Toward the integrated optimization of steel plate production process

— A proposal for production control by multi-scale hierarchical modeling —

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Integrated optimization of production in the steel industry to simultaneously minimize lead time and improve productivity is a real challenge. Lean manufacturing, recognized as a leading successful example of such optimization, is characterized by synchronization of time scale of production with that of the mainline. However, in the steel industry, it is inherently difficult to implement synchronization and reduction of production time to the same degree as in the automobile industry. This difficulty motivated our method for integrated optimization of production at the plant level in the steel industry, by modeling the production control as a multi-scale hierarchical structure in time. This paper describes an attempt to systematize production knowledge in industry by a synthesis of practical knowledge (of shop-floor engineers) and company experiences.

Keywords : Steel industry, integrated optimization, production control system, multi-scale hierarchically structured model, lean production system

1 Introduction

Integrated optimization in production control for manufacturing an unlimited variety of products with zero defect, using minimum resources, in the minimum manufacturing lead time[Term 1] and with zero stock, is the ultimate goal of *monozukuri* (manufacturing). Generally, production control is classified largely into pull- and push-types.[1][2] The pull-type production control is used for the type of manufacturing for which in upstream processes optimal parts and intermediate goods are provided sequentially to the requirement of downstream processes or customers and is applicable to assembly industries. One such industry is the automobile industry, which gave birth to the lean manufacturing system, one of the major successes of the 20th century. In contrast, in push-type production control, instructions for production are given to feed parts and intermediate goods starting from the entrance of processes and to channel them from the upstream processes to those of downstream. It is applicable to many industries including process industries such as steelmaking and chemical. The issue here, where push-type production control is concerned, is how the integrated optimization of production can be achieved, while simultaneously realizing the minimization of manufacturing lead time and the improvement of efficiency (productivity).

This paper analyzes examples of relevant cases of Kimitsu Works of Nippon Steel Corporation, and studies how the concept or methodology of the lean production system originally derived from pull-type production control is made applicable to the manufacturing processes of the steel industry that has a process structure suited to push-type production control. In the Plate Mill of Kimitsu Works, the production control system was remodeled to realize integrated optimization in a process industry resulting, in the early 2000s when demand rose sharply due to the rapid expansion of the Chinese economy, in a substantial shortening of manufacturing lead time thanks to the reduction of in-process stock (Fig. 1) and in the faster expansion of production compared with other plate mills in Japan (Fig. 2). How could optimization at the level of the entire plate mill be achieved, where the manufacturing flow is complex and the constraint hurdles are quite high? This paper explains how the innovation of the production control system on the shop floor was realized, and what the steel industry, a process industry, can learn from the lean production system, by identifying and modeling the realized production control system as a multi-scale hierarchical structure.

2 Manufacturing of steel plates

The manufacturing processes in a steelworks[Term 2] consist of producing pig iron at the blast furnace that consumes raw materials of iron ore, coal, etc., then producing steel by refining iron at the converter. Steel thus produced is molded into slabs (oblong sheets of steel) on the continuous casting

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line, and rolled to become steel plate products. Steel plates are produced based on orders received and on elaborate production planning. Each plate weighs about 3 tons and is manufactured from a large lot of 300 – 400 tons per one converter vessel by dividing them into small tonnage for each plate. Steel plates as products are used widely as important components of various structures including ships, buildings, bridges, construction/ industrial machinery, offshore structures for drilling offshore oil/ liquefied natural gas, etc., and they must comply with a huge variety of standards. They have characteristics that differ from other steel products. For example, their places of use are rigorously specified and each one of them is delivered in a particular specified size.

Steel plates are manufactured based on orders received and the orders are diversified and small in each lot, which explains why their manufacturing processes are complicated. First of all, in the rolling processes, plates of various sizes are manufactured, and during these processes, their metallurgical microstructure is controlled to meet varieties of specifications in their material properties. After rolling, in the finishing processes, various works are conducted including the correction of defects occurring in the upstream processes and supplementary treatments (heat treatment, coating, etc.).

By incorporating material quality (*Tsukurikomi*) during the rolling process, the thermo-mechanical control process (TMCP) was developed in Japan during the 1980s and for the 30 years that followed, TMCP played the role of one of the state-of-the-art core technologies for manufacturing high quality steel plates in Japan. The schematic illustration of the steel plate rolling processes is illustrated in Fig. 3.

TMCP enables the production of as-required steels of whichever microstructure and property by controlling the

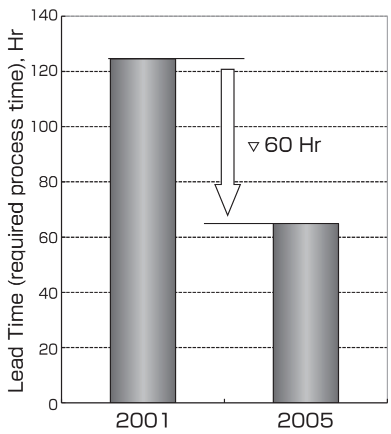

Fig. 1 Shorter production lead time in the Plate Mill of Kimitsu Works

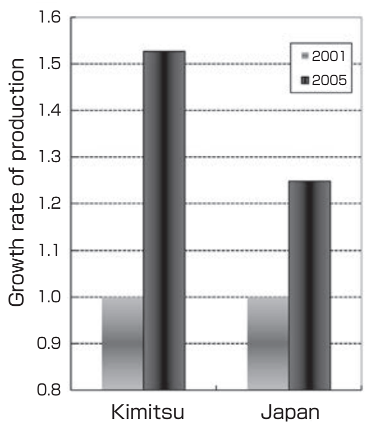

Fig. 2 Comparison of production growth rates of plate mills in Japan
(Source: Monthly Steel Statistics Report of Secured Orders of Steel Products (ordinary and specialty steel products), The Japan Iron and Steel Federation)

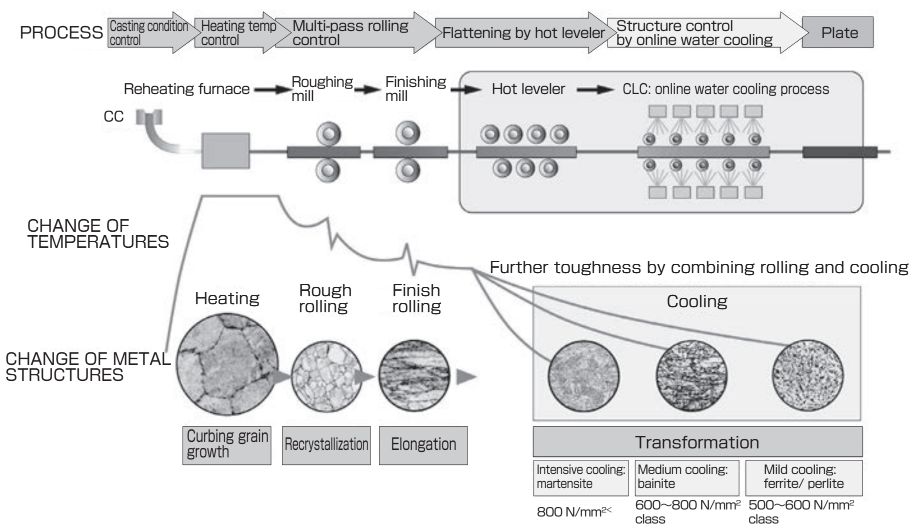

Fig. 3 Microstructure control of steel plates and TMCP technology[3]

cooling speeds after rolling, and it has been a fundamental technology in the development of new quality steel plates in recent years. However, it is difficult to manufacture TMCP steels that maintain the correct shape and the uniform cooling of a huge steel plate with several meters in length and width. Furthermore, where the manufacturing of high-quality steels is concerned, processes such as heat treatment, coating, etc. are implemented, causing problems of increased loads (process capacity vs. volume of required processing) in the finishing processes, lowered integrated production capacity, prolonged manufacturing lead time, and increased inventory, etc.

3 Comparison with the automobile industry's lean production system

What kind of production control system is the automobile industry's lean production system? Firstly, as is typical of the automobile industry, the effective use of time on the assembly line was set as an objective. To achieve this, various methodologies conceptualized as automation, just-in-time, etc. were invoked, thus eliminating *muda* (waste) on the shop floor thoroughly, and a production system that could respond flexibly to the changes of market trends and production processes was completed.[4]-[7] The essence of this production system is the pull-type production control that makes the upstream processes provide the final market with whatever the downstream needs in the exact amount required and at optimal timing.[2][8] In some of the assembly industries, mostly among electric equipment manufacturers, systems other than the assembly-line system, for example, the cellular manufacturing system, have been introduced.[9] These share their objective of adopting the lean production system in that they also control time effectively.

Now let's determine why this production system that has been successful in assembly industries has not worked well in the steel industry. When considering the reasons, it becomes necessary to understand that the structures of processes between assembly industries and process industries are intrinsically different. The lean production system is based on the assumption that the mainline is fully leveled evenly, and it will become effective when synchronized with sub-lines. In contrast, the steel industry has had as given the integrated processes of the blast furnace-converter-rolling mill, and has pursued the improvement of efficiency by constructing larger equipment/ facilities. A plate mill is located in the midst of a push-type process structure whose upstream processes pursue economies of scale, and application of the lean production system was difficult because it assumes the existence of a pull-type process structure that pursues minimization of stock and production lead time by coordinating each work process in order to satisfy the needs of the downstream processes.

In the steel industry, to improve efficiency, it is important to group together as many individual orders as possible, so that their manufacturing lot size in the upstream processes of the semi-finished product – steelmaking is increased. As a result, it used to be considered essential to have a process "to group orders into a larger lot", i.e., to manufacture steel in a large lot in the upstream processes and to divide it in the downstream processes to meet individual orders. The pursuit of scale in the upstream processes leads to the production of intermediate goods with common steel types and sizes, and because the production lot is normally larger than the delivery lot of products, it also contains the intermediate goods of products that differ in delivery timing; this flows down the downstream processes spasmodically. Such process structure causes stock to increase, and shortening the production lead time simply by studying the lean production system was difficult.

4 Efforts made for integrated optimization in manufacturing steel plates

4.1 Past efforts

The Japanese iron and steel industry, amid the long-running structural economic depression after the 1973 oil shock, reproduced on a diminishing scale and promoted rationalization, concentrating its efforts on improving labor productivity. Where the fields of shipbuilding, buildings, bridges, tanks, line pipes, etc. are concerned, i.e., major customers of steel plates, they realized weight saving, higher functionality and combined characterization, demanding the steel industry to deliver products, for example, with higher strength and toughness, or high environmental-resistance. New structural steels with additional functions were developed using the TMCP technology, but steels by accelerated cooling had lower rolling efficiency[Term 3] compared with steels for general use. Furthermore, as the application of the TMCP technology advanced, the load of the correction (flattening) process[Term 4] became heavier and the state of heavy load in the finishing processes became increasingly commonplace as the product mix shifted to a mix of more sophisticated products. In such a situation, the necessity of reinforcing the finishing capacity became increasingly recognized, but it was a common understanding that, where steel plate manufacturing was concerned, it was difficult to improve the integrated efficiency of the plant as a whole. Solving the bottleneck problem in the production system had not been prioritized as a management objective of high priority, partly because the shorter production lead time could not demonstrate a short-term profit improvement effect.

Furthermore, because the upstream processes of ironmaking-steelmaking occupy a significant part in the cost structure of an integrated steelworks, steelworks management with a cost-oriented consciousness tended to be more interested in them.

As a result, actions to deal with the problems of increasing in-process stock and of smaller order lot sizes resulting from the highly sophisticated product mix tended to wane. Under the circumstances where operation under chronically excessive in-process stock was accepted as the norm, the bottlenecks in the finishing processes surfaced when demand increased and delivery delay due to substantial prolongation of the manufacturing lead time occurred. Situations arose where adjustment of the amount of orders to be received was required, which used to be dealt with symptomatically by, for example, increasing the number of workers in the bottleneck process.

4.2 Management innovations that enabled integrated optimization

In order to realize production control that enables optimization at the level of each individual plant, there has to be a series of management innovations that makes it possible. During the many years when Japanese crude steel production stagnated, Nippon Steel continued its long-term efforts to streamline its management. During the 1990s, under the strong leadership of top management, it made innovations in terms of its organization/ management structure, aiming to fortify its competitiveness. The core innovations made were the individual product-type-wise management that contains the integration of production and sales,[10] and the drastic integration/ restructuring of organizations was realized by streamlining head office functions and compressing hierarchies.[11] The organizational reform at the corporate level effectuated in 1997 authorized middle management such as plant superintendents to make independent and centralized decisions on shop floor operations, giving them the opportunity to work as entrepreneurs. Kimitsu Works used to have an organizational structure where one department oversaw production scheduling etc. of the whole company and supported each division that manufactured individual products. However, as a result of the organizational restructuring, all the categories concerning the production of steel plates, of production scheduling, quality control and equipment maintenance that used to be overseen overall at headquarters were placed under the management of the Plate Mill. Under this new structure, the Plate Mill superintendent initiated the innovation of the control structure for plate production. Based on the understanding that it is integrated optimization at the level of individual plants that creates the power to maintain the product competitiveness for a long period of time, the management paradigm of the production control shifted substantially from the conventional system that aimed at enhancing productivity at the level of each facility to one that aims at shortening the manufacturing lead time through the curtailment of in-process stock. This was the start of the challenge to apply the lean production system developed in a pull-type industry to the plate manufacturing that is intrinsically compliant with the push-type industry.

4.3 Actions taken by middle management on the shop floor

The rolling process greatly affects the quality and cost of a plate mill. Therefore, the superintendent, aiming first to enhance the rolling efficiency, worked on the development and application of a support model of production control. Then, to solve the predicted problem of insufficient capacity of the finishing processes that would occur once the rolling efficiency was enhanced, he worked on enhancement of the efficiency of each one of the finishing processes in addition to the bottleneck processes (flattening process, etc.). The finishing processes used to be positioned as subordinate processes to rolling and their equipment was maintained mainly based on the breakdown maintenance (BDM). However, the superintendent changed it to the total productive maintenance (TPM), under which the functions of equipment maintenance and manufacturing work together in unison, aiming to keep the equipment/ devices functioning properly whenever required.

Furthermore, the optimization of plant management as a whole required a series of supporting activities by the staff related to the integrated optimization. Among all the problems, the reduction of in-process stock in the finishing processes works in opposition to the enlargement of production lot sizes in the preceding processes, and may become a short-term cost-push factor. This means that the reduction of in-process-stock in the finishing processes gives rise to problems that the efficiency enhancement of individual equipment alone will not solve, thereby requiring “Heijunka” leveling for allocating even process loads at the planning level. The designing of production lot sizes (material procurement design) is the responsibility of scheduling staff, but at the time, there was no system capable of conducting material design that took into consideration the even distribution of loads in the finishing processes. In order to solve this problem, engineers who were familiar with the shop floor operation and knowledgeable also in system development were deployed to the production scheduling group and a support system was developed for leveling the loads of finishing processes evenly from the perspectives of cost, efficiency and manufacturing lead time. Technical details describing the way in which the above was achieved in a time series are mentioned in the following chapter.

5 Innovation in the production control system of the Plate Mill

5.1 History of support system development

Production control schedule and schedule types are classified into the primary schedule (overall production), secondary schedule (reference production) and detailed schedule (order of manufacturing), and for each type, the planning elements are organized by the time scale of plan, units of scheduling and frequency of modifying the plan, product categories, and subjects matters covered by the planning.[12]

Regarding the support systems of production control, MRP (material requirements planning) was introduced by General Electric in the mid-1950s, and since then for reinforcing the limitations of early MRP, support systems such as MRP Ⅱ, ERP (enterprise resource planning) and APS (advanced planning and scheduling) have been developed. Regarding their deployment and diffusion, the results of application of MRP and APS to simple and stabilized manufacturing processes have been reported. However, there is still no report on the result of their application to complex manufacturing processes where production volume changes frequently.[12]-[21] This reflects the fact that in the assembly industries where the pull-type production control represented by the lean production system is effective, the plan is reviewed in multi-phases and the accuracy of the plan of parts ordering, etc. are automatically improved as the time of actual production approaches.[12] Therefore, there has not been much need to build a comprehensive model/ support system that dynamically and organically connects plans with different time scales.

In contrast, in the steel industry, a typical process industry, for operating integrated and continuous large-scale production facilities, an enormous amount of information for equipment control and production control has to be handled. Therefore, it introduced a production control system supported by large-scale computers ahead of other industries.[13] The production control system in the steel industry, corresponding fundamentally to the push-type production control system, prioritized the optimal control of the processes of intense heat and high temperatures, responses to the production fluctuation of upstream processes, and the maximization of each manufacturing lot size by integrating order information. Therefore, only very limited energy has been spent for supporting planning and scheduling for achieving the integrated optimization in terms of the manufacturing lead time and the in-process stock of intermediate goods. Furthermore, the sophistication and diversified specifications of recent products increased the complexity of the production control of plate manufacturing. Since large-scale production was carried out combining orders of various steel types whose processes to be completed were different, it was nearly impossible to determine at the very start of manufacturing the completion processes of individual intermediate products, and it was extremely difficult to predict and control manufacturing lead time.

To realize the pull-type production control under such an environment, it is necessary to dynamically realize the optimization of manufacturing lot sizes and manufacturing lead time in all the processes by developing a model capable of defining comprehensively the influence of the size of manufacturing lots on the efficiency of each process and the manufacturing lead time, and by deploying support systems. In the steel industry where production fluctuation and variation are substantial, applying the existing MRP, APS, etc. was practically impossible, so we developed a series of models and introduced them to the shop floor operation one by one.

5.2 Development of a new set of production control systems

(1) Efficiency model

For improvement in the efficiency of rolling processes (for rolling processes, tonnage of slabs rolled per hour), the rolling processes that are the mainline in plate manufacturing were always the most important elements. Conventional evaluation implemented concerned mainly the reinforcement of individual pieces of equipment, but investment in the reinforcement in a short cycle means a large extra load in terms of management, and this is not easy to achieve. To overcome the issues of heavier load in rolling as a consequence of expanding TMCP technology application and the lower efficiency caused by diversified products, we began concentrating our efforts on enhancing the efficiency of the entire rolling processes arranged continually, directly, and in tandem. The efficiency of each process in rolling varies greatly depending on product specifications. Moreover, friction of the preceding and subsequent material processing (idle waiting time accrued due to the difference in the preceding and subsequent processing time) frequently occurs, changing sequentially the bottleneck processes of the materials being processed. The importance of bottleneck countermeasures is clearly indicated in the theory of constraints (TOC),[14] but because it is difficult to apply simple bottleneck countermeasures to rolling processes, we developed a new efficiency model that enables quantitative evaluation of the lowering of efficiency attributable to the friction between individual rolling processes. The development of this efficiency model was based on the assumption that the TOC is applicable also to the solution of problems in complex and continued processes like rolling processes.

(2)Manufacturing lead time model

Thanks to the efficiency model, the optimization of process design and appropriate equipment reinforcement of bottleneck processes were realized and the production efficiency of the rolling processes improved dramatically. This, however, verified the lack of capacity in the finishing processes, resulting in the increase of in-process stock caused by the fluctuation in the amount to be processed. To deal with this, we worked on the efficiency improvement of each process throughout the finishing processes, and with the help of a research and development crew, developed a logistics simulator using a simulation tool for modeling discrete event systems, in an attempt to reduce in-process stock and shorten the production lead time. However, we did not succeed in obtaining a satisfactory result. The simulator assumes as given the parameters of daily manufacturing lot sizes, product mix, processing capacity of each finishing process, equipment utilization rate, etc., and has as its objective the fine-tuning of the priority order of processing, which we consider was the fundamental cause of this failure to obtain a satisfactory result.

We learned again through the study of the existing cases of the lean production system and also from understanding the limitations of the logistics simulator that it is most important to realize leveled production, together with an appropriate investment in bottleneck processes. Therefore, to ensure the enlargement of manufacturing lot sizes and the leveling of loads on finishing processes simultaneously, we worked on the development of a production lead time model capable of describing comprehensively the relationship between the manufacturing lead time variation and the success rate of delivery time, as well as the relationship between the product mix and manufacturing lot sizes and between the manufacturing lead time and the amount of stock.

(3)Required time/ in-process stock model

The above undertaking identified the relationship between the manufacturing lead time of each product type whose estimation used to be difficult and the corresponding time required to complete each process. However, even at this stage, it was not fully understood how the required completion time of each process is determined and which control factors played a part therein. In contrast, for the analysis of waiting time for cases where there is a variation in the frequency and intervals of events and in the intervals of processing, the queuing system theory was applicable.[12] The development of a model capable of describing the required completion time and in-process stock volume of each process became possible by the development of a required time/ in-process stock model based on the queuing system theory.

5.3 Development of an efficiency model

We have already explained that the plate production is classified largely into the upstream rolling processes and the downstream finishing processes. The rolling processes are comprised of heating, rolling, cooling, etc. and each one of these processes is arranged continuously, in direct connection and in tandem. In contrast, the finishing processes are comprised of heat treatment, ultra sonic testing (UST), coating, gas cutting, cold leveling (CL), oil-press leveling (OL), surface grinding, etc., and each process is arranged independently and in juxtaposition.

Like the plate rolling processes where many types of steel mix and flow, changing greatly the efficiency of each process and where the processes are arranged continuously, in direct connection and in tandem, the efficiency of each process changes in response to the process conditions of each material, and the bottleneck processes change sequentially. In association with this, the friction of preceding and subsequent processes occurs frequently, changing greatly the efficiency of the plant as a whole. In contrast, if the processes are arranged independently, it is possible to stock in a sufficient amount between processes as a buffer, and the friction of inter-process processing rarely occurs, resulting almost uniquely in the efficiency of each process by the process conditions of each material.

In order to overcome the issues of heavier load in rolling as a consequence of having expanded the application of TMCP/ accelerated cooling technology and of diversified products, the most important issue is to reduce the inter-process friction of processes in rolling caused by the diversification of process conditions associated with the diversification of steel types and by the smaller lot sizes to be processed. We therefore attempted to develop an efficiency model that enables quantitative evaluation of the lowering of efficiency attributable to the friction between individual processes of rolling, by determining the efficiency of each process according to the process conditions matching the material specifications and to the processing lot sizes, and at the same time by identifying bottleneck processes.

Each one of the rolling processes has various factors that work against better efficiency. For example, the heating process has the temperature at the start of heating, heating conditions, etc.; the roughing process has the temperature to extract a slab after heating, rolling sizes, etc.; the finishing rolling process has the TMCP temperature, weight of the slab to be rolled, etc. We developed a rolling efficiency model

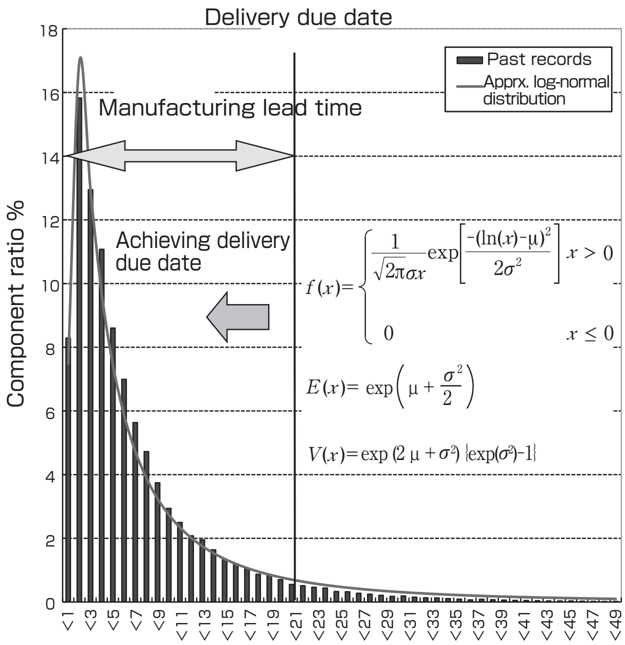

Fig. 4 Distribution of manufacturing lead time

that determines the efficiency of rolling processes as a whole particular to each product group, by properly extracting the factors of each process that affect efficiency, classifying them into product groups where these affecting factors have significant differences, calculating statistically the efficiency by each product group and comparing the efficiency of each process by each product group, and thus identifying the bottleneck processes contained in the sub-processes installed in tandem and connected directly. Once the sizes of product groups are properly adjusted, the difference between the actual records of integrated efficiency and the integrated efficiency specific to each product group is balanced out for the rolling processes as a whole, and irrespective of the changes caused by production permutation, it becomes possible to estimate the rolling efficiency with high accuracy (see NOTE 1). With this rolling efficiency model, it is also possible to estimate the rate of occurrence of processes that occur in the downstream processes for each product type.

The efficiency model's objective is to determine the efficiency and the load of each process, but by applying this model as indicated above, it achieved a substantial enhancement of rolling efficiency in the rolling processes.

5.4 Development of manufacturing lead time model

We achieved a substantial improvement in the efficiency of rolling processes, which, however, resulted in more pronounced characteristics of the push-type structure and in the increase of requirement fluctuation (fluctuation in the amount to be processed) of the finishing processes caused by the larger size of lots. In other words, this raised the issue pertaining to the necessity of optimization in pursuing simultaneously the enlargement of the lot size for the upstream processes of steelmaking to rolling processes and the leveling of the loads of the downstream processes of finishing.

The total amount of intermediate in-process product stock nearly equals the product of the production volume per day and the manufacturing lead time (number of days), and the correct amount of product stock is determined by the variation of manufacturing lead time and the targeted rate of deliveries made within the due date. However, in the past, it was difficult to say that the factors affecting these two items and their relationship were quantitatively grasped and the production scheduling for accurate and optimal control was implemented. Therefore, to shorten the manufacturing lead time and realize a lower stock level, it is necessary to determine the relationship between the lead time variation and the targeted rate of deliveries made within the due date, but at the same time, to develop a model that is capable of describing comprehensively and quantitatively the consequences that are generated by the order mix of product types and manufacturing lot sizes in each process and in the integrated manufacturing lead time and stock volume.

The manufacturing lead time is a variable that is the shorter the better, and is never in the negative, but the average of the number of days and the standard deviation show a linear relationship to some extent. The simplest model expressing this event is that the size of variation is proportional to the instantaneous value, but in this case, because the distribution of variation is a lognormal distribution, we assumed the distribution of manufacturing lead time borders on the lognormal distribution (Fig. 4). If we assume that the manufacturing lead time follows the lognormal distribution, it becomes possible to calculate in a simplified way the number of days considered necessary for achieving the targeted delivery time, which makes it very useful in developing or evaluating the manufacturing lead time model. The lognormal distribution is expressed by the following formula, where μ is the logarithmic mean of x, and σ is the logarithmic standard deviation of x.

$$f(x)=\begin{cases} \dfrac{1}{\sqrt{2\pi}\sigma x}\exp\left[\dfrac{-(\ln(x)-\mu)^2}{2\sigma^2}\right] & x>0 \\ 0 & x\leq 0 \end{cases}$$

The past records of the spare days of the manufacturing completion against the delivery due date are distributed almost normally and if their average value and standard deviation are determined, the probability that the delivery achievement ratio, i.e., the number of spare days against the delivery due date (manufacturing completion until delivery), is recorded as more than zero can be calculated easily by using the cumulative probability distribution function given below:

Ratio achieving delivery due date:

$$p\ (x>0;\ \mu,\sigma\ )=1-\int_{-\infty}^{0}\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\left(\frac{(t-\mu)^2}{2\sigma^2}\right)\right]\mathrm{d}t$$

where x = spare days until delivery, μ = average of spare days, σ = standard deviation of spare days

Next, we studied the factors contributing to the variation of the number of spare delivery days. The order specifies the delivery due date and based on the transportation facilities and the specification of each product type, the timing to start rolling is decided, at which time, because the ordered diversified products are grouped in a lot for delivering, the spare delivery days and the individual manufacturing lead time become independent. Furthermore, the rolling start timing is affected by the fluctuation of production in the upper stream process of steelmaking. The variation of spare delivery days is affected by the variation of rolling start timing (spare days for starting rolling against delivery day: rolling start until delivery day) and the variation of manufacturing lead time (rolling start until manufacturing completion). If component events occur independently, the sum of variance of each independent event equals the sum of variance for the total, which means, if respective variations are determined independently, the standard deviation of the number of spare delivery days is estimated by the following formula:

$$\sigma_{\text{spare days until delivery}} = (\sigma_{\text{spare days for starting rolling against delivery}}{}^{2} + \sigma_{\text{manufacturing lead time}}{}^{2})^{1/2}$$

where, $\sigma_{\text{spare days until delivery}}$: standard deviation of the number of spare days until delivery (manufacturing completion until delivery)

$\sigma_{\text{spare days for starting rolling against delivery}}$: standard deviation of spare days for starting rolling against delivery date (rolling start until delivery)

$\sigma_{\text{manufacturing lead time}}$: standard deviation of manufacturing lead time (rolling start until manufacturing completion)

The estimated number of spare days of delivery is in good agreement with the past records and the validity of the assumption that each one of the events is independent was confirmed. Using the formula above we calculated the contribution of each term to the standard deviation of spare delivery days, and revealed that the contribution of the spare days for starting rolling against delivery date to the standard deviation of the number of spare days until delivery and the variation of manufacturing lead time were 70 % and 30 % respectively, and it was confirmed that the former contributed predominantly. Therefore, to reduce the standard deviation of spare delivery days, it is important to narrow down the standard deviation of rolling start timing against the delivery day, which means that for lowering the stock level, it is essential to control the lot size of rolling/ steelmaking casting (see NOTE 2).

5.5 Analysis for the contribution of manufacturing lead time – lead time of each process

Then, we studied the contribution of each plate manufacturing process to the variation of manufacturing lead time. Assuming that the required completion time of each finishing process is determined independently, the variance of the manufacturing lead time as a whole is expressed in the following formula as the sum of variance of the required

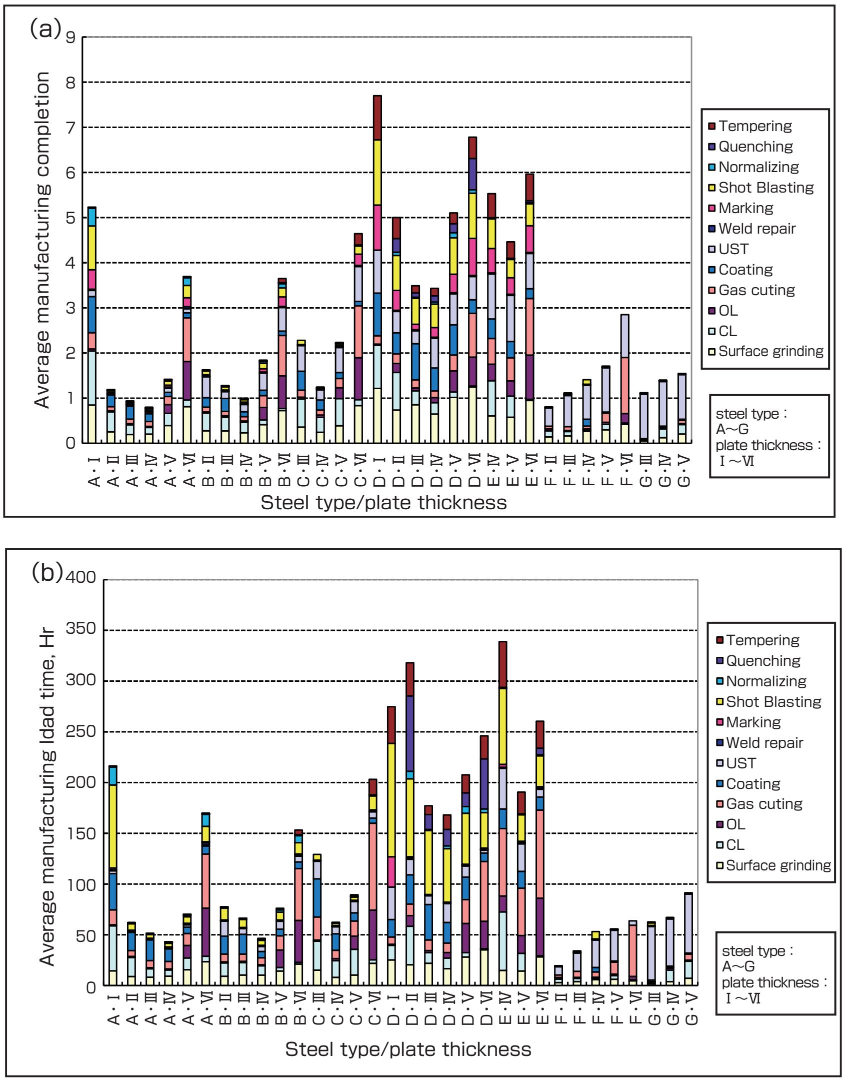

Fig. 5 Average number of processes to be passed and the manufacturing lead time for individual product types

(a) Average number of processes to be passed for individual product types

(b) Average required completion time for individual product types completion time of each process. The standard deviation of all the plate manufacturing processes and that of the rolling + shearing + finishing calculated by the following formula, assuming that the required completion time of each one of the finishing processes is determined independently, are nearly equal and the validity of the assumption that the required completion time of each process is independent was confirmed. Therefore, if the following formula is used, the impact of the fluctuation of the required time and of the capacity of each process on the manufacturing lead time of the entire plate manufacturing can be easily estimated.

$$\sigma_{\text{rolling + shearing + finishing}} = (\sigma_{\text{rolling + shearing}}{}^{2} + \sum \sigma_{\text{each finishing process}}{}^{2})^{1/2}$$

where, $\sigma_{\text{rolling + shearing + finishing}}$: standard deviation of rolling + shearing + finishing lead time

$\sigma_{\text{rolling + shearing}}$: standard deviation of rolling + shearing lead time

$\sigma_{\text{each finishing process}}$: standard deviation of required completion time of each finishing process (surface grinding, CL, OL, gas cutting, coating, UST, weld repair, marking, shot blasting, normalizing, quenching, tempering)

As a result of the above evaluation, the contribution of rolling + shearing to all the manufacturing lead time of all processes is no bigger than 20 % and the effect of the enhanced rolling efficiency on the shortening of manufacturing lead time is limited. In contrast, where the lead time of finishing processes is concerned, most of the time spent was on waiting, and their contribution to necessary work time was no bigger than 5 %. In other words, if the variation of rolling start against the delivery due date is reduced and appropriate lot sizes are assured, realizing at the same time operation where the required time of each process and the in-process stock level is minimized, it is highly possible that the manufacturing lead time will be substantially shortened.

The number of processes for each product type to pass and the manufacturing lead time are shown in Fig. 5, which indicates that the number of processes to be passed and the manufacturing lead time differ greatly depending on the product type, and that the manufacturing lead time is dependent almost entirely on the number of processes to be passed. Therefore, it is observed that for leveling the load of each process, it is necessary to maintain the input of each product type at an even level, and for preventing the input volume from being in spasm, it is important to control the lot sizes.

We adopted a method to identify the distribution of manufacturing lead time for each manufacturing product type by seeking the distribution of manufacturing lead time for each pass pattern and by dividing it proportionally by the component percentage of pass pattern for each product type to be manufactured (see NOTE 3). We estimated the manufacturing lead time using this manufacturing lead time model, found the estimated time agreed well with the past records, and the validity of this model was thus confirmed. Therefore, if the process to be passed and the required time are known, the manufacturing lead time can be calculated.

5.6 Development of a required time/ in-process stock model

If the processes are arranged independently, and if it is possible to have enough stock between processes, the efficiency of each process is seldom affected by other processes. In contrast, if there is not enough in-process stock, there are “risks” of deteriorating efficiency such as waiting for the processing from other processes, increase in time for changing set ups, etc. Therefore, as long as the stock was within the storage yard capacity, no incentive to reduce stock was instigated, resulting in very sluggish progress in the minimization of in-process stock even after the reinforcement of the finishing processes’ equipment. The lead time of the finishing processes, as explained earlier, contributes no more than 5 % to the necessary work time, and establishment of an operation that minimizes the required time of each process and in-process stock was sought before achieving a shorter manufacturing lead time.

Queuing theory is effective for analyzing waiting time, when there is variation in the occurrence frequency and its intervals and in the processing intervals, as in the case of the plate finishing processes. Therefore, to develop a model capable of describing the required time of each process, we applied the queuing theory to plate manufacturing, and developed a predictive model of the required time and the in-process stock volume of each process (required time/ in-process stock model), and then verified its validity (capable of giving a sufficiently accurate prediction of the in-process stock and required time of product in each process).

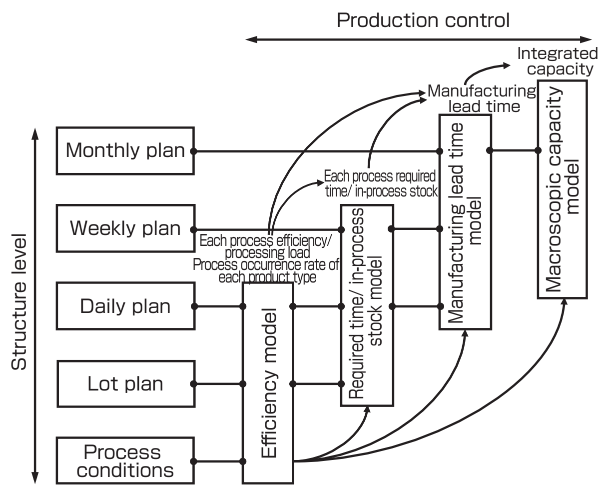

Fig. 6 Production control multi-scale hierarchically structured model

If the occurrence and processing frequency in every hour changes in the general distribution pattern, and if the frequency of stops and time caused by equipment failures, etc. changes, the required time and in-process stock of a certain process is derived as in the following formula using the queuing theory [22]:

$$W = \frac{1}{1-\rho_X(1+\rho_Y)}\left[\frac{1}{2}\rho_X(1+\rho_Y)^2\left(1+C_{SX}{}^2\right)E_X + \frac{1}{2}\frac{\rho_Y}{1+\rho_Y}\left(1+C_{SY}{}^2\right)E_Y\right]$$

$$= \frac{1}{1-\rho_B}\left[\frac{1}{2}\rho_X(1+\rho_Y)^2\left(1+C_{SX}{}^2\right)E_X + \frac{1}{2}\frac{\rho_Y}{1+\rho_Y}\left(1+C_{SY}{}^2\right)E_Y\right]$$

$$N = \lambda W$$

however, the requirements for waiting time W and in-process stock N to stabilize are

$$P_B = \rho_X(1+\rho_Y) < 1$$
$$\rho_Y = 1 - \rho_L\rho_X$$

where, W: average waiting time, N: average number of lots in stock in the process, E_X: average processing time, E_Y: average equipment stop time

C_{SX}: proportion of the standard deviation of processing time and average processing time, C_{SY}: proportion of the standard deviation of stop time and average stop time

P_B: total utilization ratio, ρ_X: utilization ratio, ρ_Y: stop ratio, $1-\rho_Y$: operation rate,

λ: average occurrence rate, ρ_L: operation rate of preceding processes

We applied this required time/ in-process stock model to the plate finishing processes and estimated the required time and stock level. It was revealed that both the required time and the in-process stock level agreed well with the past records even in the cases where there was variation in the frequency of occurrence, processing and stops, and the validity of this model based on the queuing theory was confirmed.

6 Toward the systemization of manufacturing knowledge

6.1 Proposal of a multi-scale hierarchically structured model for production control

In the preceding chapter, we explained, in a time-series schedule, how the support system was developed for solving individual problems of production control, taking examples from the Plate Mill of Kimistu Works. In this chapter, we now consider how and from which viewpoint the realized production control system can be converted into a conceptual model, so that a deeper understanding of the integrated optimization in the process industry can be acquired. We synthesize the knowledge we acquired from our problem solving efforts to solve the individual technical issues we experienced, and propose the following conceptual model.

In the lean production system outlined in this paper as an already existing system, the time-wise process structure of a manufacturing line operating on the second time scale/ production plan of monthly scale/ very long manufacturing lead time/ stock, which is common knowledge in the conventional production control, synchronizes the flow of stock with the flow of the manufacturing line (just-in-time), which then synchronizes the time scale in the production control with that of the mainline. In contrast, an examination of the time process structure of the production control for manufacturing plates reveals that it is established as a time-wise multi-scale hierarchical structure of the processing (second time scale), lot planning (hour time scale), daily plan (day time scale), weekly plan (week time scale) and monthly plan (month time scale), and that the shop floor operation and the production control by the staff in charge have been implemented on the basis of such given hierarchical structure. In the past, a macroscopic capacity model calculated the capacity of each process using a spreadsheet based on the product mix forecast in the monthly plan. However, in the course of realizing the integrated optimization of plate manufacturing we developed the following three models: efficiency model, required time/ in-process stock model and manufacturing lead time model. These models meet the time-wise multi-scale hierarchical structure in plate manufacturing; namely, the efficiency model is for the second (processing) → hour (lot) plan → day plan; the required time/ in-process stock model is for the hour (lot) plan → day plan → weekly plan; and the manufacturing lead time model is for the day plan → weekly plan → monthly plan; and these three models are mutually inclusive. The efficiency model shows the efficiency and the load to be processed, but it also gives the occurrence rate of processes that products complete in the downstream processes for each product type (process occurrence rate for each product type). By inputting this processing load and process occurrence rate for each product type together with the day/ weekly plan into the required time/ in-process stock model, the required time of the process and the in-process stock volume can be obtained. For the product type determined by the daily/ weekly plan and monthly plan, if the process occurrence rate of the product type obtained from the efficiency model and the required time obtained from the required time/ in-process stock model are input to the manufacturing lead time model, the manufacturing lead time can be calculated (see Fig. 6).

As described in the preceding chapter, trial and error on the shop floor resulted in the establishment of a production control system of plate manufacturing that has complex processes and product specifications and that ensures different time scales (hierarchy) are covered without contradiction, of both the required accuracy of plan and the responsiveness to the fluctuation of production/ orders. We propose to identify this system from the viewpoint of multi-scale hierarchical structure, and conceptualize it as a multi-scale hierarchically structured model for production control.

In the field of material researches for steels having a complex structure, Olson proposed a spatial multi-scale hierarchically structured model and demonstrated that the model is capable of specifying comprehensively the property extending from the millimeter level to the meter level of commercial steels, by organically combining physical models developed for each hierarchy.[23] We apply this spatial multi-scale hierarchically structured model to the description of time-wise multi-scale structure, namely, we propose dividing the time scale of production control into three levels, and to each level, the efficiency model, required time/ in-process stock model and manufacturing lead time model are assigned respectively together with a time-wise multi-scale hierarchically structured model for the integrated production control that links them organically (see Fig. 6). This is an integrated model that determines the multi-scale nature for time in plate manufacturing and enables the quantitative evaluation of decision-making from the micro (processing in individual processes) to the macro (control of manufacturing lead time) level and the search for the optimal point. This model made it possible to search for the optimal schedule for achieving well balanced coordination of two types of needs difficult to satisfy at the same time, i.e., the optimization of process conditions in the upstream processes based on the push-type production control methodology and the shortening of manufacturing lead time in the downstream processes that anticipate the application of the pull-type production control.

The difficulty of the production control model lies with the multi-leveled time scale, but specifying complex physical phenomena having hierarchical structure is one of the most fundamental research themes of R & D in ferrous metallurgy. One of the authors learned and assimilated the knowledge as his own during his pre-doctoral researches in the USA that it is effective to simplify matters by dividing structures into every level when developing the model of a mechanism that elicits physical phenomena. This engineer, in addition to studying theories, was moved to the manufacturing shop floor, and it can be said that the knowledge of the existing lean production system and his already acquired know-how for advancing his researches were amalgamated through such on-site activities, enabling him to analyze complex phenomena as hierarchical structure.

6.2 Significance of the multi-scale hierarchically structured model

The routine practices of the production control of iron and steel manufacturing is broken down into each task level from the viewpoint of pursuing work efficiency. Therefore, even if the skill for each process is acquired, it is extremely difficult to picture the total view of the production control system in manufacturing. The main significance of the multi-scale hierarchically structured model lies in its ability to provide a framework that enables detailed technical examination of the management issues of integrated optimization via the production control at the level of individual plants by providing an overview of the overall picture of the system. From the very beginning, the basic premise for engineers, when performing work whose mission is to realize continual improvement by designing and redesigning manufacturing systems, is to have an overview of the overall picture of the production control system, and the role played by the proposed model is important.

However, the model proposed at this time does not possess the optimization evaluation function that realizes overall optimization, and does not guarantee the overall optimization theoretically and quantitatively. To realize the optimization, the existence of various models is essential, but compared with the assembly industries represented by the automobile industry, in the steel industry, the fluctuation of daily production and operation in the upstream of iron making and steel making processes is extremely marked and moreover, plans are frequently changed. In such an environment, because the model is developed based on past records that contain also external disturbances, it is difficult to make a highly accurate estimate and its reliability is naturally limited. It is evident that the deterministic approach that seeks optimal answers assuming full-information is available does not fit, and it is not realistic time-wise and from the viewpoint of effectiveness to conduct a complex and large volume of calculation by integrating a model obtained through a top-down analysis.

In contrast, reviewing the history of the development of the proposed models, in the production control system covered by this research, we understand that (i) the individual elements constituting the system are locally organized and the structure that realizes the functions required by the system is sequentially decided through trial and error (hypothesis formation and verification), and (ii) the derived adaptive solution (even if it is not the optimum solution) provides an answer beyond expectation, to complex problems and supports effectively the decision-makings on the shop floor working in a dynamic environment. Our observation strongly suggests that the processes constituting the proposed model were emergent processes.[24]

So, how were the emergent phenomena witnessed in this case example induced? Business scholars who interpret the strategic development of an organization as an emergent process claim that by setting an appropriate “place” (environment) for business activities, it is possible to promote the induction of emergent phenomena among individual persons constituting the organization.[25]-[27] We believe, as mentioned in chapter 4, in this case example, thanks to the management innovation at the level of the head office and under the leadership of middle management at the level of plants, that the basic environmental setting for inducing the emergent phenomena on the shop floor was implemented.[26]-[27] Furthermore, from the viewpoint of how the production control system was made possible, it is important that core persons capable of taking charge of the bottom-up type synthesis were fostered systematically, and such persons played the role of promoting emergent activities on the shop floor.

To introduce the roles of the "technical group" to which the engineers that contributed to the development of the proposed models belong, the group is positioned at the relay point that links the manufacturing site and the staff departments. It has a broad coordination function not limited simply to manufacturing technology for the operation of the plant, and plays the core role in the operation and innovation of the production system (see NOTE 4). It is general practice to assign technical staff to the "technical group" at the time of new recruitment to the company, and as new recruits, they experience on-site work in three shifts. After this period, technical staff gain experience in various job positions but exceptional engineers and leaders of steelworks including the superintendent tend to remain in the "technical group." Such career path suggests that the company has had the intention of fostering the staff in the "technical group" as principal enablers[29] (persons who help others to realize objectives in emergent activities) in the emergent processes by having them physically embed in the staff the knowledge on coordination and means of problem solution acquired through OJT in many fields (corresponding to the habitus of P. Bourdieu[Term 5 [28]]).

Engineers working as system integrators are responsible for achieving both technical superiority by the sophistication of equipment/ operational technologies and economic rationality. The costs and risks that arise when introducing the lean production system to the steel industry at the meticulous level of the automobile industry are imagined to far surpass the authorized scope of decision-making by the on-site plant management. The integrated optimization of the production processes needs to be evaluated from the viewpoint of overall optimization in plant management and the proposed models provide a quantitative guideline for examining in concrete terms how the shop floor management balances the conflicting needs of technologies and management. For example, for the promotion of the lean production system, it becomes necessary to eliminate bottleneck processes, and when studying the optimal equipment investment, it was not possible in the past to evaluate quantitatively the increment of integrated efficiency that the reinforcement of equipment in the finishing processes will incur, making it difficult to make a proper decision in investment in the finishing process equipment. The proposed model opened the possibility of effectively presenting to the management of Kimitsu Works and sales departments of the Headquarters, not to mention within the Plate Mill, the advantages and the necessity of integrated optimization. We also developed in succession the production control systems for the improvement of on-site operation, the optimization of material design aiming to improve production control activities conducted by the staff in charge, the optimization of the tapping schedule and the development of the infrastructure for supply chain management and others. And during such development work, the efficacy of the quantitative analyses made using the multi-scale models was verified.

As explained above, the history of the formation of the multi-scale models proposed in this research has the following bilateral characteristics. Firstly, if the models are considered in terms of their formation process, it is recognized that the structure of the models was determined by the know-how gained in the research method used by the engineers who were in charge of the development, more specifically, by the hierarchical structure approach to complex phenomena. Contrastively, when we saw a series of models that we introduced be developed and emerged in the form of a production control system, we recognized that it is worthwhile to widely propagate the system in the industrial society, and we recognized anew, while working on the formalization of the system, the merits obtainable by systematizing the model as a multi-scale model.

7 Summary and future considerations

If the essence of the manufacturing industry is "transcribing information into materials," the lean production system that creates material flows synchronized with the flow of information is one of the "aspects to be targeted" in the pursuit of the essence of the manufacturing industry.[30] The quest for economies of scale by the mass production system initiated by Ford created the time-wise multi-scale hierarchical structure of production control, represented by the second time scale manufacturing lines, production plan on the monthly time scale and very prolonged lead time / large stock. Ohno who took the lead in the lean production system, under the slogan of "Overcome economy of scale," however, succeeded in this by controlling manufacturing lot sizes and pursuing the synchronization of manufacturing with the production line.[4] When the lean production system is considered within the framework of time-wise multi-scales, it can be understood as the result of the convergence of the manufacturing time scales on that of the mainline. In contrast, because the steel industry is a process industry, and due to the fact that the influence of manufacturing lot size on productivity and quality is larger compared with the automobile industry, an assembly industry, it is fundamentally difficult to realize the similarly high level of manufacturing synchronization and compression of time scales as that of the automobile industry. However, the case example analyzed in this paper shows that the integrated optimization may even be realized in industries other than steel by understanding the production system as a time-wise multi-scale hierarchical structure, and by linking properly each stratum via support systems.

In many industries, the shortening of the time required for manufacturing is an essential element for the development of diversified value-added products and manufacturing them as competitive products. For example, even in the pharmaceutical field that appears to be at the extreme opposite end of the spectrum, we are now in an age where the competitive edge of products is determined by price and speed. In the past, in the field of pharmaceutical products, having differential products protected by patents gave a company its competitive edge. However, due to the diffusion of generic products, having the capability to produce drugs of various kinds as price competitive products is becoming an important management issue. For example, tablets are manufactured into a wide variety of products using a series of equipment and manufacturing processes for mixing, granulation, sieving, mixing, tableting and coating.[31] and these processes are controlled elaborately by computers as it is with the iron and steel manufacturing processes. In other words, the industry has many issues similar to the steel industry also in the fact that efforts to meet various products are required also in terms of its process structure and the approach proposed in this paper of developing a model is considered to enable horizontal deployment in many process industries including pharmaceuticals.

In Japanese manufacturing companies, a succession of technical staff has steadily taken charge of innovation in manufacturing technologies and production control on the shop floor. The manufacturing knowledge acquired during the course of such innovative efforts is expected to be documented and published as educational materials and also engineering as a practical science is expected to be systematized as part of academic fields.[32] It goes without saying that to realize the integrated optimization on the manufacturing shop floor, it is necessary to understand the phenomena at each stratum extending from the micro to macro level, to develop models, and compare them within a developed framework against best practices in other business sectors and companies. The multi-scale hierarchically structured model for production control proposed in this paper was developed based on the knowledge of field engineers obtained from their wide and in-depth OJT throughout their career, and this paper strongly suggests the necessity of systematizing manufacturing knowledge from industries.

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Notes

Note 1) In the actual production, because manufacturing is conducted in combination with more than one product group, the bottleneck processes change sequentially and situations very often occur where the bottleneck process is different from the one particular to the product group concerned. Therefore, the past records of rolling process efficiency observed in actual production vary, unlike the particular integrated efficiency recorded in the case of continued manufacturing of the same product group, in every term for which records were aggregated as influenced by the combination of production permutation that varies in every term. In this efficiency model, this problem was avoided by defining product groups after extracting the factors affecting the processing efficiency of each process so that the efficiency of actual rolling processes as a whole distributes the specific integrated efficiency as the median. In terms of the rolling processes as a whole, irrespective of the production permutation, the product group sizes were adjusted so that the difference between the past record of integrated efficiency and the integrated efficiency specific to the product group was balanced out, thus succeeding in producing highly accurate estimates of the overall efficiency of rolling processes compared with conventional models.

Note 2) The production of steel plates is characterized by receiving orders for various products (products of the same specification in one order are about 3 t), manufacturing them in lots (condition of the same steelmaking: min. 300 t, but considering productivity, desirably over 2,000 t) and delivering products in the unit of a lot (for the same customer, delivery date, transportation means). The delivery date is specified for the same shipment lot, but as requested by the customer, orders of various products are contained in one shipment lot, and the manufacturing lot does not generally agree with the shipment lot. Therefore, even though the timing to start rolling is determined by counting backward the manufacturing lead time set from the delivery date, variation is inevitable when grouping products in a manufacturing lot.

Note 3) With the help of the existing correlation between the number of processes to be passed in the finishing processes and the manufacturing lead time, the following method was adopted: (1) after having estimated the completion pattern of finishing processes (rows of 01 indicating yes or no of completion (a pass)) based on the manufacturing specification, (2) a system to estimate a lead time distribution by each product type is introduced by defining as one group a character string that has added to this completion pattern a category code representing product types grouped in a major category. The category code was added because even though it concerns the same completion pattern, the completion frequency (occurrence rate) of the occurrence process differs and there are cases where the lead time distribution differs. Even though the completion pattern and the completion frequency are the same, depending of the product type, there are cases where the set value of the delivery success rate differs.

For plate manufacturing, for which it is unknown at the time of deciding the order specification which processes for the intermediate goods to pass, such as surface grinding or gas cutting and flattening, and where there are occurrence processes determined regarding their completion after rolling, it is therefore not possible to calculate the completion pattern of finishing processes with a simple logic based on the manufacturing specification of the order. Therefore, using the decision tree that is a methodology used generally for data mining, we developed a completion pattern estimation model.

When seeking the lead time distribution of each product type to be manufactured, the simple method is to collect plates of the same manufacturing product type from the existing data, and use the histogram of their actual lead time data to draw the lead time distribution. However, there are also product types that are manufactured rarely, and the lead time distribution of such product types with a small number of data tends to be low in reliability. Therefore, we adopted a method to obtain the lead time distribution for every production type to be manufactured by obtaining the lead time distribution for each completion pattern and by dividing it proportionally by the component percentage of the completion pattern for each type of product to be manufactured.

Note 4) The technical group in addition assumes the roles of transmitting information to the works' top management (accountability on behalf of the line division, or representing the technical division), coordination with the relevant staff department involved with short-term issues relating to line management (production technology, production scheduling, general affairs, personal affairs, labor, equipment), planning of middle and long-term plans, development of R & D strategies with the R & D department, and the role of overall coordination for various problems that occur mainly with the line division, including areas for which the job description is not necessarily clear such as the coordination with staff department based in the head office.

Terminology

Term 1. Manufacturing lead time: A term used in the steel industry, signifying the duration of time required for manufacturing. Its definition is varied including the duration of time from receiving an order to the delivery of a product and from the start of manufacturing to its completion, but in this paper, it is defined as the time required from the start of rolling a plate to the completion of its manufacturing.

Term 2. Manufacturing processes in a steelworks: A steelworks manufacturing steel products in an integrated manner from iron ore is called an integrated iron and steelmaking works and its processes are generally classified into three processes of ironmaking, steelmaking and rolling, the first consisting of ironmaking by reducing iron ore in a blast furnace; the second in steelmaking by removing carbon from pig iron and adding necessary alloy elements in a converter; and the third in manufacturing various products by rolling semi-products manufactured in the steelmaking process. A steel plate mill is one of the rolling processes and it rolls and produces steel plates.

Term 3. Rolling efficiency: Efficiency indicates the ratio of work accomplished in a given amount of time. Because the rolling process has a series of equipment for heating, rolling, cooling, etc. that are arranged continuously in tandem and are directly connected, the efficiency of continuously making such series of equipment function is called rolling efficiency.

Term 4. Correction (flattening) process: The process where a defect in flatness detected after the rolling process of plates is corrected by a roller leveler or a press.

Term 5. Habitus: As a concept similar to habitus, there is tacit knowledge [Polanyi, M.: The Tacit Dimension, Doubleday Anchor, N.Y. (1967)]. Habitus can be considered as tacit knowledge in scientific activities and is the expertise in the broad sense of the term related to the method of conducting research.

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In 1996, graduated from the Graduate School of Faculty of Science and Engineering, Waseda University. In 1996, entered Nippon Steel Corporation. At the plate mill of Kimitsu Works, worked mainly on higher efficiency, TMCP technical development, etc., improvement of operation techniques, as well as equipment planning and drastic improvement of plate manufacturing processes. In 2005, dispatched to the World Steel Association, and at present, the steel plate technical group manager of the Plate Mill, Nagoya Works. To this paper, he contributed as a member of the technical staff to shop floor reform and operation improvement.

Hirofumi KAWASAKI

In 1980, graduated from the Graduate School of Mechanical Engineering of Osaka University. In 1980, entered Nippon Steel Corporation. Engaged in the improvement of plant operation techniques as a member of the technical staff belonging to the Plate Mill of Kimitsu Works. After posts as assistant manager in the Plate Technical Department in Head Office, superintendent (general manager) of the Plate Mill, Kimitsu Works, presently executive counselor in the Plate Division of Head Office. In 2008, received the Watanabe Kensuke Memorial Award of the Iron and Steel Institute of Japan. In relation to this paper, he was assigned the post of superintendent of the Plate Mill in 2001, and succeeded in the shortening of lead time and production increase.

Yasunori BABA

In 1977, graduated from the Faculty of Economics, Tokyo University. In 1986, completed a doctorate course at the University of Sussex, Ph. D., SPRU fellow. After working as chief researcher in the National Institute of Science and Technology, and others, and from April 1993, the assistant professor at the Research into the Artifacts Center for Engineering, and in 1997 became the professor of the same Center. After July 2001, professor at the Research Center for Advanced Science and Technology. Also, from April 2007, professor at the Department of Advanced Interdisciplinary Studies, Graduate School of Engineering, Tokyo University. In this paper, he took charge of the synthesization and systematization of knowledge.

Discussions with Reviewers

1 Productivity of steel plate manufacturing processes

Comment (Kanji Ueda: AIST)

This paper investigates the most difficult problems of optimal integrated production in process industries. It identified the items to be solved through practical undertakings, and developed models and summarized the actual data collected in specific steel plate manufacturing processes and is considered as appropriate in terms of synthesiology. The scenario in this paper is based fundamentally on the recognition of the difficulty of ensuring simultaneously the minimization of lead time and improvement of productivity. However, please describe clearly what is meant by the enhancement of productivity in this paper.

Answer (Kiyoshi Nishioka)

Productivity is the volume of production per hour, namely it is "efficiency." The process reform/ process improvement in the steel industry used to focus on the enhancement of the efficiency of mainlines. However, the enhancement of efficiency of individual pieces of equipment or a group of equipment does not lead to the minimization of manufacturing lead time, and sometimes, it works counter to it. The main subject of our research concerns how to make these two coexist.

2 Middle management

Question (Kanji Ueda)

As one of the arguments in this paper, it describes the importance of the role of middle management in management innovation. Please be more specific in your definition of middle management.

Answer (Kiyoshi Nishioka)

When referring to middle management in this paper, we mean managers at the level of plant superintendent. Top management has the authority to change the corporate-level organizations and systems. Middle management, on the other hand, has the authority to change operation and evaluation within a given range of system and structure. This paper suggests that by synchronizing the reform of corporate-level organizations and work structures implemented under the strong leadership of top management and the innovative efforts of middle management in charge of on-site management, organizational activities that by nature tend to resist changes are rejuvenated completely and become capable of responding actively to the changing market environment.

3 History of modeling multi-scale hierarchical structure and its future development

Question (Kanji Ueda)

Chapter 6 claims that a new model is proposed toward the systematization of manufacturing knowledge. The content is very interesting, but it is not clearly stated how this model was obtained. Please also describe how this proposed model should be deployed horizontally and to which industries and processes in the future.

Answer (Kiyoshi Nishioka)

The proposed model has not been deductively derived, and if a model that was developed through trial and error is understood inductively, the paper claims that it has a model structure that straddles time strata. In contrast to the conventional result-based production control that is based on manufacturing results, it is suggested that the multi-scale hierarchically structured model makes it possible to implement appropriate time control and production control by adding the viewpoint linking the causes and the result of phenomena that occur time-wise. The lean production control gave birth to an epoch-making production control that enables the pursuit of the limit of integrated optimization in the interrelation of lines called processing. In contrast, in the equipment-heavy industries, or process industries where the renewal of existing equipment or changes of its installation layout are difficult, integrated optimization is feasible only within the time span of processing, and it is difficult to realize the integrated optimization for all. In other words, in order to ensure integrated optimization in many industries where the time structure of *monozukuri* extends from the micro to macro level, the understanding of phenomena that are beyond time strata is considered necessary, which means the development of a cause – result-based model is also necessary. There are three categories of these strata in the present case, but this naturally could be two or four depending on the process. What is important is to determine which strata are to be straddled and in what form the model should be developed, so that it contributes to the proper understanding of the phenomena of the process and to the integrated production control, and the present example presents one of such examples.

In many industries, the shortening of time necessary for manufacturing is an essential element for developing a wide variety of value-added products and for manufacturing them as competitive products, and if the time structure in the production control is understood systematically by using the currently proposed model, we consider it will be of some help to it. For the future outlook, please see chapter 7.

4 Application scope of the multi-scale hierarchically structured model

Question (Kanji Ueda)

In the paper, the intent of overall optimization instead of partial optimization is stated. However, the methodology of this paper does not theoretically seek the overall optimization, and therefore, I think it is not guaranteed that an answer for overall optimization will be obtained. Therefore, I think you should refer to the effectiveness or limitation of the application of the present methodology.

Question (Motoyuki Akamatsu, Human Technology Research Institute, AIST)

The contention of this paper is the composition using three different time scale models, which enables quantitative evaluation extending from the micro to macro level and finds the optimal point. However, how do you integrate or interrelate multi-scale models and use them?

Answer (Kiyoshi Nishioka)

The model proposed at this time does not have the optimization evaluation function that realizes overall optimization, and does not guarantee the overall optimization theoretically and quantitatively, nor can it be used as it is by installing it in the production control system.

The steel industry, the representative case of process industries, especially with integrated iron and steel manufacturers having blast furnaces, has physical constraints specific to its processes: its symbolic blast furnaces use natural resources as raw materials; its processes contain those of intense heat and high temperatures; and raw material yards, etc. are in the open air and are easily influenced by the weather/ climate. To overcome these problems, the steel industry has always pursued integrated continuous facilities, higher productivity and higher energy efficiency of high temperature processes by building larger-scaled works.

For conducting smooth production activities in such integrated and continuous large-scale production facilities, an enormous amount of information on equipment control and production control has to be handled, and therefore, it introduced a production control system supported by large-scale computers earlier than other industries. The production control system of an integrated steelworks has constraints as described above, in the upstream processes of the raw materials, ironmaking and steelmaking, which inevitably result in somewhat large fluctuation or variation in production. In the processes of intense heat and high temperatures, time constraints are substantial and no in-process stock is allowed, therefore, fundamentally its production structure is of the push-type. The “product” of the upstream processes of raw materials – ironmaking is mono-grade. During the early days of integrated steelworks, the final product types were limited and there were no such complicated requirements as today. Because of the above reasons, focus had been directed on the optimal control of high temperature processes, measures to deal with the production fluctuation/ variation of the upstream processes and the maximization of manufacturing lot sizes in the upstream processes by summarizing product order information. In contrast, very limited actions were taken for planning overall optimization of integrated manufacturing that examines, from the viewpoint of linking the quality control and delivery of ordered products, the manufacturing lead time and the in-process stock level in the processes of intermediate products such as hot rolling and plate mills, and for supporting scheduling.

To search for optimization, the existence of various models is essential, but compared with the assembly industries represented by the automobile industry, in the steel industry, the fluctuation of daily production and operation is large and moreover plans are frequently changed. In addition, because the model is developed based on the past records that also contain external disturbances, it is difficult at present to make a highly accurate estimation using models, and therefore, it is understood that the optimal answer that depends on the models that contain many errors is naturally limited in its reliability.

In such a situation, it is not realistic from the viewpoint of effectiveness, calculation load, and other work load, to conduct elaborate scheduling in daily routine work that rigorously searches for the answer to the overall optimization, and therefore, the approach to an optimal answer has to be continuous and asymptotic as shown by the example in this paper.

The proposed model grasps actual data for every term and in addition to the result-based production control that performs control based on such data, it identifies the cause-based phenomena from which such data are born. It can be considered as a tool for conducting better control. As a practical problem, huge difficulties may arise if a comprehensive model is to be created that covers all the time strata extending from the micro events that occur in a short time called processing in individual processes to the macro events that occur over a long time called manufacturing lead time that extends from the rolling start to the completion of manufacturing. If models developed through trial and error are overviewed as a whole, the structure is such that respective models link the overall picture going over the time strata, and therefore, this model is called the multi-scale hierarchically structured model. In other words, the proposed model is cause/ result-based straddling of a certain level of time strata, and even though it contributes to the understanding of phenomena extending structurally from the micro to macro level, it is not a model that guarantees an optimal answer. However, it can be understood that it provides a means of approach to the optimal answer continually and asymptotically. The above viewpoint is added in 6.2 “Significance of the multi-scale hierarchically structured model.”

5 Efficiency model

Question (Motoyuki Akamatsu)

What is the difference between the efficiency model and the conventional methodology of conventional production control?

Answer (Yasushi Mizutani)

Processing efficiency is defined, in the rolling processes, as the weight of slabs processed per hour, and in the finishing processes, as the number of plates processed per hour.

The rolling processes are comprised of the processes that are arranged continuously, in tandem and in direct connection and the processes are the slab yard process, heating process, roughing process, finish rolling process, accelerated cooling process and shearing process. In the slab yard process, slabs received from steelmaking are cut; in the heating process, the slabs are reheated; in the roughing process, the reheated slabs are rolled to the specified width; in the finish rolling process, the slabs rolled to the desired width are rolled to the specified thickness and length and the material property is integrated by controlled rolling; in the accelerated cooling process, the slabs after finish rolling are quenched using a large amount of cooling water, to integrate a quenched structure; and in the shearing process, the slabs after rolling/ cooling are divided. Steel plate products come in a wide variety of thicknesses, widths and lengths and of specifications in standards, and because the process conditions of each process are inevitably varied, the processing efficiency of each process varies significantly in response to the product specification. In other words, because the rolling processes are in a large scale and are also of mixed-flow production of many product types, and because the buffer between processes is small, friction between the preceding and subsequent material processing frequently occurs. Therefore, as the bottleneck processes found during processing change sequentially by every material, the efficiency of the overall rolling processes changes substantially, and therefore, it has been technically difficult to predict the efficiency accurately and easily. Most of the existing planning of production, manufacturing and processing used to be implemented by making various assumptions of conditions and calculating sequentially individual events that respond to their respective conditions, evaluating and comparing the results using the evaluation function and selecting the best fitting conditions. However, for large-scale and mixed-flow production of many product types, if the production permutation, i.e., the combination of simulation calculation conditions, becomes enormous, the load on the computer becomes excessive, and such a planning method is impractical.

Each rolling process has different factors that work against good processing efficiency. For example, in the slab yard process, they are slab cutting speed, slab weight, etc.; in the heating process, charging temperatures of the furnace, heating conditions (temperature to extract slabs from the furnace, time to keep slabs), etc.; in the roughing mill process, the extracting temperature from the furnace, slab sizes, etc.; in the finish rolling process, rolling speed, waiting time between completions for controlling rolled structure, length of rolling, etc.; and in the shearing process, cutting speed, cutting accuracy, etc.

In this efficiency model, these parameters that affect the processing efficiency of each process were extracted, and products were classified into groups for which these parameters have significant difference, and the processing efficiency was statistically calculated for every product group. In addition, a method was adopted to obtain the integrated efficiency specific to each product group by comparing the processing efficiency of each process for every product group classified in accordance with their product type, size, furnace charging temperature, etc., bottleneck processes in more than one sub-process arranged in tandem, in direct connection, and in multi-steps that are identified for each product group.

6 Integrated lead time model

Question(Motoyuki Akamatsu)

It is stated that the enhancement of the rolling process efficiency increased the requirement fluctuation of the finishing processes, but is it correct in understanding that the enhancement of efficiency led to larger lot sizes and with the increase in the lot sizes, because the finishing processes are varied, such lot has to wait for processing in the finishing processes, thereby increasing in-stock volume?

Regarding the variance of the spare delivery days, you state that the spare days for starting rolling against delivery date and the manufacturing lead time are independent, and the variance can be obtained by the sum of the respective variances. However, rolling start → manufacturing completion is contained in the rolling start → delivery date and it seems both are mutually dependent. Please additionally state why the spare days for starting rolling against the delivery date and the manufacturing lead time can be considered independent.

Answer (Yasushi Mizutani)

If the daily rolling volume increases thanks to the enhancement of the efficiency of the rolling process, inevitably the flow into the finishing processes, i.e., the required processing volume of the finishing processes, increases resulting in the increase of the fluctuation requirement. Your statement that “the enhancement of efficiency led to larger lot sizes” is correct. Larger variation of processing requirement in the finishing processes leads to longer waiting time and higher stock level.

The production of steel plates is characterized, as already stated in the paper, by receiving orders for various products (products of the same specification in one order are about 3 t), manufacturing them in lots (condition of the same steelmaking: min. 300 t, but considering productivity, desirably over 2,000 t) and delivering products in the unit of a lot (for the same customer, delivery date, transportation means). The delivery date is specified for the same shipment lot, but as requested by the customer, orders of various products are contained in one shipment lot, and the manufacturing lot does not generally agree with the shipment lot. Therefore, even though the timing to start rolling is determined by counting backward the manufacturing lead time set from the delivery date, variation is inevitable as a result of grouping products in a manufacturing lot, and at the same time, variation associated with the fluctuation of operation in the upstream process of steelmaking that is independent from plates exists.

In contrast, the manufacturing lead time is dependent on any processing requirement and on the operation fluctuation, and therefore, it is also with variation. Therefore, the spare delivery days are obtained as the difference in the spare days for starting rolling against delivery date (rolling start until delivery day) and the manufacturing lead time.

Spare delivery days = spare days for starting rolling against delivery date (rolling start until delivery day) – manufacturing lead time

If the two terms on the right are independent, the formula given in this paper of

$$\sigma_{\text{spare days until delivery}} = (\sigma_{\text{spare days for starting rolling against delivery}}{}^2 + \sigma_{\text{manufacturing lead time}}{}^2)^{1/2}$$

is valid. We verified this against past records to confirm that the relation expressed by the above formula is valid, and we concluded that the assumption of “the two terms on the right are independent” is quasi valid.