Kindai Management Review Vol. 13, 2025 (ISSN: 2186-6961)

Process Innovation Revisited: Two Routes for Process Integration

Sungwoo Byun

Toyo University, Japan

Abstract

It is no exaggeration to say that research on product and process innovation is one of the most important areas of innovation management research. Abernathy (1978) provided an important framework for explaining the dynamics of innovation at the industry level. Although Abernathy's framework explains that process innovation is moving from a fluid phase to a specific (rigid) phase, it oversimplifies the characteristics of process technology and does not examine changes in process technology in detail, such as process modularization, functional consolidation, process shortening, and process integration.

This study focuses on the development stages of manufacturing process technologies and presents a typology of process innovation leading to process integration. Specifically, this paper explains process modularization and process interlocking as methods for managing manufacturing processes and clarifies the characteristics of those methods. This paper defines 'process integration' that incorporates the following elements: (compared to existing processes) (1) superior quality, cost, and lead time, (2) flexible production capabilities to accommodate product diversity (product types and quality grades), and (3) flexible selection of process functions and scope.

This paper analyzes two industrial cases to explain the two routes for process innovation. Firstly, to elaborate on the process modularization route for process innovation, this paper introduces a case study of functional consolidation in the machine tool industry, which is an assembly industry. Secondly, the process interlocking route for process innovation is explained using steel industry case study, which is a process industry.

Keywords: *process innovation, process integration, process modularization, process interlocking, functional consolidation, process shortening*

1. ANALYZING A PRODUCTION PROCESS AS A FLOW

Analyzing a production process is, essentially, the same as analyzing a flow. The purpose of the analysis is to make the flow smoother, thereby improving productivity. Generally, in the early development stage, initial production processes of a factory are relatively short and start out as 'separated islands(machines)'. When a task is completed in one process, it is passed on to the next island (machine) to make the product. This type of process may be flexible, but it is limited for cost reduction through mass production. Therefore, a common challenge in all manufacturing sites was to connect multiple production processes and get as close as possible to a 'smooth' flow.

Improvements at Japanese manufacturing sites, GENBA, have also been made from the same perspective to improve productivity. In Japanese industrial improvement activities, KAIZEN, which place emphasis on value stream maps are used to identify

Table 1: Definition of integration

	Definition	Managerial interpretation
1	to combine two or more things in order to become more effective	technology and process integration
2	to mix with and join society or a group of people	Integrated management of the organization

bottleneck processes and aim to synchronize them with other processes. The Toyota Production System (TPS) is a typical example. Manufacturing (MONOZUKURI) is all about creating and managing a flow (Fujimoto, 2001). Goldratt's theory of constraints (TOC) also emphasizes the idea of identifying bottleneck processes in the production process flow and improving the capacity of those processes to improve the productivity of all processes (Goldratt, 1990).

Innovation is defined broadly as the introduction by a firm of a technical change in product or process (Myers and Marquis, 1969). Existing research on innovation has analyzed product innovation and process innovation together. A product innovation is a new or improved goods or service that differs significantly from the firm's previous goods or services and that has been introduced on the market. And a business process innovation is a new or improved business process for one or more business functions that differs significantly from the firm's previous business processes and that has been brought into use by the firm (OECD, 2018).

Product innovation is innovation related to the specifics of a product and its elemental technologies, while process innovation is innovation related to the process for producing a product and its elemental technologies.

Furthermore, there are two types of innovation, radical innovation, which is made up of technologies that are completely different from existing technologies, and incremental innovation, which is made up of repeated improvements to existing technologies. All those views are applicable to analyze process innovation. To analyze process innovation, it is necessary to look not only at discontinuous, radical, and macroscopic perspectives such as the replacement of old technology with new process technology, but also at incremental changes and developments in production lines at the factory level.

Yet, existing research on process innovation does not adequately categorize the process development stages leading to process innovation. The routes to process innovation have not been extensively studied or understood. The purpose of this study is to fill that gap.

This paper presents a framework for two routes to process innovation and explains the characteristics of each stage. The purpose of process innovation is the integrated management of production processes. There are two dictionary meanings of integration (Oxford English Dictionary). One is to combine two or more things in order to become more effective. For example, it is to consolidate separate production processes (machines) into one process. Broadly interpreted, it can be understood as the integration of technology.

Another meaning of integration is to mix with and join society or a group of people. For example, when multiple process organizations are involved in the production of a finished product, integrated management may be used to ensure that all processes work together to create the final product, not just one's own. Broadly interpreted, this can be understood as organizational integration. A comparative study of the competitiveness of the Japanese and U.S. automobile industries since the 1980s has emphasized integrated management of automobile development organizations and development processes (Womack, Jones & Roos, 2007).

Process innovation, by managing processes in an integrated manner, brings about superior performance in terms of shortening production lead times, improving manufacturing flexibility, and even automation, compared to existing process management. To analyze process innovation in detail, this paper defines process innovation in more detail. Process innovation refers to innovation that brings about a new process that is superior in terms of quality, cost, lead time, and flexibility compared to the processes currently in use.

New manufacturing processes are technologies that can manufacture products of the same

or better quality as existing processes, quickly and cheaply, and that can flexibly manufacture a wide variety of products or products of multiple quality grades. Process innovation does not refer to a specific technology. It refers to the ongoing efforts to improve the quality, cost, lead time, and flexibility of existing process technologies, and the upward direction it takes. Therefore, categorizing the stages leading to process innovation is very useful for understanding process innovation in detail.

2. EXISTING RESEARCH ON PROCESS INNOVATION

2.1. Abernathy's product-process life cycle model

Product-process life cycle model presented a pattern of product and process innovation (Utterback & Abernathy, 1975; Abernathy, 1978; Abernathy & Utterback, 1978). Abernathy posited that a wave of product innovation comes first, followed by a wave of process innovation. Specifically, in the early stages of product innovation, various product-related technologies coexist, but the rate of product innovation steadily declines as a dominant design emerges. This triggers process innovation. In other words, processes are introduced and improved to produce dominant design products most efficiently. Eventually, both product technologies and process technologies are standardized, and costs are reduced gradually with mass production. However, it has been pointed out that this also creates a dilemma for management because the standardized process can only manufacture specific products which means losing flexibility of manufacturing process.

Product-process life cycle model suggests that the initial process technology, which was in fluid stage, gradually moves to a specific stage. With the emergence of dominant product designs such as Ford Model T, the process technology was further improved. Specifically, around 1914, the production process was revised from a stationary assembly in which a car was placed at certain places and components were transported and assembled to moving assembly lines using conveyor belts. This change of process technology established the basis of flow production.

In addition, by introducing dedicated machines specially made for Model T, automobile components could be made with high precision level and parts interchangeability was achieved. Additionally, in-house press process for the automobile steel sheets was used in car bodies and other parts. Ford deployed an extreme vertical integration strategy, building its own steelworks and perfecting the process technology that allowed production from steel to cars in just two days.

The essence of process innovation in Abernathy's product-process life cycle model is that by making manufacturing processes as a flow, mass production is realized while shortening the production lead time. However, Abernathy's model does not categorize the process of technological developments in detail.

2.2. Utterback's innovation dynamics research

Product innovation and process innovation are interrelated. One important observation was that the rate of process innovation increases as the rate of product innovation decreases. For example, in manufacturing light bulbs, between 1880 and 1920, the number of steps in the manufacturing process decreased from 200 to 30. Skilled workers using common tools were replaced by specialized equipment that could be operated by unskilled workers as well. Light bulb manufacturing moved from individual production to mass production, and finally to continuous production (Utterback, 1994).

Utterback analyzed process innovation, focusing on the difference between assembly and non-assembly (process) industries. He found that many of the trends in innovation models for assembly industries also apply to process industries. In particular, he emphasized that in non-assembly industries, the phenomena of process integration and gradual expansion are process innovations that focus on improving productivity.

The model for non-assembled products is based on the emergence of an enabling technology in process innovation. Once the enabling technology has emerged, there is further incremental innovation. The Utterback model stressed the process combination and elimination. Process combination and elimination can be achieved by introducing a new process technology.

Enos (1962), Hollander (1965), Allen (1967), and Stobaugh (1988) focused on the changes in process technology and integration. In his study of the petroleum refining industry, Enos (1962) noted that process improvements enabled the production of higher quality petroleum products in larger quantities at lower cost, and that processes that were initially discontinuous gradually became continuous. Hollander (1965) conducted a detailed study of five DuPont rayon plants and found that relatively small technological changes were most important in explaining cost reductions. 77% of technology-induced cost reductions were due to minor technological changes. Allen (1968) studied innovation in the steel industry and chemical industry. In the steel industry, the rudimentary economic aim is to produce steel to a required specification at minimum cost. However, the iron and steel industry has long been characterized by a tendency towards integration, backwards through scrap procurement, iron making, the manufacture of metallurgical coke and consequential by-products, and forward towards the casting, rolling, shaping and forging of angles, shapes, sections, rods, plate, strip etc. And Stobaugh (1988) studied innovation and competition in the petrochemical industry at the same time. He found that any new process that is only a minor innovation may soon face additional competition from other processes developed subsequently. In contrast, a major innovation is much less likely to face competition from a subsequent major innovation.

Citing the works above, Utterback noted that while there are many commonalities between product and process innovation in assembly and non-assembly industries, there are also notable differences.

The first is that the innovation process is prominent and occurs quickly in the non-assembly industries. The second is that process innovation in the non-assembly industries involves fewer reforms, and rather productivity improvements are brought about by relatively small, incremental process improvements. Other existing studies have also focused on the characteristics of process development and product development in the process industry (Barnett and Clark, 1996; Pisano, 1997).

2.3. Product-process matrix (PPM)

Though the product-process matrix is not a framework for analyzing process innovation itself, it is a useful framework for analyzing the types of process technologies because it classifies production processes based on their characteristics (Hayes & Wheelwright, 1979). In the product-process matrix, production processes are classified into job processes (job shop), batch processes, line processes, and continuous flow processes. As a process moves from job processes to the continuous flow, diversity decreases while the production process becomes more continuous.

The product-process matrix shows that there exist matching relationships between products (variety, production volume) and processes, and that matching area is located on the diagonal of the matrix. However, the matrix does not focus on the changes in the process itself due to the development or change of process technology. For example, a process using a batch process may change to a line process as process technology develops. In order to analyze process innovation, it is necessary to analyze based on the development stages of process technology.

2.4. Process analysis using product architecture concepts

Product architecture is a concept that was originally devised on the product design, not manufacturing process. When a product designer designs a product, he or she breaks down the product's functions and components(structure), and then further break them down into sub-functions and sub-components and consider the correspondence between them. If the relationship between functions and components is close to one-to-one, the product has a modular product architecture, while if it is close to many-to-many, the product is judged to have an integral product architecture. Product architecture has also been used in innovation research (Henderson & Clark, 1990).

If one can break down manufacturing processes according to a certain criterion and analyze the corresponding relationships just like with product architecture, one can apply the basic framework of product architecture framework to process

Table 2: Process innovation in previous studies

	Previous research	Characteristics of process innovation
1	Product-process lifecycle	• As process technology proceeds from a fluid phase to a specific phase and eventually becomes standardized, productivity increases but flexibility is lost. • The specific process of technological development is not shown.
2	Innovation Dynamics	• Process innovation in the non-assembly industries has been less about change and more about productivity gains through relatively small, incremental process improvements.
3	Product-process matrix	• Although the types of production process are explained, no attention is paid to technological changes in the processes.
4	Process architecture	• Analyzed the production process by dividing it into processes and functions.

architecture as well. And like product architecture, the basic types of process innovation can be broadly categorized into modular and integral types. The challenge is to determine the criteria for distinguishing between the two types.

Existing research has attempted to distinguish architecture types by focusing on the relationships between (1) manufacturing processes, (2) product structure (components), and (3) product functions (Fujimoto & Kuwashima, 2009). However, analysis of the relationships among the three has rarely been used as a framework for process analysis due to its complexity.

As shown in Table 2, existing research analyzing production processes generally gave more attention to the relationships between product innovation and process innovation, and categorization of production processes and production process types, than to the mechanism of process shortening and process integration, which can be said to be the essence of process innovation.

Some literature defines process integration as the coordination of operations and consolidating data to simplify processes and increase efficiency (APICS and ASCM, 2020). This paper defines 'process integration' as a process innovation that incorporates the following elements: (compared to existing processes) (1) superior quality, cost, and lead time, (2) flexible production capabilities to accommodate product diversity (product types and quality grades), (3) flexible selection of process functions and scope. This study considers the purpose of process innovation to be process integration and analyzes the steps leading to process integration from the perspective of changes in the production process.

One way to integrate production processes is to consolidate process functions and shorten production processes, which requires consolidating the 'functions' of each process. This task is defined as 'modularizing' the process. Another way to achieve process innovation is to connect consecutive processes and manage the entire process as a 'single flow'. To achieve this, it is necessary to manage the entire flow tightly by coordinating between processes, that is, by creating seamless and strong linkages. This task is defined as 'interlocking' the process.

3. TWO ROUTES TO PROCESS INNOVATION: PROCESS MODULARIZATION AND PROCESS INTERLOCKING

In general, the more steps a product goes through, the higher value-added it is classified as. This is because processing through many steps means that it was made with more time and effort. Also, a product that goes through many processes means that it is made with more complexity than a product that goes through fewer steps. For example, the body of luxury automobile model goes through more painting processes than a general model. Also, a high-end steel product such as hot-dip galvanized steel sheets for automobiles are the ones that go through the longest production processes that steel manufacturers have. Meanwhile, manufacturing companies are devising ways to shorten long production processes, because the length of the process is directly linked to production performance, such as production lead time.

Route 1 Process modularization: process integration through functional consolidation

Every production process has its assigned job.

When a production line is first launched, it generally starts with a process of a specific function, but as new processes are added, the production line becomes physically longer and functionally more complex. Consider an office which has a telephone, printer, copier, scanner, and fax machine. Imagine that a manager purchases a telephone for business purposes. At this stage, the telephone alone may be sufficient to deal with customer information, but as the number of orders increases, the amount of information that needs to be processed increases, and it becomes impossible to process everything with just the telephone.

After that, the manager purchases office automation (OA) equipment such as printers, copiers, scanners, and fax machines. In other words, the manager has telephones with voice capabilities, printers with printing capabilities, copiers with copying capabilities, scanners with scanning capabilities, and fax machines with the ability to send and receive image information. However, times have changed, and the same manager can purchase a multi-function machine instead of purchasing each equipment. In other words, a single multi-function machine contains all the functions mentioned above.

A multifunction machine can be understood as a machine that consolidated all the functions of a telephone, printer, copier, scanner, and fax machine into a single machine. A multifunction machine takes up less space than a telephone, printer, copier, scanner, and fax machine, and a manager can choose functions to use. In this way, extracting the functions of each machine (process) and consolidating them into a module can be defined as 'modularization of the process'.

To modularize processes, the following requirements should be met. First, there must be no restrictions on the working order (sequence) of the tasks. Users can select and use one or a combination of telephone, printer, copier, scanner, and fax functions, so the order should not matter. Second, because multiple processes are combined into a single machine, the hardware also needs to be designed in a way that there is no interference between the multiple functions. For example, when a document is being read using the copier function of a multifunction device, the scanner cannot be used at the same time.

The benefits of consolidating functions through process modularization are not limited to shortening production lead times. Another benefit is increased flexibility, which comes from being able to select functions. Also, in general, the more processes are consolidated, the easier they tend to be automated.

Route 2 Interlocking processes: process integration through inter-process coordination

Unlike the case of the multifunctional OA machine mentioned above, some products cannot be completed unless the order of the production process is properly or strictly followed. By adding and connecting processes with different functions, the process itself can look continuously working, but the processing and manufacturing environments of each process are completely different, and it can be difficult to combine them into one process.

The beer manufacturing process is one of typical examples (Fujimoto & Kuwashima, 2009). The beer production process is roughly divided into five steps, which are carried out in the following order: malting, brewing, fermentation and storage, filtration, and packaging. Unlike the modularization of processes mentioned above, the functions of these processes place strong constraints on the order of processing. In other words, the fermentation process always comes after the brewing process. Furthermore, it is not possible to selectively use only filtration process. Furthermore, because the fermentation process is centered on chemical reactions, it cannot be grouped together with the packaging process, which is centered on physical work.

In this case, the key to process innovation is not just to connect processes, but also to manage connecting points between processes. In the example of beer production, the brewing kiln and the fermentation tank are connected with pipes, and quality is maintained by thoroughly controlling the speed of the intermediate product flowing through the pipes and the temperature at that time (Fujimoto & Kuwashima, 2009). In other words, by viewing the entire process as a single flow and adjusting between each process, it is possible to manage it into a seamless flow. This paper defines a seamless

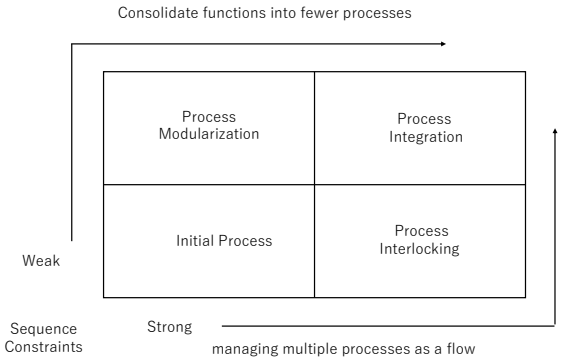


Figure 1: Process modularization and process interlocking

flow as 'interlocked' since manufacturing processes are managed tight just like a seamless flow, not just added and connected separately.

When there is a strict constraint in the sequence of manufacturing processes, interlocking processes by tightly linking and managing them is required. The benefits of process integration through process interlocking are shorter production lead times, improved flexibility, and automation.

Figure 1 shows two paths to process integration as a goal of process innovation. When an initial production process is expanded, it tends to acquire more functions and become longer. To manage processes in an integrated manner, there are two methods, extracting functions and combining them into a single process, and managing multiple processes in an integrated manner.

The former is used when there are loose constraints on the sequence of operations, while the latter is used when there are strict constraints on the sequence of operations. Process modularization is used when modularization of functions is possible. On the other hand, process interlocking is a technique for managing multiple processes as a flow. Both methods aim for process integration. Process integration is a process innovation that includes the following elements: (compared to existing processes) (1) superior quality, cost, and lead time, (2) flexible production capabilities to accommodate product diversity (product types and quality grades), (3) flexible selection of process functions and scope.

4. CASE STUDY: MACHINE TOOL INDUSTRY AND STEEL INDUSTRY

To illustrate these two routes of process innovation, this study introduces two case studies, the machine tool industry and steel industry. These cases are based on field studies, which included multiple visits to production sites and interviews with managers. A case study method is used because the research is exploratory, and the subject of study is dynamic.

4.1. Modularization of processes in the machine tool industry

Machine tools, which are machines that make machines, are often called mother machines. They use sensors to detect, control, and transform the workpiece. Machine tools have a long history of the continuous production of high-precision special-purpose machines.

Conventional machines were divided into multiple processes and constituted long production lines. In addition, the running costs of managing multiple processing machines and the maintenance costs of maintaining performance were also large. Furthermore, as the production process became longer, the range of responsibilities of the workers managing those processes tended to be broad. Conventional production lines were a combination of general-purpose machines and dedicated machines.

For example, in production sites where work was done with general-purpose lathes, 3-axis machining centers, and other dedicated machines, skilled workers who understood all these processes were required.

Machine tool manufacturers have succeeded in completing tasks that were previously divided among multiple machines with a single machine. By consolidating processes and functions into a machine, manufacturers have succeeded in shortening the physical length of processes.

Process consolidation has brought notable benefits. Firstly, it has reduced the set-up time between processes. Secondly, it also reduced the inventory of work-in-progress that existed between processes. This is also due to the elimination of the need to move inventory. Thirdly, assembly time

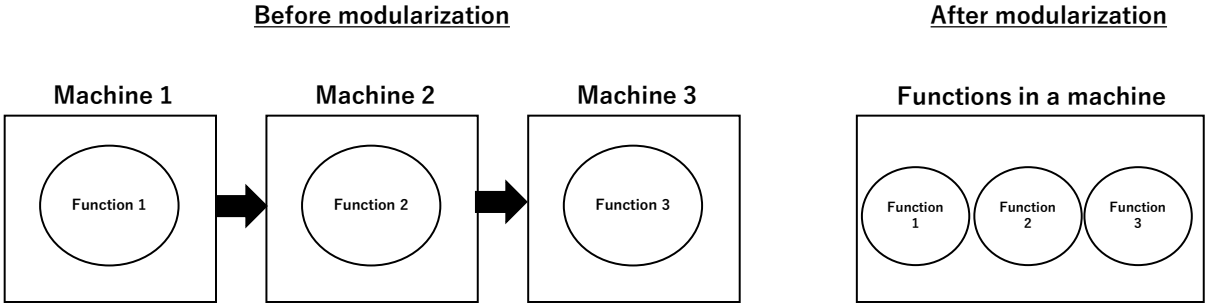


Figure 2: Shortening processes by consolidating functions into a multi-tasking machine

has been shortened, leading to faster lead time and higher productivity. Fourthly, since the work can be done with a single machine, power consumption and CO_2 emissions have also been reduced. Process consolidation leads to further automation of work. Users can also select and combine the various functions integrated into a single machine.

The essence of process reduction through process consolidation with multi-tasking machines is the consolidation of the functions of each machine tool. It can be understood as reducing the physical part of a process while maintaining all the functions. To achieve this, it is necessary to modularize the functions of each process machine. With a multi-tasking machine which is a collection of functional modules, the user can select the functions and sequences.

This method is used not only by machine tool manufacturers, but also by line builder businesses that take on entire production orders. Line builder companies receive orders from multiple companies for automobile engine production lines and semiconductor production lines. Line builders complete the production lines in their own factories and install them in their client companies' factories. Rather than customizing production lines for each customer, line builder companies aim to reduce costs and achieve the economies of scale by standardizing the parts and functions of manufacturing equipment.

Like machine tool manufacturers, line builders also modularize the functions of their client's manufacturing equipment (manufacturing process) and design it to be as integrated as possible into one piece of equipment. For example, before modularization, the process design for screw tightening consisted of an array of dedicated machines whose only function was screw tightening. However, by adding modularized functions to one piece of equipment in addition to screw tightening, the process can be shortened, and the flexibility of the range and order of possible operations can be improved. Also, like multitasking machines, it has the advantage of automation.

4.2. Process interlocking in the steel industry

The steel industry is a typical example of a process (non-assembly) industry. Unlike assembly industries where parts are assembled to create a finished product, in the steel industry there are no parts. The steelmaking process has two major characteristics (Byun, 2019; Byun, 2020; Ma & Yamamoto, 2021).

First, the steel making process can be broadly divided into chemical reaction processes and machining processes. The blast furnace, the symbol of a steelworks, and the converter, which mainly adjusts the composition, are production processes centered on chemical reactions. On the other hand, the hot rolling and cold rolling processes, which roll out plate-shaped steel into long, thin pieces, are machining processes.

Second, the grade of the products produced by steel manufacturers depends on the number of processes the product goes through. In other words, automotive steel sheets, which are high-end products produced by steel manufacturers, are processed in more processes than ordinary steels. Ordinary steel goes through fewer production steps than high-grade steel.

Generally, the first production line of a steel

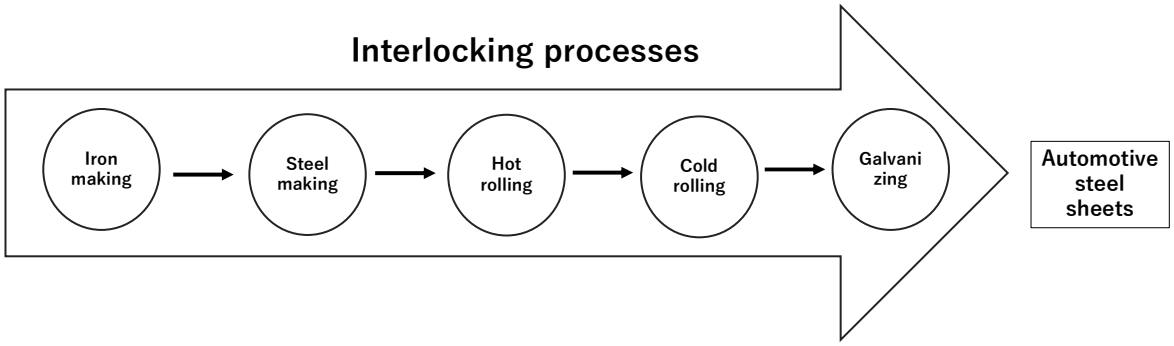


Figure 3: Interlocking processes for manufacturing automotive steel sheets

manufacturer starts with a blast furnace and converter, which are mainly used for chemical reactions. After that, to increase the variety of products and to aim for higher quality, a post-process is added, which is the rolling process (hot rolling process, cold rolling process).

The more processes a steel product goes through, the higher the added value of the product. For example, automotive steel sheet is a product that requires longest processes (full process). High-end automotive steel sheet cannot be produced if the iron-making process, steel-making process, continuous casting process, hot rolling process, cold rolling process, and hot-dip galvanizing process are managed separately. A long series of production processes must be managed as if they were a flow, tightly managing connecting joints across all the processes (Byun, 2019; Byun, 2020).

Unlike machine tools, it is difficult to modularize the steelmaking process. Not only is the equipment itself large, but it is also impossible to modularize the processes that are centered on chemical reactions and the machining processes. When it comes to integrating processes, steelmakers have focused on making more efforts on managing the overall processes as a flow. The challenges they faced at the time were as follows.

Firstly, making the process as continuous as possible is the most basic management. Secondly, in the case of high-grade steel for automobiles, it is not enough to simply add and connect them together. It is also necessary to properly manage the connecting joints between processes. Managing between processes means tightly managing all processes, sharing quality information such as tolerance information between the previous and next processes, and making fine adjustments to operations accordingly (Byun, 2020).

However, not all products require this type of control. For example, construction materials and wire rods that use billets and blooms do not pose any problems as long as they are processed in the correct order. In other words, compared to steel sheets for automobiles, they do not require a high level of consistent quality control.

Consistent process management is essential for process interlocking in the steel industry. The production of hot-dip galvanized steel sheets for automobiles is a typical example of an interlocked process. After the ironmaking process, impurities are removed in the steelmaking process to match the composition of the steel sheets for automobiles. Then, in the hot rolling process, the product with its composition adjusted is reheated. At that time, the reheating temperature, rolling speed, and rolling pressure level are fine-tuned. In the cold rolling process, fine adjustments are made for the surface treatment, and the product is then brought to the galvanizing process.

Steel manufacturers have not only been able to connect previously separate processes but have also come to realize the importance of inter-process management and have built up the ability to coordinate between processes.

5. CONCLUSIONS AND IMPLICATIONS

This study focused on the development stages of

Table 3: Two routes to process innovation

	Process modularization	Process interlocking
Key management point	Consolidation of process functions	Management of inter-process connections joints
Constraints of order	Weak or none	Strong
Process shortening effect	Strong	Weak
Case	Machine tools (multi-tasking machines)	Automotive steel plate manufacturing process

manufacturing process technologies and presented a typology of process innovation leading to process integration. Specifically, this paper explains process modularization and process interlocking as methods for expanding manufacturing processes and clarifies the characteristics of those methods. Both routes are for managing processes in an integrated manner, though the ways of integration are different. The effects of process integration include improved productivity through shorter production lead times, improved flexibility, and progress in automation. The increased flexibility achieved by modularizing processes means that users can flexibly select and use the aggregated functions. And the increased flexibility achieved by interlocked processes is the benefit of managing multiple processes seamlessly as if they were a single flow, and it means improved ability to flexibly respond to products that go through different numbers of processes.

The difference between the two routes is whether there are order constraints on process functions. In the case of function consolidation through process modularization, there is weak or no major interference between the functions. For example, in the case of a multi-function OA machine, the copy and scan functions use the same component (motor), so it is necessary to select one of the functions. In the case of multi-function machine tools, functions can also be freely selected for processing.

On the other hand, interlocking processes place strong constraints on the order of manufacturing processes. Since steelmaking processes are divided into processes centered on chemical reactions and processes centered on machining, the constraints are strong. Steel products are made by flowing them in order from the first process, the iron making process, to the final process, the cold rolling process. However, adding the cold rolling process does not mean managing only the added process. When expanding a production process, new operational knowledge and pattern knowledge (recipe) for the new combination of operational parameters must be acquired.

To integrally manage the processes from start to finish, it is important to manage the connection joints between processes and to manage all processes across the joints. Rather than managing each process separately, tight management is required that interlocks all processes.

Although this study has explained two development paths, this model is closer to an incremental innovation model rather than a model that represents discontinuous process innovation that invalidates existing process technology. In the history of steel industry, technology of a completely different nature emerged in early 2000s. With previous technology, iron ore and coal were pre-processed before being fed into a blast furnace, where they were melted at high temperatures to produce pig iron. However, the new iron-making technology could produce pig iron without pre-processing the raw materials. As a result, productivity improved through shortening of processes and production lead time. We would like to leave as future work the possibility of researching discontinuous process innovation, which was not the subject of this study. And comparative research with gradual process innovation will be fruitful.

It is a challenge to categorize innovation in all industries. This research mainly focuses on the machine tool industry and the steel industry as examples of process innovation. Although the efforts of the machine tool industry are highly suggestive of process modularization, the examples of the machine tool industry do not necessarily apply to all assembly industries. The same can be said about the steel industry. While steelmaking, glassmaking, and papermaking have many things in common, they also have many differences. This

research will proceed cautiously in broadening the interpretation of commonalities found in some industries to other process industries such as glass-making, and papermaking industry.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Number 22K01671 (FY2022–2026).

REFERENCES

Abernathy, W. J. (1978). *The productivity dilemma: Roadblock to innovation in the automobile industry*. Johns Hopkins University Press.

Abernathy, W. J., & Utterback, J. M. (1978). Patterns of industrial innovation. *Technology review*, 80(7), 40–47.

Allen, J. A. (1967). *Studies in innovation in the steel and chemical industries*. Manchester University Press.

APICS (American Production and Inventory Control Society) and ASCM (The Association for Supply Chain Management) (2020). *APICS DICTIONARY: The essential supply chain reference*, 16th edition, APICS/ASCM.

Barnett, B. D., & Clark, K. B. (1996). Technological newness: an empirical study in the process industries. *Journal of Engineering and Technology Management*, 13(3–4), 263–282.

Byun, S. (2019). Managing tolerance stack-up through process integration team in steel industry. *Annals of Business Administrative Science*, 18(6), 223–236.

Byun, S. (2020). Managing the interdependence among successive stages of production in steel industry. *Annals of Business Administrative Science*, 19(6), 223–236.

Enos, J. L. (1962). *Petroleum Progress and Profits*, MIT Press.

Fujimoto, T. (2001). *Seisan manejimento nyumon (I): Seisan sisutemu hen* [Introduction to production management (I): Production system]. Tokyo, Japan: Nihon Keizai Shimbun Shuppansha (in Japanese).

Fujimoto, T. and Kuwashima, K. (2009). *Nihongata purosesusangyou* [Japanese Process Industry]. Tokyo, Japan: Yuhikaku (in Japanese).

Goldratt, E. M. (1990). *Theory of constraints*. Croton-on-Hudson: North River.

Hayes, R. H., & Wheelwright, S. C. (1979). Link manufacturing process and product life cycles. *Harvard Business Review*, June, 2(1)

Henderson, R. M., & Clark, K. B. (1990). Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative science quarterly*, 9–30.

Hollander, S. (1965). *The sources of increased efficiency: A study of DuPont rayon plants*. MIT Press.

Ma, J., & Yamamoto, M. (2021). *Growth Mechanisms and Sustainability*. Springer Singapore.

Myers, S., & Marquis, D. G. (1969). *Successful industrial innovations: A study of factors underlying innovation in selected firms*, 69(17). National Science Foundation.

OECD (2018), Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition. (https://www.oecd.org/en/publications/2018/10/oslo-manual-2018_g1g9373b.html)

Oxford English Dictionary, https://www.oed.com/

Pisano, G. P. (1997). *The development factory: unlocking the potential of process innovation*. Harvard Business Press.

Stobaugh, R. (1988). *Innovation and competition: the global management of petrochemical products*. Harvard Business School Press.

Utterback, J. M. (1994). *Mastering the dynamics of innovation*. Harvard Business School Press.

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. *Omega*, 3(6), 639–656.

Womack, J. P., Jones, D. T., & Roos, D. (2007). *The machine that changed the world: The story of lean production*. Simon and Schuster.

Sungwoo Byun is Associate Professor of Faculty of Business Administration, Toyo University, Japan. Email: byun@toyo.jp