce the cost by decreasing the time and number of changeovers. Examples of lot aggregation are given below:

- In a heat-treatment shop that uses batch furnaces, workpieces with an identical annealing temperature are processed together in one furnace to reduce fuel consumption and to improve productivity.
- In a rolling shop that produces sheets of ferrous and non-ferrous metals, workpieces requiring rolls with an identical surface roughness are processed as continuously as possible to reduce the changeover of the rolls.
- In a surface-treatment shop, workpieces that require an identical type of paint or identical chemicals are processed together as much as possible, since the changeover takes an extremely long time.

Normally, there is a certain degree of freedom in the number of workpieces constituting a lot. The lot size and setup time in between lots, determined within that degree of freedom, affect not only the productivity of each apparatus but also the productivity of the entire plant, as well as the WIP, lead time, and cost, etc. In the material manufacturing process of multi-product, mixed-flow type, in which the job sequences are complicated, it is difficult to forecast the intermediate WIP and the production lead time while considering the aforementioned lot aggregation. Hence, a simulation model that can flexibly express lot organization in accordance with apparatus characteristics is required for conducting various investigations.

## 2. Characteristics of simulation model

### 2.1 Queue structure for lot organization

The basic structure of the model is a queue type and is characterized by a hierarchical structure[12), 13)] to perform lot organization in an efficient, fine-tuned manner (**Fig. 1**). In other words, a queue corresponding to the conditions of lot aggregation

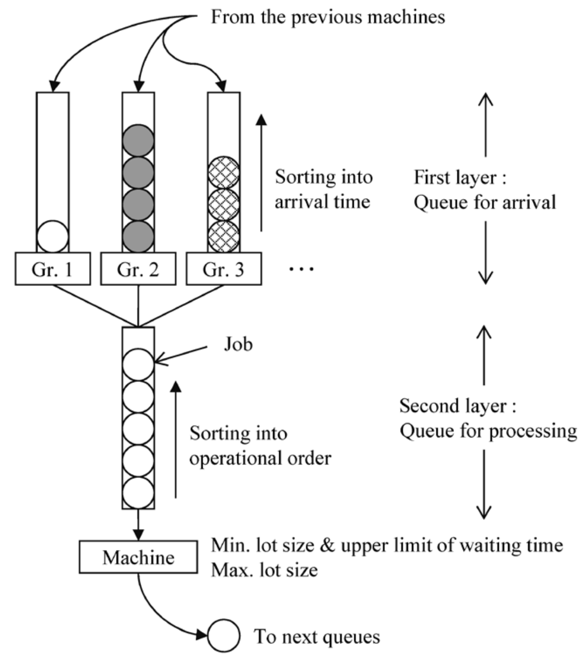



Fig. 1 Hierarchical queue structure for lot formation

for each apparatus is placed at the first layer and workpieces are stored there in the order of arrival. Since the types of lot aggregation conditions always change, this queueing model automatically generates queues in accordance with the specific attributes of each job. For each queue, calculation is conducted for the number of workpieces, aggregated in accordance with the progress of simulation, and for their waiting time so as to determine whether they are processable as a lot.

Meanwhile, each apparatus searches the arrival queues when it is ready to process the next lot, selects one queue where lots are available to be processed and extracts a predetermined number of lots from the top as the lots to be processed next. The extracted workpieces are sorted in processing order under the conditions set for each apparatus, stored in the processing reservation queue in the second layer in front of the apparatus, and are processed for the job one by one. In this way, the hierarchically structured queues enable efficient searching of the lots to be processed next and the rearranging of the workpieces.

### 2.2 Parameters used for lot organization

As the parameters of the simulation, which is equivalent to the lot organization guideline, the following values can be set for each apparatus:

- Minimum number of workpieces ; The minimum unit that can be processed as one lot. It is often set as an operational guideline for the sake of production efficiency, cost, or workability.
- Maximum number of workpieces: The maximum

unit that can be processed as one lot. It is usually determined by the apparatus specifications and operational restrictions.

- Maximum lot-waiting time: Until the minimum number of workpieces are available, the workpieces that have arrived are in a waiting state. The maximum time this state can continue is the maximum lot-waiting time. To prevent long-term stagnation, any stagnation longer than this time period allows organization as a lot even if the lot consists of fewer than the minimum number of workpieces.
- Setup time: The time it takes for the changeover between lots. In determining the next lot to be processed, productivity can be increased by preferentially selecting one with a short setup time.

## 2.3 Function for forecasting lot completion time

In the case where there are only a few workpieces with identical lot aggregation conditions and it is difficult to fill the minimum number, it is easier for implementation in the system to keep the workpieces stagnated until the above maximum lot-waiting time expires and then to process them as an incomplete lot. In real operations, however, when it is anticipated that a lot will not become available after waiting the maximum length of time, the incomplete lot is processed without waiting until the expiration of the maximum time to suppress stagnation loss.

Hence, as shown in **Fig. 2**, the present model incorporates a mechanism for forecasting the earliest starting time of each lot from the estimated arrival time of the workpiece at the queue, thereby enabling the same determinations as those for actual operation.[13] The outline is as follows:

(1) Not only each workpiece that has arrived and is waiting for its next step is stored in the queue, but also all the unfinished workpieces to be processed later are stored in the queue as workpieces scheduled to arrive.

(2) For each scheduled-to-arrive workpiece in the queue, its estimated arrival time is calculated and set on the basis of the work completion time at the corresponding apparatus and the lead time between standard steps, as shown in Equation (1).

$$\overline{T}^{S}_{j,n}(t)=\max\{\overline{T}^{S}_{j,n-1}(t)+L_{j,n},\ e_{j,n}(t)\} \quad \cdots\cdots (1)$$

Wherein

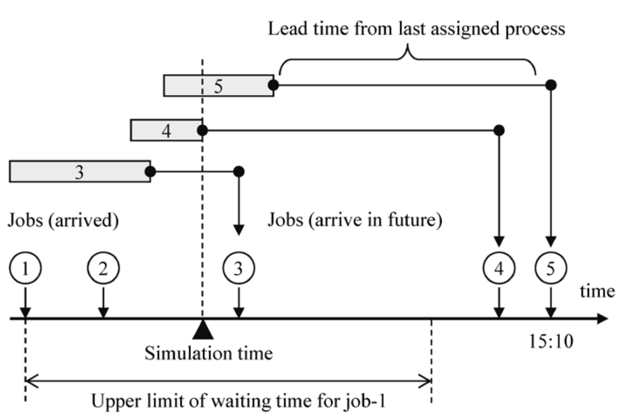
$\overline{T}^{S}_{j,n}(t)$: The estimated arrival time or arrival time at the $n^{th}$ process step of the workpiece $j$ at simulation time $t$.

$L_{j,n}$: Standard lead time between the $(n\text{-}1)^{th}$ and $n^{th}$ steps of workpiece $j$. This lead time includes the standard processing time and waiting time.

$e_{j,n}(t)$: The time when the apparatus that is to process the $n^{th}$ step of workpiece $j$ completes its last task at the simulation time $t$.

(3) The completion time for the minimum lot size is estimated on the basis of the estimated arrival time of each workpiece. More specifically, the arrival time or the expected time for the workpiece to be in the arrival queue is sorted in order starting with the earliest, and the time at which the last workpiece constituting the minimum lot size arrives is set as the estimated completion time of the lot. This time is re-calculated sequentially with the renewal of the simulation time.

(4) If there is no workpiece that can arrive by the expected lot completion time and there are workpieces waiting longer than the maximum lot waiting time in the queue, they are regarded as processable as a lot even if the lot is smaller than the minimum lot size. In Fig. 2, Workpieces ① and ② have already arrived, and Workpieces ③, ④, and ⑤ are scheduled to arrive. At this simulation time, it is determined that 5 workpieces, the minimum lot unit, will not be available within the maximum waiting time of Workpiece ①. Workpiece ③, however, may arrive before the maximum waiting time of Workpiece ① expires; hence the simulation time can be advanced until the arrival of Workpiece ③ so as to have Workpieces ①, ②, and ③ organized and processed as an incomplete lot.




| | |
|---|---|
| Min. lot size | 5 |
| Lot size within upper limit of waiting time | 3 |
| Estimated time of lot completion | 9/10 15:10 |

Fig. 2 Forecast of lot completion time

## 3. Verification of proposed model

### 3.1 Effect of forecasting lot completion time

In order to confirm the validity of the forecast function of lot completion time, or the estimation of lot completion time (ELC), the estimated time before the minimum lot unit becomes available, a simple example of a job-shop process consisting of 5 steps, 10 items, and 1,000 jobs, in which each step has 3 to 5 lot types, was prepared to compare the differences in simulation results obtained with and without ELC.[14) The results are shown in **Fig. 3**. From this figure, the following characteristics and effects of this function are confirmed.

- For a given maximum lot waiting time, the lead time is shortened when ELC is turned on. This is probably because workpieces are processed without waiting until the completion of the maximum time if a minimum-sized lot does not become available.
- When the maximum lot waiting time is short, the lead time shortening effect is small. This is probably because the processing is often performed without waiting until the minimum lot size even when ELC is OFF, making any difference between them unlikely to occur.
- The number of setup times tends to increase when ELC is ON.
- When the maximum lot waiting time is extremely short or extremely long, the difference in the number of setup times is small. As described above, when the maximum lot waiting time is short, small lots are likely to be processed regardless of whether ELC is ON or OFF, making a difference between them unlikely to occur.

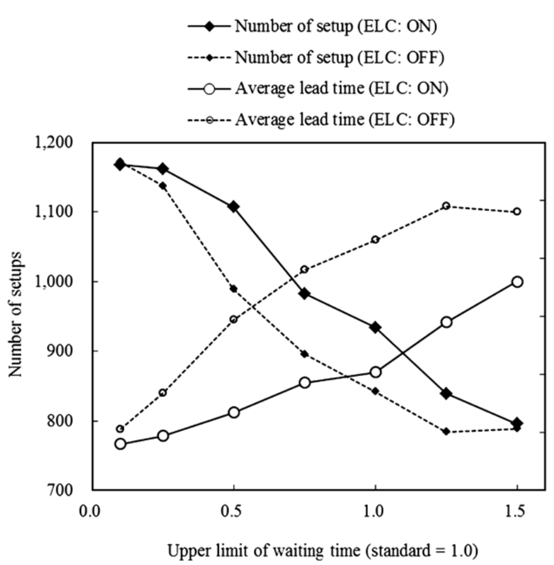



Fig. 3 Difference in number of setups and lead time based on predicted lot completion time

In addition, it is considered that, when the maximum lot waiting time is long, a lot that has not become available even after the waiting period can be processed early as having the same size.

Next, the above experimental results were compared on the two axes of the number of setups and the lead time. The results are shown in **Fig. 4**. It is confirmed that there is a trade-off relationship between the two regardless of whether ELC is ON or OFF, and when ELC is ON, it is shown that the trade-off is relaxed. This indicates that, when ELC is ON, the production can be accomplished with a smaller number of setups for a given lead time, or with a shorter lead time for a given number of setups.

### 3.2 Verification in realistic scale process

#### 3.2.1 Target process

Next, the production process at Kobe Steel's aluminum rolling plant was set up in the present simulator to perform an experiment verifying the lot organization guideline, assuming actual utilization in the plant. **Fig. 5** outlines the aluminum rolling process. A slab produced in the melting & casting step is processed through several to dozens of steps including hot rolling, cold rolling, heat treatment (in batch/continuous furnaces), straightening, surface treatment, and cutting before being shipped as a plate or a coiled product. The simulation targeted the steps of hot rolling and thereafter, in which the number of apparatuses is assumed to be approximately 70 and the number of workpieces charged per day to be approximately 100. In addition, the conditions for lot organization were set for each main apparatus (**Table 1**). It should be noted that there were several lot attributes for apparatuses with a smaller number of attributes and several dozens for apparatuses with a greater

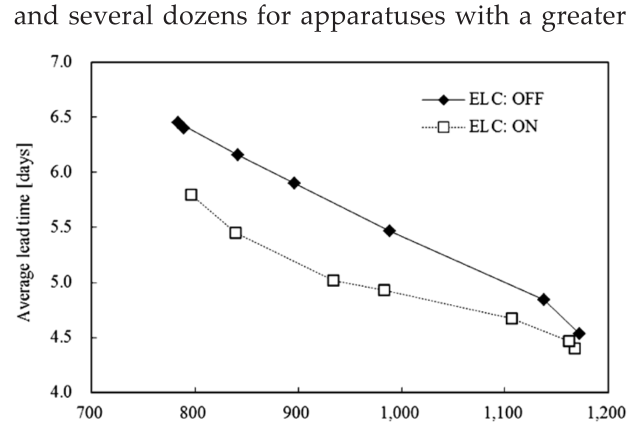



Fig. 4 Relationship between number of setups and lead time

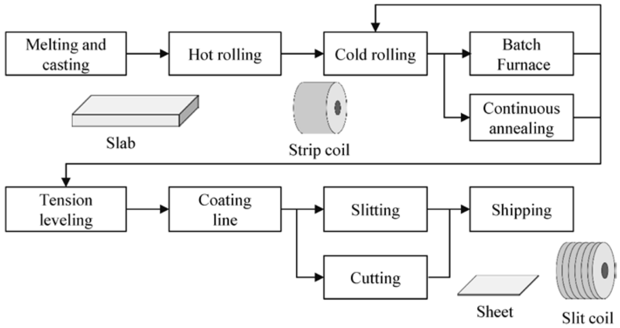



Fig. 5 Example of manufacturing process in aluminum rolling mill

Table 1 Example of lot organizing conditions

| Facility | Collecting attributes | Lot size* (min., max.) | Max. lot wait [days] |
|---|---|---|---|
| Cold rolling | Roll surface type | (3, 100) | 7 |
| Batch furnace | Treatment temperature | (5, 15) | 7 |
| Continuous annealing | Treatment temperature | (5, 62) | 7 |
| Coating line | Paint type | (13, 44) | 30 |

*Lot size is the ratio to when maximum lot size of cold rolling = 100

number of attributes (an indentical attribute allows organization into one lot).

### 3.2.2 Verification of lot organization guideline and productivity index

As a guideline of lot organization, a 3-month-long simulation was performed by changing the minimum lot size (minimum number of workpieces) exemplified in Table 1 to examine representative productivity indices.

First, the settings of minimum lot size were changed for the main apparatuses in the production process to examine the changes in the resulting lot sizes organized by the simulator. An example of the continuous annealing furnace is shown in **Fig. 6**, and an example of the surface treatment apparatus is shown in **Fig. 7**. In either example, increasing the set value for the minimum lot size increases the average size of the lot organized in the simulator, and the amount of the increase gradually decreases. This is probably because when the minimum lot size becomes larger, workpieces whose waiting time exceeds the maximum lot waiting time occur before the minimum lot size is reached, resulting in an increase in the number of lots smaller than the minimum lot size. It should be noted that the dotted line in the figure shows, for reference, the average lot size manually calculated from the actual data.

The minimum lot size was set to approximately 20% at maximum for the continuous annealing furnace and to approximately 70% for the surface treatment apparatus in the hope of simulating a lot size close to that of actual operations.

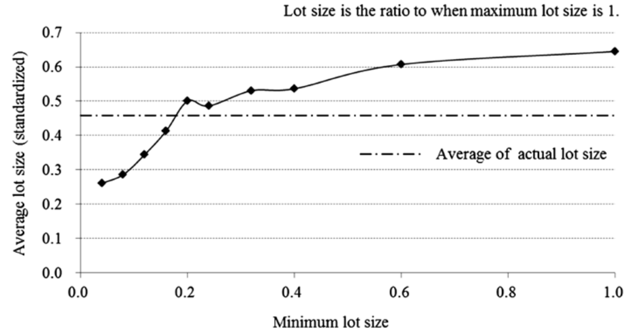



Fig. 6 Relationship between minimum lot size setting and average lot size of simulation results in continuous annealing line

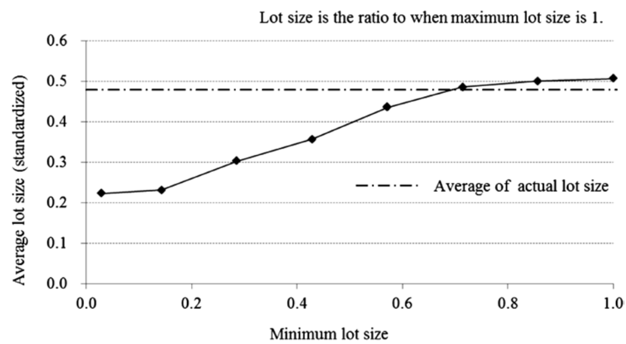



Fig. 7 Relationship between minimum lot size setting and average lot size of simulation results in surface coating line

Next, the main apparatuses with high loads were selected (about 1/3 of the whole), and the minimum lot size was changed with a constant ratio to the maximum lot size to study the total number of setups and the average lead time from the hot rolling to shipping. The results are shown in **Fig. 8** and **Fig. 9**, respectively. It is shown that, as the minimum lot size increases, the number of setups decreases, but the decrement becomes smaller. On the other hand, the lead time increases almost linearly, raising concern that making the minimum lot size too great may increase the disadvantage of increased lead time rather than the advantage of a decreased number of setups. The number of setups affects the production cost and work load, while the lead time affects WIP inventory and the ability to respond to the deadline. For this reason, it is important to utilize the guideline of the minimum lot size on the basis of the allowable level of setups and target lead time.

### 3.2.3 Accuracy verification based on macro logistics performance

A prerequisite for using the simulator to forecast the future logistics situation in order to utilize it for various operation investigations is to adjust the parameters of the simulator so that the logistics situation at a certain time can be reproduced with

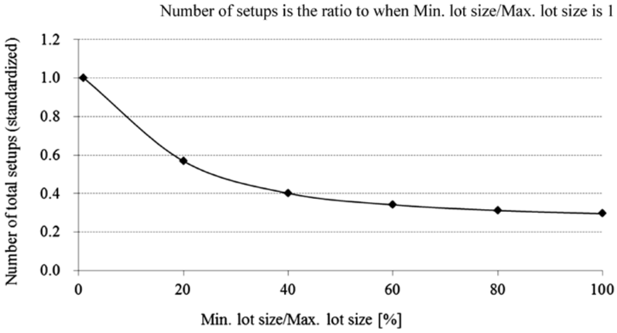



Fig. 8 Relationship between minimum lot size and number of total setups

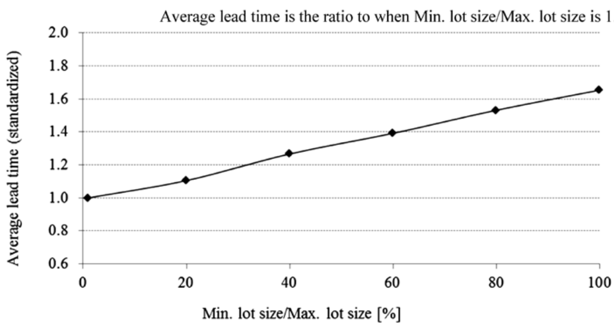



Fig. 9 Relationship between minimum lot size and average lead time

reference to a certain period in the past. This allows the setting of the base for future forecasts. Hence, a certain period in the past (half a year) was chosen, and the processing time, setup time, operation rate, item composition, yield, etc., were set as the actual base for the period in addition to the minimum lot size verified in the previous section. Thereupon, a comparison was made between simulation results and the actual values, in which the simulation was based on a virtually prepared charge plan. The results include the amount of intermediate WIP in the plant obtained in this way, as well as the amount of daily transportation among storage locations.

In the evaluation of a logistics system, maximum values count as well as average values. **Table 2** shows the results of comparing the average value and the maximum value of the amount of intermediate WIP for a typical storage location and the amount of transportation taking place between them. As shown in this table, the average values and the maximum values of the simulation results differ by 5% or less from the actual results. Given that the actual maximum values are 125% to 150% of the average, these results are well within the practically acceptable range for evaluating macro logistics. In particular, the maximum values agree well, which is the key point in considering the enhancement of the storage location and the transportation capacity, confirming that the present simulator can be an effective tool for the future verification of logistics resources.

Table 2 Comparison of amount of work in process and transportation amount between actual values and simulation results

| | | Work in process | | Transportation amount | |
|---|---|---|---|---|---|
| | | Total | Cold rolling | ShopA →ShopB | ShopC →ShopD |
| Max. | Actual | 125 | 125 | 155 | 150 |
| | Sim. | 117 | 122 | 148 | 143 |
| Ave. | Actual | 100 | 100 | 100 | 100 |
| | Sim. | 96 | 102 | 99 | 102 |

Each value is the ratio to when actual average is 100.

## 4. Example of simulator application

The simulation model proposed this time is intended to be applied in studying the operational policy in a plant where lots are organized uniquely at each step in the production and to investigating investment in apparatus and logistics resources. The following describes application examples.

### 4.1 Formulation of guideline for lot organization in accordance with load

From the results described in Section 3, it was found that the minimum lot size set for each apparatus strongly affects the changeover setups (which relates to the production cost) and lead time (which relates to the ability to respond to deadlines). Hence, the simulation model is expected to be utilized as a source of guidelines for minimum lot size, obtained from the number and time period of setups acceptable for a plant and the target lead time to achieve the production plan. For example, when the order-receiving schedule changes significantly, the guideline of lot organization may also change greatly as the productivity required for each apparatus changes. To cope with this, the present simulator imposes a restriction on the setup time of the bottle neck apparatus acceptable for each apparatus to achieve the productivity required for, e.g., the order-receiving schedule, and provide the guideline for minimum lot size to realize said setup time. Moreover, the simulation results allow the estimation of lead time for such a case. These provide the basis for providing a planning guideline for each apparatus in a coordinated manner and for calculating the production period for each item.

### 4.2 Consideration of necessary WIP amount and storage capacity at each location

In general, it is necessary to increase the amount of WIP held in front of an apparatus in order to increase the lot size for the apparatus of the intermediate process and perform the operation with less setup time.[15] The present simulator analyzes the relationship between the minimum lot size and the setup time or the WIP amount, as shown in Fig. 8 and Fig. 9, so as to grasp the amount of WIP to be kept for the setup time allowable for production management. For this reason, this simulation model can be utilized in supporting decision making in formulating WIP holding plans when preparing monthly or periodic production plans and in the study of the minimum lot size guideline considering the capacity of storage locations. Especially in the case where products, ferrous and non-ferrous, are large in size and manufactured in large quantities, it is difficult to secure storage locations within a plant, and planning based on such a viewpoint becomes important.

### 4.3 Consideration of charge cycle for each item

In a material processing plant, there is also a process characteristic in the fact that, further back in the upper-stream steps, the differences in the degree of freedom for apparatus selection and in production conditions become smaller within an identical item ("Item," as used here, generally refers to an order for identical applications and characteristics of products"). Hence, how to set the charging intervals for each item at the plant is also an important decision item in production management. **Fig.10** shows an example of the simulation results for the WIP transition at a certain storage location when the rolling interval for an item is changed in the hot rolling process. Here, two different comparisons are made for the case where the hot rolling interval of an item is N days, and one where the interval for the same has been doubled to 2N days.

As shown in Fig.10, the longer the charge intervals of an item in the hot rolling, the greater the WIP fluctuation becomes, with a higher peak value. It should be noted that, although not shown in these figures, the longer the charge interval, the fewer the setups. This is because a longer charge interval allows an item to be charged in a greater volume during a given period of time, increasing the tendency of large lots to be supplied to specific apparatuses and storage locations.

A typical situation is considered where the capacity of a storage location is not large enough, as with the case in the previous section. It is assumed that the capacity of a storage location is 650 items and the charge interval is N days. In this case, the WIP can be temporarily stored in a different location

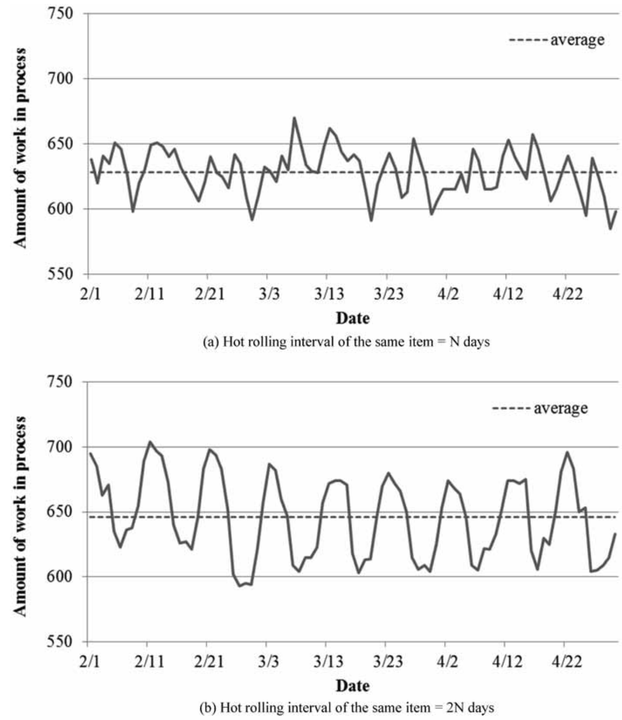


Fig.10 Hot rolling interval and work in process

(e.g., in a rented warehouse outside the plant) only for a few days in a period of three months until it is refreshed. If the charge interval is doubled to 2N days, it must be refreshed within about half that time period. In addition, a larger amount results in a substantial cost increase. In such a case, it is necessary to compare the cost increase due to the increase in the setup and the cost increase due to the WIP movement to the external warehouse to determine the charge interval. Although it is necessary to calculate the specific cost separately, the application of the simulation results of logistics to the decision making in production management enables an advanced decision which would be difficult to reach with experience and intuition alone.

### 4.4 Capacity evaluation of transportation resources

In the production steps of material processing, multiple apparatuses often share one storage location. Hence, the present simulator allows the arbitrary setting of the correspondence between the apparatuses and the storage locations. This has made it possible to evaluate not only the amount of WIP for each storage location but also the number of WIP items moving among storage locations in chronological order. Transportation means, such as track, forklift, crane, or dolly, are determined by mutual relationships among the storage locations, and it is possible to estimate the capacity required for these means of transportation. Hence, the present simulator can be applied to decision making concerning investment to correct inadequate transportation capacity and to negotiations with the parties that outsource transport services.

## 5. Challenges for platformization

Kobe Steel intends to continuously utilize the developed simulator as a simulation platform for the making of various decisions in actual plants. However, practical applications are difficult only with the simulation model introduced this time, and further enhancement of functions as described below is considered to be necessary.

- For utilization in online decision making based on the present time, it is necessary to adjust the initial state of the simulator to the present state of the plant. To that end, it is necessary to establish an environment where the actual data of the plant (WIP status, start/completion time for each apparatus) and finalized process plan can be acquired in real time.
- The apparatuses and operations in the plant are continuously improved, and it is essential to periodically adjust the capabilities and setup conditions of the apparatuses. Since there are a vast number of apparatuses and setup conditions, a mechanism is necessary for automatically calculating these conditions from the accumulated actual data and registering them in a master.
- When the production plan changes drastically, the conditions based on past achievement may fail to produce the planned amount in a predetermined period. Under such circumstances, it is necessary to change the production procedure within a technically allowable extent to distribute the apparatus load. This area requires an expert's decision, and there is a need for an interactive mechanism.
- It is also an important role of simulation to derive conditions for obtaining intended results. Such cases reveal the importance of a visualization tool for determining which conditions should be modified by searching for simulation results, as well as a tool for analyzing the result data.

## Conclusions

This paper has described a simulation model that can quantitatively evaluate the influence of the lot organization conditions on the flow of production on the basis of the product and process data while focusing on the operation with lot organization, which is the operational guideline for material manufacturing processes of a multi-product, mixed-flow type. In constructing the model, a method of generating a queue for each lot group at each step was adopted to efficiently and precisely reproduce the process-specific lot operation at each step. In addition, it was made possible to adjust the stagnation time for lot aggregation at each apparatus by providing the maximum time that a workpiece can wait in the queue until a lot with a predetermined size becomes available. Furthermore, a mechanism was incorporated to suppress unwanted stagnation time, which occurs when the lot does not become available within the maximum waiting time, by forecasting the time when the workpieces, including the ones in not-yet-started steps, will arrive at the queue.

A case study has verified that the maximum waiting time until a lot with a predetermined size becomes available and the minimum lot size can be parameters for adjusting the trade-off between the number of changeover setups and the production lead time. Also, a function to forecast the arrival time at each queue was introduced, and thereby the trade-off between the number of setups and the production lead time was confirmed to have been relaxed, as compared with a case where this function was not used. In addition, a comparison of the execution results based on a product and its process data at an aluminum rolling plant and actual logistics data has confirmed the accuracy feasible in the practical use in macro logistics verifications.

The future plan is to acquire knowledge concerning the parameter setting related to lot formation, which provides guidelines that have not necessarily been clarified in actual process management, although it is necessary to adjust the minimum lot size and maximum lot waiting time, etc., in accordance with the production environment with the aim of enabling more accurate calculation of the production flow in the actual factory. A challenge for the more distant future is to develop a technology to automatically adjust many parameters related to the lot organization and setup conditions in accordance with the changes in operation so that the present system is continuously utilized in supporting daily planning and operation review.

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