Managing the Interdependence among Successive Stages of Production in Steel Industry

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Abstract: Only a small portion out of ~200 steel-makers in the world can produce high-grade steel such as hot-dip galvanized steel sheets and directional electrical steel sheets. For equipment-related industry such as steel industry, technical knowledge is embodied in their equipment; thus, technology transfer and catch-up are somewhat easy. However, for high-grade steel production, steel-makers in emerging countries equipped with large-scale capital investment and state-of-the-art equipment continued to struggle. The reason for this is when a new process is added to the existing process and not just the added process, the operational parameters of all processes must be coordinated. Thus, when a number of processes increases, it leads to a massive number of combinations of operational parameters to be coordinated, thus requiring time to acquire knowledge patterns.

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**Introduction**

Only a small portion of \(-200\) steel-makers in the world can produce hot-dip galvanized steel sheets and electrical steel sheets. For process industry such as steel industry, knowledge is embodied in their process equipment; thus, technology transfer and catch-up are relatively fast (Gershenkron, 1962). Large steel-making equipment is not of standard specifications but is not rich in variations, either. Furthermore, the equipment for blast furnace, converter, continuous casting, hot rolling, cold rolling, annealing, and galvanizing line are supplied by a few makers or their consortium. With large-scale capital investment and policy assistance in the background, many steel-makers in emerging countries are introducing state-of-the-art equipment and starting their operation. However, steel-makers who are able to produce steel sheets for automobiles are limited to \(-10\%\) of all steel-makers. In particular, there are few makers who are able to produce high-grade, hot-dip galvanized steel sheets. Therefore, automobile makers advancing in emerging countries get their supplies of steel products or heavy goods from outside emerging countries. To meet this demand, Japanese steel-makers and trading companies are developing coil centers overseas for automobile makers (Byun & Lee, 2015). This is not limited to steel sheets for automobiles. A highly functional material, electrical steel sheets, is high-grade steel that can only be produced by a small number of steel-makers.

In this study, with the production of steel sheets for automobiles
and electrical steel sheets by South Korean steel makers as an example, we clarify technical issues steel-makers in emerging countries equipped with large-scale capital investment and state-of-the-art equipment struggle with for high-grade steel production. Although the steel industry is a massive process industry, it requires detailed operational technology in the inter-process coordination. When connecting a new process to existing processes (expansion of a production line), the connection between the existing process and additional process must be readjusted from the perspective of whole processes. Steel products have an interdependent relationship between production processes; thus, with increase in the number of processes, the combinations of operational parameters become massive, and a long period of trial and error becomes necessary to develop a pattern.

**Expansion of Production Lines: How Processes Interact**

In the steel industry, depending on the grade of products, advanced technology may not be required. However, despite being a massive process industry, certain products, such as steel sheets for automobiles and electrical steel sheets, require delicate control straddling over multiple processes. Steel-makers that are producing such high-grade steel were not successful at the start but achieved the production after trial and error.

The history of the steel industry is a history of technology transfer and introduction. The USA introduced technology from Europe; Japan introduced technology from the USA and Europe; and South Korea and China introduced modern steel-making technology from Japan and took on the steel industry as the state capital. The manufacturing equipment and operational technology is essential for steel-making technology. Companies that introduce foreign-developed technology quickly start their operation with
imported equipment and operational technology (Byun, 2016).

Steel-makers in emerging countries that introduce technology begin with the construction of blast furnace, the symbol of steelworks, and build the production process from the converter to continuous casting. This is sufficient to produce normal grade products such as slabs. Subsequently, the hot-rolling process has been added to produce a hot-rolled coil. To produce cold-rolled coil with higher added value, cold rolling process and annealing process are added to the hot-rolling process.

As such, steel-makers increase the types of steel products by adding production process in an order (Figure 1).

At the initial stage of operation, the process “from blast furnace to hot rolling” is prepared, thus primarily producing hot-rolled coil (①). It is relatively easy to line up the introduced equipment for production up to this stage. However, when cold rolling and galvanizing process are subsequently added, difficulty suddenly increases. Next, to produce cold-rolled coil for home appliances, cold-rolling process is added (②). To produce electrical steel sheets, annealing process must be added after the cold-rolling process. To produce hot-dip galvanized steel sheets, the final hot-dip galvanizing process must be added for operation (③).

![Figure 1. Expansion of steel manufacturing processes](image-url)
It may be relatively easy to line up equipment up to hot rolling for production; however, when the production processes go from ①–② to ②–③, not only added process but existing processes also require coordination of their operational parameters. Although products appear to flow in one direction on the production line, there is interdependence between processes, and the operational parameters of each process is delicately adjusted while considering necessary compositions for the ultimate product. For example, as per the treatment and processing conditions, parameters such as ingredient adjustments in the converter, reheating temperature in the hot rolling process, hot rolling speed, cold rolling, and plating amount are changed. Because there are variations in tasks in each process, the parameters of the subsequent processes are carefully coordinated as per the result of tasks in the previous process. In such a case, there are strong characters in the postprocess in response to variations in the previous process. Therefore, operational parameters of ① and operational parameters of ② and ③ in Figure 1 often differ.

For these reasons, when expanding a production process, new operational knowledge and pattern knowledge (recipe) for the new combination of operational parameters must be acquired. For example, to produce hot-dip galvanized steel sheets, contents of five major elements to be adjusted by the converter, i.e., C, Si, Mn, P, and S, are changed. Accordingly, in the subsequent rolling process, reheating temperature and pressure are adjusted. Because there are variations in the task results, inter-process coordination is made while sharing tolerance information for the previous processes (Byun, 2019). Making adjustment with such causal knowledge is known as inter-process coordination. Figure 2 shows the examples of typical operational parameters for each process and their combinations.

If the pattern of interdependence between processes is clarified, management can be planned. For steel-makers, how recipes are acquired and efforts required for coordination can be reduced
through such recipes (e.g., inter-process communication) are important. Such pattern seeking is often observed by steel-makers participating in the initial stage of new vehicle development by automobile makers because they develop a new type of steel. If patterns become completely stable, automated operation would be a reality. It is a characteristic of the steel industry where inter-process coordination is required during the development and production stages.

The reason it is difficult for steel makers in emerging countries to move onto ② and ③ even if they accumulate know-how on the operations in the production process ① in Figure 1 is the requirement to search for these operational parameters. Actually, among about 200 steel makers with blast furnace, only –10% have reached the production process ③.
The Challenges of Acquiring Knowledge on Operational Parameters

Operational parameters shown in Figure 2 are only a small portion, and on the actual production floors, many parameter operational information and resulting values fill the screens in the production control rooms. Operators monitor each process in the control room.

Figure 3 shows the process of accumulating knowledge on patterns. As explained in Figure 1, by adding production processes, operational technologies that manage connections and knowledge on patterns are accumulated. If patterns are unclear, there is no knowledge on the new combination of operational parameters when adding production processes; thus, existing parameter combinations are adhered to and only parameters of the new process are operated. It takes some time before realizing that adjustments to existing parameters are necessary.

Once patterns are understood through both trial and error, it moves onto the next step. Not only parameters of the new process but also referring to the information from previous processes, multiple operational parameters are combined and tried before production is successful. Coordination is understood and burden of inter-process coordination can be predicted.

Finally, it reaches the stage of standardization and automation to reduce the load of inter-process coordination using this recipe. The combination of operational parameters for each process is entered

**Figure 3.** Acquiring knowledge on operational parameter
into the production system, and parameters of subsequent process are changed as per the operational conditions of previous processes. Furthermore, rather than performing this task manually each time, it is automated. If adjustment is absolutely necessary, adjustments are made based on a plan.

Case Study 1: Electrical Steel Sheet

Electrical steel sheets are particularly functional among steel products and used for generators, voltage converters, and motors. They are used in devices that control magnetism and exchange energy between magnetism and electricity. They are a functional material that reduces losses in the power conversion process from power generation to consumption, thus contributing to energy conservation. A type of electrical steel sheet, directional electrical steel sheet, easily becomes magnetized in one direction, thus making it essential in voltage converters. This steel sheet is extensively used throughout the world, including emerging countries in which electricity demand is rapidly increasing.

To produce directional electrical steel sheets, steel-making, hot-rolling, cold-rolling, and annealing processes must be prepared. However, unlike typical cold-rolling products, coordination tasks from previous processes are essential. A technology is necessary to align all crystals, microstructure of products, in the same direction as the rolling direction in an orderly manner.

Steel-makers of Japan began production by introducing such technology from the USA about 50 years ago and have improved technology and reduced conversion loss. For this purpose, completely removing impurities during the steel-making process and thinning the sheets during hot rolling and cold rolling processes are necessary. As sheets become thinner, the properties of directional electrical steel sheets tend to improve. The addition of Si and Al is
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highly effective, but an excessive amount has a negative impact. Thus, by carefully controlling crystals to supplement performance, advanced control is performed as per characteristics that require a balance. Different combinations of parameters from the existing cold-rolled products are necessary.

A Korean steel maker, A, that has been planning to enter the directional electrical steel sheet market introduced a complete set of cutting-edge manufacturing equipment from Europe in the 1990s; they then began full-scale production of directional electrical steel sheets. The maker A already had a good track record for general cold-rolled products; however, the quality of their directional electrical steel sheets did not stabilize, and the export that was initially planned was not possible. In the company, being assigned as the supervisor of electrical steel sheet production led to resignation, which workers wanted to avoid.

A technical wall the maker A faced was inter-process adjustments and parameter adjustments for the steel-making, hot rolling, cold rolling, and annealing processes. As per the existing operational parameter, directional electrical steel sheets could not be produced. The maker A continued to fail for multiple years and finally signed a contract with retired technicians from Japanese steel makers to obtain know-how and information. With that, the quality of their electrical steel sheets was improved, thus allowing export to China. However, in 2007, the staff of the maker A illegally sold the said technology to a Chinese steel-maker. The illegal pathway they used to obtain the original technology came to light, thus leading to an international problem. The maker A ultimately paid the Japanese steel maker equivalent of ¥30 billion in a settlement.

Case Study 2: Galvanized Steel Sheet

A South Korean steel maker B that was established in the 1970s
introduced the equipment from Japan and Europe, and began their steel production. In the early stage, their experience with steel was nearly nonexistent; thus, they had no choice but to pay an expensive fee to learn foreign operational technology. At this stage, there was no equipment to manufacture steel sheets for automobiles because all they had was a process to produce hot-rolled coil. The maker B introduced the state-of-the-art equipment and completed the second steelworks designated for steel sheets for automobiles in 1992. They began their high-grade steel production at a full scale; however, it took many years of trial and error to determine the parameter combination from the blast furnace to the galvanizing line. It took time to identify parameter combinations and inter-process coordination for steel sheets for automobiles, which were different from what they have performed before.

It is after year 2000 that maker B started producing steel sheets for automobiles in full swing. The maker B established a company-wide project in 2003 to share the production by having all departments associated with production of steel sheets for automobiles participate to build skills for inter-process coordination. This project led to close communications between the plating department and previous processes such as a steel-making process. In this manner, the maker B was able to quickly respond to detailed requirements of automobile makers. Subsequently, research institutes joined in to operate the project. The manager of the plant in the plating department who experienced the effect of coordination across departments proposed the establishment of a new department for consistent quality management; however, this proposal did not come to fruition.

**Discussions**

In terms of technology transfer to developing countries that are lacking in skilled labor, the capital-intensive type is more efficient
(Hirschman, 1958). For the process industry, such as steel industry, operational knowledge is embodied in the process equipment; thus, even if the embodied technology is highly advanced, it is easy to transfer to least developed countries where technology transfer and catch-up would be relatively fast. As long as least developed countries make a considerable capital investment, efficient production that utilizes the economies of scale is possible (Gerschenkron, 1962). However, in reality, high-grade steel production did not achieve such efficiency. For more accuracy, there are products for which catch-up is fast and those for which catch-up is reduced. As shown in this study, steel-makers in emerging countries especially struggle with high-grade steel production in terms of operational technology and technical issues with inter-process coordination.

Resource-based view (RBV) argues time compression diseconomies, e.g., when trying to accumulate in half the time, investment required doubled (Dierickx & Cool, 1989; Takahashi & Shintaku, 2002). Inter-process coordination and capacity building both require relearning combinations of operational parameters from the beginning including those for the existing processes. Thus, time compression is severe for introducing the latest equipment, thus presenting an example of time compression diseconomies. For acquiring operational technology, there is a recognition lag in the awareness of the necessity for readjustment of the link between the existing processes and additional processes from the perspective of the overall process, as well as a learning lag regarding relearning these adjustments.

For diverse fields, such as general system theory, product development theory, and product architecture theory, interdependence and associated management have been examined. However, most studies focused on spatial interdependence between parts, and not paid much attention to
temporal interdependence and its management such as the interdependence of processes. Even if there were complex interdependence between parts, as long as the pattern of such interdependence is known and stable, management is not difficult (Teece, 1976). Similarly, inter-process coordination depends on operational technology that manages their connection.

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