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REVIEW ARTICLE

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Review of *seru* production

Abstract *Seru* production is regarded as a new production mode and derived from the production site of Japanese electronics industry. This production mode is proposed to overcome the low flexibility of the assembly line. *Seru* production has been successfully implemented in Japanese electronics industry, such as Canon and Sony. Benefits from *Seru* production include rapid response, good flexibility, and high productivity. *Seru* production has received extensive attention in academic research and production practice. This study reviews the background, characteristics, types, and operation of *seru* production. The advantages and applicable scenes of *seru* production are summarized from the perspective of business practice. We compare *seru* production and famous production modes, i.e., assembly line, cellular manufacturing, and Toyota Production System. The literature on *seru* production is surveyed and classified. Furthermore, future research directions are provided.

Keywords *seru* production, production mode, flexibility, literature review

1 Introduction

With the dynamic market demands, companies must respond rapidly to the market demands and provide diversified and personalized products. The need for high efficiency and flexibility in production systems has promoted the growth of management science, operation management, and industrial engineering. Current well-known production modes are the scientific management principles developed by legendary engineer Frederick W. Taylor, mass production (assembly line) represented by Ford Production System, Toyota Production System (TPS) developed by Toyota Motor Corporation of Japan, and cellular manufacturing (CM) based on group technology (GT). However, assembly line and TPS cannot work efficiently due to high value-added products, dynamic demands, short life cycle, high variety, low volumes, and variable volumes. Japanese companies, such as Sony and Canon, developed a Japanese CM to meet the market demands. They call this mode *seru* production to distinguish it from the traditional CM (Yin et al., 2008; Stecke et al., 2012; Yin et al., 2017).

Seru production has been widely used in Japanese electronics industry, such as Canon, Sony, Panasonic (Matsushita), Fujitsu, NEC, and Hitachi, has achieved great actual effects (Sakazume, 2005; 2006; Yin et al., 2017), and has received extensive attention (Yin et al., 2008; Stecke et al., 2012). Several Japanese monographs have introduced the characteristics and implementation processes of *seru* production. Singhal mentioned *seru* production as a popular field (Roth et al., 2016). *Seru* production is considered more flexible than TPS and is the next generation of lean production. A paper (Yin et al., 2017) in *JOM* entitled "Lessons from *seru* production on manufacturing competitively in a high cost environment" systematically introduced *seru* production. In the past 10 years, over 20 academic papers on *seru* production were published in important journals, such as *JOM*, *EJOR*, *IJPE*, *IJPR*, and *CIE*.

This study aims to survey and summarize the concept, characteristics, background, and research of *seru* production. We summarize the concept, characteristics, and types, survey the background, and analyze the advantages and application scenarios of *seru* production. We compare *seru* production and famous production modes, i.e., assembly line, CM, and TPS. We survey and classify the literature on

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seru production. Finally, we provide the future research directions.

2 Background and application scenarios of *seru* production

2.1 Concept and characteristics of *seru* production

Seru is the pronunciation of cell in Japanese, which not only distinguishes the meaning of the unit from the traditional CM but also defines the specific meaning of the Japanese cell. *Seru* is an assembly unit that includes simple equipment and one or several workers to operate most or all the processes of production. *Seru* is a human-centered manufacturing system with a high degree of *Jiritsu*. *Jiritsu* means autonomy, self-management, learning, and self-evolution (Yin et al., 2018). *Seru* system refers to a production system that utilizes the flexible characteristics of *seru* and improves the productivity through rapid reconfiguration of workers, equipment, and products. *Seru* production is based on the *seru* system.

Seru comprises three types (Stecke et al., 2012; Yin et al., 2017; 2018), namely, divisional *seru*, rotating *seru*, and *yatai*. A divisional *seru* is a short line staffed with several partially cross-trained workers. Tasks within a divisional *seru* are divided into different sections. Each section is in charge of one or more workers, and one section is completed and then handed over to the next section. The workers are cross-trained but not fully skilled. As shown in Fig. 1, a divisional *seru* consists of two workers and five tasks, where worker 1 is responsible for section 1 with tasks 1–2 and worker 2 is responsible for section 2 with tasks 3–5. A rotating *seru* is composed of several workers. Each worker can assemble an entire product from start to finish without disruption, i.e., fully skilled. Figure 2 shows an example of a rotating *seru*. A *yatai* is a *seru* with only one worker. A *yatai* owner performs all operational and managerial tasks by her- or himself. In comparison with the rotating *seru*, a *yatai* contains only one worker. The balance can reach 100% without being affected by other workers. Figure 3 presents an example of a *yatai*.

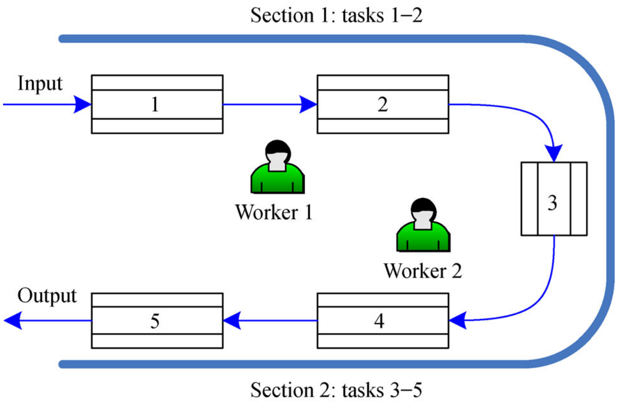

Fig. 1 Example of a divisional *seru*

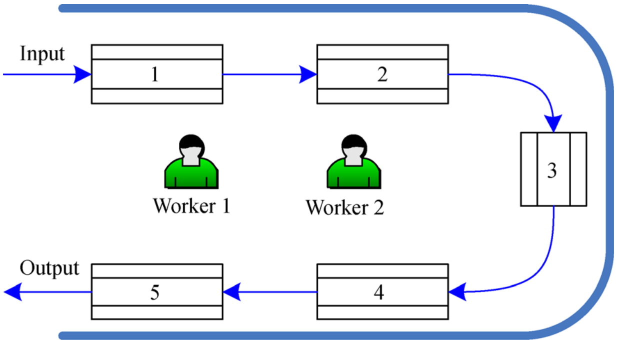

Fig. 2 Example of a rotating *seru*

The *seru* system is the production system that contains one or more *serus*. This system can be classified into pure and hybrid *seru* systems. A pure *seru* system contains only one or more *serus* without an assembly line. This system can be divided into pure divisional *seru* system, pure rotating *seru* system (Figure 4), and pure *yatai* system. The hybrid assembly line *seru* system is the production system that includes one or more *serus* and a short assembly line. This part of the assembly line is retained because (1) the equipment is expensive and inappropriate for replication in each *seru* or (2) the worker can only operate one or few tasks. Figure 5 (Yu et al., 2017a) presents an example of a simple hybrid *seru* system with five workers and five tasks. The hybrid *seru* system is more practical and complex than the pure *seru* system.

Seru production has the following characteristics (Yu and Tang, 2018): (1) *Kanketsu* (completeness)—all required tasks of producing a product are completed form start to finish within the *seru*. Workers are multi- or fully skilled. Workers in a *seru* complete most or all tasks of a product from start to finish; (2) Autonomy—in *seru* production, workers are responsible for most or all tasks; therefore, workers can improve the skill by themselves; (3) Continuous improvement—this characteristic includes the continuous improvement of worker skill and *seru*

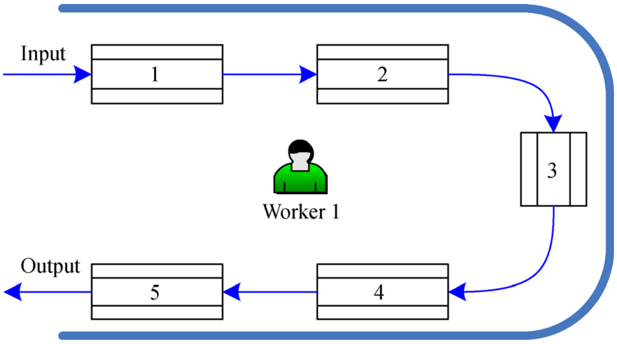

Fig. 3 Example of a *yatai*

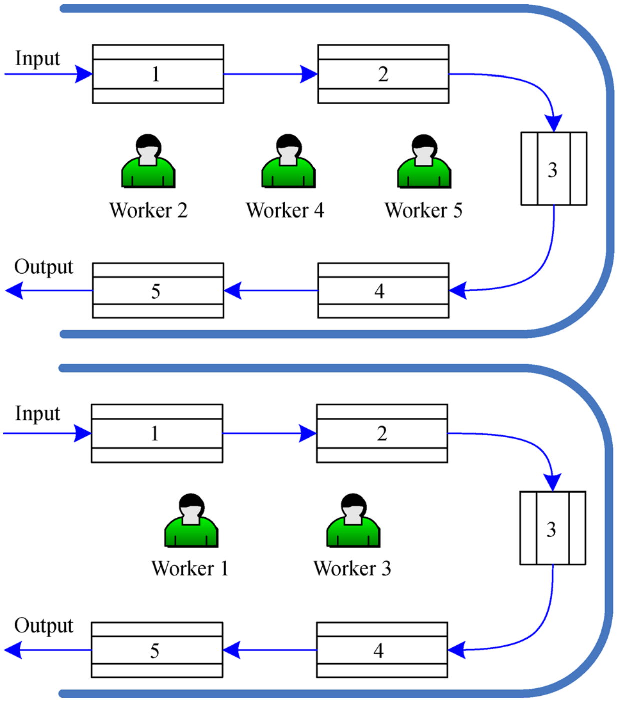

Fig. 4 Example of a pure rotating *seru*

performance; (4) Parallelization production—*seru* production contains one or more *serus*. A *seru* can produce one or more products; thus *seru* production is a parallel production. In parallelized *seru* production, when the equipment/worker is abnormal, only the *seru* with the equipment/worker is affected; (5) Reconfiguration (high flexibility)—*seru* production can be rapidly reconfigured in accordance with customer demands. Reconfiguration is based on simple and movable equipment and multi-skilled workers.

2.2 Background of *seru* production

Seru production originated from production sites in Japan in the 1990s and was related to Japanese technology accumulation, economics, corporate culture, and market environment.

Before 1970, the assembly line was popular in the assembly processes of mass production in Japan due to its high efficiency. With the customer demand change and diversity increase, companies must meet the demands of high variety and low volume. The competition among enterprises was becoming increasingly fierce. Although TPS can handle multiple varieties, its premise is that the varieties are relatively stable and the batches are inconsiderably small. For some high-tech products, such as cameras and mobile phones, the market demands are characterized by short life cycle and dynamic demands. Scientific production plans in accordance with customer demands based on assembly line and TPS are difficult to formulate due to the rapid change and uncertainty in customer demands. A new production mode is necessary to meet market demands of high variety and low volume, variable varieties and batches, and short life cycle. Thus, *seru* production was developed. Most electronic companies in Japan (Yin et al., 2013; Yu et al., 2013b), such as Canon, Sony, Panasonic (Matsushita), Fujitsu, NEC, and Hitachi, have adopted *seru* production. This new production mode has also been used in companies in Dalian and Guangdong, China. In comparison with the assembly line, *seru* production not only saves human resources, space, inventory, and lead time but also improves productivity. European and American scholars have investigated *seru* production.

The reasons for the emerging *seru* production in Japan can be summarized as follows.

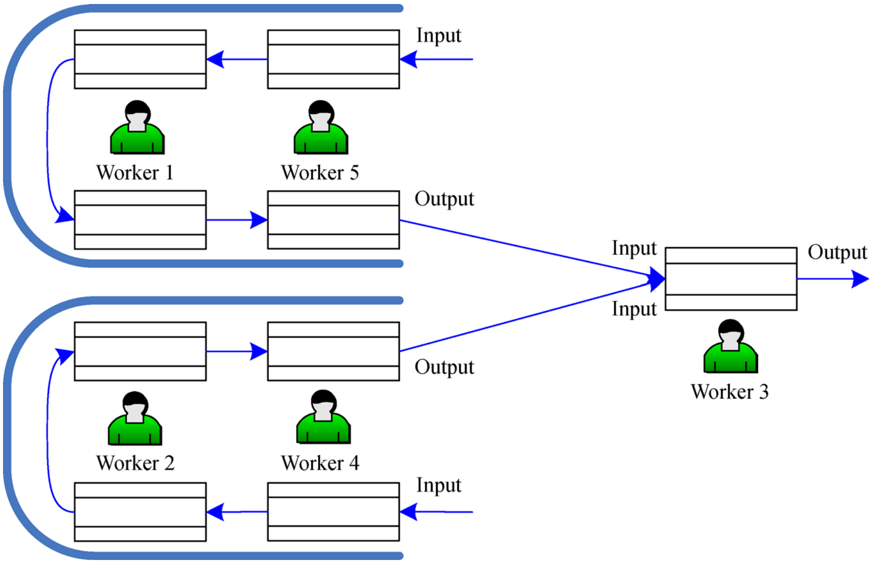

Fig. 5 Example of a hybrid *seru* system

(1) Industrial and economic environment. After the 1990s, Japanese economics downturned. The sharp appreciation of Japanese yen led to labor cost increase. Many factories moved the assembly line to the countries or regions with low labor costs, such as China and Southeast Asia. Few assembly lines were left in Japan to meet the high-quality requirements of customers. Moreover, the aged tendency of employees and the reduction in youth labors were significant.

(2) Japanese unique corporate culture. As long as employees do not resign, the Japanese companies do not lay off employees. However, the abolition of the assembly line resulted in many workers remaining. Companies must produce and meet the customer demands to feed these workers. A new production mode is necessary to be profitable by meeting the dynamic demands.

(3) New market demands. The customer demands were becoming increasingly diversified (Tan et al., 2018), the life cycle of products was shortened, and the varieties and volumes of products were becoming increasingly unstable. The assembly line, CM, and TPS could not meet such market environment.

2.3 Advantages and application scenarios of *seru* production

The case reports of implementing *seru* production have stated that *seru* production has the following advantages (Yu et al., 2012; Yin et al., 2017): (1) it can adapt to the demands of high variety and low and variable volumes and can flexibly reorganize the production system in accordance with the dynamic demands; (2) it can improve productivity and save space; (3) it can reduce product defect rate; and (4) it can improve workers' sense of responsibility. For example, after implementing *seru* production (1) Canon and Sony reduced their work space by 72000 and 710000 m^2, respectively (Stecke et al., 2012; Yin et al., 2017); (2) Sony reduced 35976 workers, approximately 25% of total labors (Yin et al., 2017); (3) Canon saved 55 billion Japanese yen in cost in 2003 (Yin et al., 2008); and (4) Sony Kohda subsidiary reduced the makespan by 53%, which made its average productivity higher than that of Toyota.

Nevertheless, *seru* production cannot improve productivity at any case. For example, in mass production, the efficiency of *seru* production is worse than that of the assembly line. Johnson (2005) studied the conversion from the assembly line to a *seru* system. In the production of sheet metal products, when the due date was short and the products were customized by customers, *seru* production should be implemented. Kaku et al. (2009) proposed a multiobjective *seru* production with makespan and labor hour minimization. They concluded that enterprises should implement *seru* production in an environment of high variety and low volume. Yu et al. (2012) stated that pure *seru* production should be implemented in cases of high variety and low volume through an analysis based on full-factor experiments. By using empirical study, Yin et al. (2017) highlighted that *seru* production is proposed in response to a dynamic market environment and high labor costs in a high-cost environment. *Seru* production inherits the merits of lean production, agile production, and grouping technology. Yin et al. (2017) empirically analyzed the flexibility and quality of the production system through *seru* production by using an example from Sony and Canon. From the perspective of management model, Stecke et al. (2012) explained that the *seru* system is an extension of the just-in-time (JIT) organization (relatively, the TPS model is the JIT on raw materials) and can realize a smart factory. Zhang et al. (2017) studied the key enabling technologies of *seru* production in terms of sustainability from a system perspective. The factors included conversion from the assembly line to *seru*, multi-skilled worker applications, equipment improvement, and distribution system optimization. The sustainability of *seru* production was evaluated through the four key enabling technologies. *Seru* production is appropriate for enterprises that are seeking supply and demand matching. The difficulty in matching supply and demand is how to meet the due date of orders. *Seru* production can reduce the lead time.

3 Comparison of *seru* production and other famous production modes

Since Frederick W. Taylor developed scientific management principles in the early 20th century, various production organization and management modes have emerged. They promoted the development of operations management and management science. The well-known production modes are scientific management principles, mass production (the assembly line or Ford Production System), TPS, and CM. Henry Ford developed the first auto assembly line, where a car was moved by a conveyor belt, while workers added components to it until the car was completed. The assembly line greatly improved productivity and reduced costs. This type of universal production mode has been widely adopted by manufacturing enterprises worldwide. However, the assembly line is mainly adapted to the market environment of mass demands and single product type. The TPS was proposed to adapt to the market environment of high variety and low volume. TPS uses a mixed assembly line to produce similar products. TPS solves the production problems of low and medium volumes with relatively stable demands. TPS includes JIT, total quality management, and team work method.

We compare *seru* production with the assembly line, CM, and TPS.

3.1 Comparison of *seru* production and the assembly line

The first auto assembly line was implemented by Henry Ford in 1913, also known as Ford Production System, mass production, or conveyor assembly line. The assembly line uses the division of labor of Adam Smith and Taylor's scientific management principles. Assembly lines are designed for the sequential organization of workers, tools, and parts. Each worker typically performs one simple operation. Before assembly line emerged, most products were made individually by hand. Each part of a product was processed by a single craftsman. Table 1 presents the comparison of *seru* production and assembly line.

3.2 Comparison of *seru* production and CM

CM was proposed on the basis of GT by a group of European companies (David and Huang, 1985; Wemmerlov and Johnson, 1997; Wemmerlov and Hyer, 2002). Cell in the CM refers to a machining center composed of machines with similar functions. Cell is centered on expensive machines, especially numerical control equipment. CM responds to market demands by changing the organizational structure and provides high flexibility for processing part families with similar tasks (Celikbilek and Süer, 2015). GT combines parts with similar structures, materials, and processes into one part group (Yin et al., 2018). Therefore, GT increases the volume size, reduces the varieties, and improves the productivity. When the equipment is expensive, the CM profit is significant. Cell loading is performed on the outcome of the CM system design (Celikbilek and Süer, 2015). *Seru* production utilizes the flexibility of *seru* and improves the productivity through a reasonable configuration of workers, equipment, and products. *Seru* production is an extension of lean production, mainly for the assembly process. Table 2 presents the comparison of *seru* production and CM.

3.3 Comparison of *seru* production and TPS

TPS was proposed by Toyota Motor Corporation. The core of TPS is to reduce and eliminate all redundancy and waste in the factory. TPS includes JIT, kanban, and zero inventory. TPS produces similar products by the rapid change of the mixed line. Table 3 presents the comparison of *seru* production and TPS.

4 Research review on *seru* production

On the basis of the used methods, the research on *seru* production (Kono, 2004; Yu et al., 2015) can be classified into empirical study, experiments, comparative analysis, statistical analysis, model, and optimization algorithm. The

Table 1 Comparison of *seru* production and assembly line

Comparison	*Seru* production	Assembly line
Flexibility	High	Low
Volume	Low	High
Inventory	Few finished-product and WIP inventories	A large amount of finished-product inventory and WIP inventory
Production	Make-to-order	Make-to-stock
Organization management	Multi-skilled worker, autonomy	Division of labor, single-skilled worker
Production form	Parallelization	Serialization
Objective	Highest efficiency of all workers	To improve the efficiency of the slowest worker
Equipment investment	Low	High
Degree of automation	Low, manual operation	High
Worker enthusiasm	High	Low
Worker management	Initiative improvement	Passive management
Energy consumption	Low	High
Defective products	Easy to trace	Difficult to trace
Completeness	High	Low
Layout	Straight line, U shape, petal shape	Straight line
Preconditions	Multi-skilled worker, high variety and low volume, variable varieties and volumes	Mass production
Disadvantage	Multi-skilled worker, difficult management	Low flexibility, bottleneck, high investment, unsuitable for high variety and low volume
Advantage	High flexibility, low investment, suitable for high variety and low volume, variable varieties and volumes	Single-skilled workers, high efficiency in mass production, simple management

Table 2 Comparison of *seru* production and CM

	Comparison	*Seru* production	CM
Similarities	Market environment	High variety and low volume, variable varieties and volumes	High variety and low volume
	Layout	U-shaped and other compact layouts	U-shaped and other compact layouts
	Worker	Multi-skilled workers	Multi-skilled workers
Differences	Background	Japanese industry in the mid-1990s	European industry in the mid-1960s
	Name of the unit	*Seru*	Cell
	Facing the center	Worker-oriented	Machine-oriented
	Objective	To overcome the shortcomings of assembly line, i.e., low flexibility and bottleneck	To improve the productivity of the job shop
	Key technology	*Seru* formation and *seru* scheduling	GT
	Processing type	Mainly for assembly processes, such as inspection, packaging, and baling	Machining, cleaning, forming, casting, and heat treatment processes
	Equipment	Simple, cheap, light, and movable	Expensive and multifunction
	Unit construction	*Seru* formation and equipment layout	Device grouping and device layout
	Similarity	Similarity of worker skill levels	Part/product similarity
	Multi-skilled worker	Multi-skilled workers operating multiple tasks in *seru*	Multi-skilled worker operating similar parts/products
	Reconfiguration	Rapidly reconfigure *seru* in accordance with market demand	Unsuitable for frequent reconfiguration
	Evolution	Continuous improvement and evolution, from divisional *seru* to rotating *seru* and from rotating *seru* to *yatai*	No evident evolutionary trend

Table 3 Comparison of *seru* production and TPS[a)]

	Comparison	*Seru* production	TPS
Similarities	Market environment	High variety and low volume, variable varieties and volume	High variety and low volume
	Reduced waste	Zero inventory, JIT, kanban	Zero inventory, JIT, kanban
Differences	Organization	Multiple *serus*	Mixed product line
	Multi-skilled worker	Must be multi-skilled workers	Can be multi-skilled workers but not necessary
	Due date	Short	Long or customer can wait
	Variety change	Small or no impact on the production system	Large impact on the production system
	Application area	Electronics industry	Auto industry
	Exception process	Relatively simple	Automation
	Equipment	Simple, cheap, light, and movable	Expensive and multifunction
	Reconfiguration	Rapidly reconfigure in accordance with market demand	Unsuitable for frequent reconfiguration

a)Comparisons of *seru* with the TPS and cells are discussed by Yin et al. (2018)

research has focused on implementation scenarios, performance improvements, successful cases, influence factors, model complexity, optimal *seru* system formation, and optimal *seru* system scheduling. They can be summarized in the following aspects.

4.1 Preconditions and application scenarios of *seru* production

Liu et al. (2014) proposed an implement architecture for *seru* production and indicated that multi-skilled workers are the precondition of *seru* production. Necessary skills must be trained in accordance with the requirements of the product process before the *seru* system design. After satisfying the basic needs of the *seru* system, they continued to conduct comprehensive skill training. Kaku et al. (2008b) investigated the effect of worker ability on the implementation of *seru* production. They emphasized that staff exchange should be strengthened and a good training method should be provided to improve the performance of the *seru* system. Aiming at the specific problem of multi-skilled worker training in *seru* production, Liu et al. (2013) constructed a multiobjective model with the lowest training cost and the best balance of each *seru* and proposed a heuristic algorithm to solve this model. The heuristic algorithm based on the relationship between product process requirements and worker ability was to find an efficient solution for worker training. Ying and Tsai (2017) studied the minimum cost problem of multi-skilled worker training and assignment in *seru* production, constructed a single-objective model, and proposed a two-stage algorithm from the perspective of queuing theory.

Yin et al. (2017) implied that *seru* production is proposed in a high-cost environment in response to a dynamic market environment and high labor costs. Examples of Sony and Canon showed that *seru* production can improve productivity, quality, and production system flexibility. Stecke et al. (2012) demonstrated that *seru* production is appropriate for companies implementing JIT, which realizes a smart factory. Johnson (2005) emphasized that *seru* production should be used when the due date is short and products are customized by customers. Kaku et al. (2009) stated that *seru* production should be implemented in the market environment of high variety and low volume. Yu et al. (2013b) indicated that pure *seru* production should be conducted in the market environment of high variety and low volume. The efficiency of pure *seru* production decreases if the product needs too many operational tasks. Yu et al. (2014) stated that the hybrid *seru* system is appropriate for situations under which the equipment is relatively expensive and the skills of certain workers are low.

4.2 Theoretical analysis of the complexity and optimality of *seru* production

Different *seru* systems have different complexities. *Seru* systems with different objectives also have different complexities, and optimal solutions have different properties. The pure *seru* system is a special case of the hybrid *seru* system, i.e., no short line in the system. A comparison of Figs. 4 and 5 indicates that the complexity of the hybrid *seru* system is considerably higher than that of the pure *seru* system. Therefore, most research has focused on the pure *seru* system. Yu et al. (2012; 2013b; 2014) and Sun et al. (2014; 2016) simplified the mathematical model of the hybrid *seru* system (Kaku et al., 2008a; 2009; Yu et al., 2017a) and proposed the optimal operation model of the pure *seru* system. They investigated the optimal operation of pure *seru* systems with several main evaluated performances and clarified the complexity of such systems and the characteristics of optimal solutions. Yu et al. (2014) stated the key decision processes of the optimal operation of pure *seru* systems with makespan and total labor hour minimization. They showed that one decision variable determines *seru* formation (i.e., the optimization design of pure *seru* systems), and another decision variable determines *seru* scheduling (i.e., batch scheduling of pure *seru* systems). The complexity of the optimal operation of pure *seru* system was clarified from the theoretical point of view by combining *seru* formation and scheduling. Yu et al. (2012) identified the situations under which the pure *seru* system can effectively reduce makespan and labor hours by solving a large number of experiments using enumeration and intelligent algorithms based on nondominated sorting genetic algorithm II (NSGA-II). Yu et al. (2013b) established a mathematical model for the optimal operation of the pure *seru* system with the minimization of the number of workers and makespan. The problem was proven to be NP-hard. Sun et al. (2019) formulated a *seru* system operation with total tardiness minimization and analyzed the solution space. They decomposed the nonlinear model into *seru* formation and scheduling, which was formulated as a linear model. Thus, the small-scale instances could be solved exactly.

For the optimal operation of the hybrid *seru* system, Kaku et al. (2009) proposed a *seru* system model with makespan and total labor hour minimization. They used the model to analyze how *seru* production can obtain optimal performance. Liu et al. (2012) proposed a mathematical model for the optimal operation of the hybrid *seru* system and used a reasonable method to implement *seru* production on the basis of the model. Gong et al. (2009) constructed a minimal inventory model of the hybrid *seru* system and conducted an analysis. Yu et al. (2017a) developed several frequently used hybrid *seru* system operation models. They stated that the hybrid *seru* system operation includes four decision-making processes, namely, worker allocation, *seru* formation, *seru* scheduling, and short line scheduling. They clarified the solution space and complexity of the hybrid *seru* system. The hybrid *seru* system operation was proven to be an NP-hard problem. An exact algorithm was proposed to solve the optimal solution of small-scale instances. Several management insights on how to operate the hybrid *seru* system were summarized and proposed.

4.3 *Seru* system formation and solutions

The *seru* system formation is the most critical decision in the optimal operation of *seru* systems. The *seru* system formation must consider several factors, such as layout, *seru* type, varieties, system objective, volume, worker relationship, skill difference, and scheduling rules. The system objectives include minimal makespan, total labor hours, number of workers, and total costs and minimal total tardiness. Different combinations of factors and system objectives mean different *seru* system formations.

For the optimal operation of the pure *seru* system with makespan and total labor hour minimization, Yu et al. (2014) investigated the *seru* system formation of the pure *seru* system in detail and proved that the pure *seru* system formation is an NP-hard problem. They analyzed the solution space and complexity of the pure *seru* system. To solve the optimal operation of the pure *seru* system with the minimization of the number of workers and makespan, Yu et al. (2013b) formulated the problem and proved that it is also NP-hard. The solution space and complexity were analyzed, and the complexity was more complicated than the pure *seru* system formation without reducing the number of workers. Yu et al. (2017a) investigated the *seru* system formation of the hybrid *seru* system. The *seru* system formation in the hybrid *seru* system includes two decision-making processes: worker allocation and *seru* formation. They clarified the solution space complexity and proved that the problem is NP-hard. Sun et al. (2019) proposed a cooperative coevolution algorithm for the *seru* production with minimal makespan. They investigated the global optimal solution considering the optimization by combining *seru* formation and scheduling. Wang and Tang (2018) formulated a robust *seru* production system that can respond efficiently to the stochastic demand to minimize the cost and maximize the service level of the system. The NSGA-II was improved to solve the multiobjective optimization model.

The algorithms for solving the *seru* system formation can be divided into exact and intelligent algorithms. When the problem was small, the exact algorithm can be used to obtain the optimal solution. For the *seru* system formation of the pure *seru* system with makespan and total labor hour minimization, Yu et al. (2014) obtained the exact Pareto-optimal solutions by using the nondominated sorting algorithm. For the *seru* system formation of the pure *seru* system with the minimization of the number of workers and makespan, Yu et al. (2013b) proposed an improved exact algorithm to obtain the Pareto-optimal solutions. Yu et al. (2017b) proposed two improved exact algorithms to obtain the optimal solution of the *seru* system formation of the pure *seru* system with the minimization of the number of workers without decreasing productivity. Yu et al. (2017a) proposed an exact algorithm for the small-scale *seru* system formation of the hybrid *seru* system.

For large-scale problems, optimal solutions cannot be obtained in reasonable time by adopting exact algorithms. Intelligent algorithms are often used to find the suboptimal solutions. Yu et al. (2014) proposed an intelligent algorithm based on NSGA-II to solve the pure *seru* system with makespan and total labor hour minimization. Subsequently, Yu et al. (2013a) proposed an improved algorithm of NSGA-II combined with local search to solve such system.

The complexity of the nondominated sorting algorithm for the multiobjective *seru* system is $O(M^2N)$, where M is the number of objectives and N denotes the number of feasible solutions. Therefore, Sun et al. (2014) set labor hour as a constraint and formulated a single-objective model with makespan minimization to reduce the complexity. They proposed a variable neighborhood search algorithm for large-scale instances. For the multi-objective model in the reference (Yu et al., 2013b), Yu et al. (2017b) proposed a single-objective model with the minimization of the number of workers without decreasing productivity. An intelligent algorithm based on variable length was proposed. Liu et al. (2012) constructed a mathematical model with makespan minimization and analyzed the characteristics of the *seru* number and the distribution of workers in each *seru*.

4.4 *Seru* system scheduling and solutions

After the *seru* system is constructed, the different scheduling rules of allocating batches to *seru* produce various results. Therefore, scheduling rules significantly influence the performance of the *seru* system. The scheduling of the *seru* system is a key decision process in its optimal operation. Few studies exist on the optimal scheduling of the *seru* system, compared with its formation. The pure *seru* system scheduling is an NP-hard problem.

Pure *seru* system scheduling is an NP-hard problem, that is, when *seru* system formation and scheduling are considered, the optimal operation of *seru* production is a complex problem including two NP-hard problems. Therefore, in existing studies, *seru* system formations are often investigated with a given scheduling rule, such as first come first served (FCFS) and shortest processing time (SPT). Yu et al. (2015) clarified the complexities of solution space with FCFS and SPT rules in the pure *seru* system. For the pure *seru* system with makespan and total labor hour minimization, Yu et al. (2012) investigated a reasonable scheduling method by conducting 64 full-factor experiments with the given FCFS rule. On the basis of the analysis of the experimental results, they concluded that a batch should be assigned to the *seru* with the SPT to minimize the total labor hours, and the batch allocation should consider the balance among *serus* to minimize the makespan. Yu et al. (2016) investigated the influences of 10 scheduling rules on the complexity and performance of the pure *seru* system. The 10 scheduling rules were divided into two categories: scheduling rules unrelated and related to the *seru* sequence. The complexities of the solution space with the two scheduling rules were clarified.

5 Future research in *seru* production

The review on *seru* production and the requirement from industrial and academic fields indicate many problems in *seru* production that require further research.

5.1 Analyses of specific *seru* production

The hybrid and divisional *seru* systems are not fully analyzed yet. What are the characteristics of human resources, worker skills, market environment, production environment, and prospects when implementing the hybrid *seru* system or the divisional *seru* system?

Other analyses include determining when the divisional *seru* system, hybrid type *seru* system, and *seru* production with fully skilled workers should be used. These analyses are important and can provide managerial insights on how to select the appropriate *seru* production in accordance with the characteristics of companies. These analyses require such methods as mathematical modeling, case analysis, comparative analysis, and statistics analysis.

5.2 Evaluated performances and formulation

The formulated evaluation performances of *seru* production include makespan, total labor hour, number of workers, and balancing (Yu et al., 2018). Other performances, such as due date, idle time, space, total makespan, WIP, finished-product inventory, and carbon emissions, are still unformulated. Therefore, quantitative analyses of these advantages of *seru* production must be performed. After the evaluation performances are formulated, constructing mathematical models with these performances, analyzing the features of these models, developing exact and intelligent algorithms, and providing managerial insights for the optimal operation of *seru* production are necessary.

5.3 Demands for multi-skilled workers

Multi-skilled workers are necessary prerequisites for *seru* production. Existing research assumes that all workers are fully skilled; hence, the mathematical model is simple. However, all workers might not be fully skilled. When workers are not fully skilled, only the divisional and hybrid *seru* productions can be implemented. Therefore, we must investigate the demands for multi-skilled workers of divisional and hybrid *seru* productions under optimal performances. For the divisional and hybrid *seru* productions, the relationship of minimal demands for multi-skilled workers and optimal performances must be investigated.

5.4 Multi-skilled worker training

Seru production must train multi-skilled workers. The training methods include apprenticeship, team, and interactive training. Appropriate training methods for multi-skilled workers are necessary in a special *seru* production. What are the appropriate methods of multi-skilled worker training for implementing the divisional *seru* production, *seru* production with fully skilled workers, and hybrid *seru* production? Multi-skilled worker training must consider the skill differences among workers.

5.5 Joint optimization of *seru* production

The optimal operation of *seru* production includes *seru* formation (*seru* system optimal design) and *seru* scheduling (*seru* system optimal scheduling), which are NP-hard problems. For simplicity, existing studies focus on the optimal *seru* system formation with a given scheduling rule. However, this result is not the global optimal solution of *seru* production operation. Therefore, *seru* formation and scheduling should be considered to obtain the global optimal operation of *seru* production.

5.6 Theories and methods for *seru* production

Although *seru* production has various benefits, all existing studies are based on numerical analyses of specific examples. The theoretical analyses of *seru* production are lacking, thereby causing the reasons for low carbon emissions, high leanness, and other good performances provided by *seru* production to remain unclear. For example, theoretical analyses can be performed as follows: to identify the situation under which *seru* production should be used, to develop the bound of performance improvement provided by *seru* production, and to clarify the reasons for the benefits of *seru* production. In comparison with other production modes, *seru* production is a decentralized management. Workers' game exists in *seru* production. The performance of *seru* production under game equilibrium must be investigated.

6 Conclusions

This study reviewed the background, characteristics, types, and operation of *seru* production. The main contributions are presented as follows. Initially, we summarized the concept, characteristics, and types, surveyed the background, and analyzed the advantages and application scenarios of *seru* production. Subsequently, we compared *seru* production and famous production modes, i.e., assembly line, CM, and TPS. We surveyed and classified the literature on *seru* production. Finally, we proposed the future research directions.

References

Celikbilek C, Süer G A (2015). Cellular design-based optimization for manufacturing scheduling and transportation mode decisions. Asian Journal of Management Science and Applications, 2(2): 107–129

David J, Huang L. (1985). Cell System of Production: An Effective Organizational Structure. Beijing: Mechanical Industry Press

Gong J, Li Q, Tang J F (2009). Improving performance of parts storage through line-cell conversion. 2009 Chinese Control and Decision Conference, 3010–3014

Johnson D J (2005). Converting from moving assembly lines to cells at sheet metal products: Insights on performance improvements. International Journal of Production Research, 43(7): 1483–1509

Kaku I, Gong J, Tang J F (2008a). A mathematical model for converting conveyor assembly line to cellular manufacturing. International

Journal of Industrial Engineering and Management Science, 7(2): 160–170

Kaku I, Gong J, Tang J F, Yin Y (2009). Modeling and numerical analysis of line-cell conversion problems. International Journal of Production Research, 47(8): 2055–2078

Kaku I, Murase Y, Yin Y (2008b). A study on human tasks related performances of converting conveyor assembly line to cellular manufacturing. European Journal of Industrial Engineering, 2(1): 17–34

Kono H (2004). The aim of the special issue on *seru* manufacturing. IE Review, 45: 4–5

Liu C G, Stecke K E, Lian J, Yin Y (2014). An implementation framework for *seru* production. International Transactions in Operational Research, 21(1): 1–19

Liu C G, Stecke K E, Lian J, Yin Y (2012). Reconfiguration of assembly systems: From conveyor assembly line to *serus*. Journal of Manufacturing Systems, 31(3): 312–325

Liu C G, Yang N, Li W, Lian J, Evans S, Yin Y (2013). Training and assignment of multi-skilled workers for implementing *seru* production systems. International Journal of Advanced Manufacturing Technology, 69(5-8): 937–959

Roth A, Singhal J, Singhal K, Tang C S (2016). Knowledge creation and dissemination in operations and supply chain management. Production and Operations Management, 25(9): 1473–1488

Sakazume Y(2006). Conditions for successful implementation of assembly cells. Industrial Engineering and Management Systems, 5 (2): 142–148

Sakazume Y (2005). Is Japanese cell manufacturing a new system? A comparative study between Japanese cell manufacturing and cellular manufacturing. Journal of Japan Industrial Management Association, 55(6): 341–349

Stecke K E, Yin Y, Kaku I, Murase Y (2012). *Seru*: The organizational extension of JIT for a super-talent factory. International Journal of Strategic Decision Sciences, 3(1): 106–119

Sun W, Li Q, Huo C, Yu Y, Ma K(2016). Formulations, features of solution space, and algorithms for line-pure *seru* system conversion. Mathematical Problems in Engineering, 2016: 9748378

Sun W, Wu Y T, Lou Q, Yang Y (2019). A cooperative coevolution algorithm for the *seru* production with minimizing makespan. IEEE Access : Practical Innovations, Open Solutions, 7: 5662–5670

Sun W, Yu Y, Tang J F, Yin Y, Kaku I (2014). Variable neighborhood search for line-cell towards increasing productivity. Computer Integrated Manufacturing Systems, 20(12): 3040–3047

Sun W, Yu Y, Wang J W (2019). Reducing the total tardiness by *seru* Production: Model, exact and cooperative coevolution solutions. International Journal of Production Research, in press

Tan Y J, Wang Y R, Lu X, Ge B F (2018). High-end equipment customer requirement analysis based on opinion extraction. Frontiers of Engineering Management, 5(4): 479–486

Wang Y, Tang J F (2018). Cost and service-level-based model for a *seru* production system formation problem with uncertain demand. Journal of Systems Science and Systems Engineering, 27(4): 519–537

Wemmerlov U, Hyer N. (2002). Reorganizing the Factory: Competing through Cellular Manufacturing. Portland: Productivity Press

Wemmerlov U, Johnson D J (1997). Cellular manufacturing at 46 user plants: Implementation experiences and performance improvements. International Journal of Production Research, 35(1): 29–49

Yin Y, Kaku I, Stecke K E (2008). The evolution of *seru* production systems throughout Canon. Operations Management Education Review, 2: 35–39

Yin Y, Liu C, Kaku I (2013). Some underlying mathematical definitions and principles for cellular manufacturing. Asia-Pacific Journal of Operational Research, 2: 1–22

Yin Y, Stecke K E, Li D (2018). The evolution of production systems from Industry 2.0 through Industry 4.0. International Journal of Production Research, 56(1-2): 848–861

Yin Y, Stecke K E, Swink M, Kaku I (2017). Lessons from *seru* production on manufacturing competitively in a high cost environment. Journal of Operations Management, 49(1): 67–76

Ying K C, Tsai Y J (2017). Minimising total cost for training and assigning multiskilled workers in *seru* production systems. International Journal of Production Research, 55(10): 1–12

Yu Y, Tang J F. (2018). *Seru* Production. Beijing: Science Press

Yu Y, Gong J, Tang J F, Yin Y, Kaku I (2012). How to do assembly line-cell conversion? A discussion based on factor analysis of system performance improvements. International Journal of Production Research, 50(18): 5259–5280

Yu Y, Sun W, Tang J F, Wang J W (2017a). Line-hybrid *seru* system conversion: Models, complexities, properties, solutions and insights. Computers & Industrial Engineering, 103: 282–299

Yu Y, Sun W, Tang J F, Kaku I, Wang J W (2017b). Line-*seru* conversion towards reducing worker(s) without increasing makespan: Models, exact and meta-heuristic solutions. International Journal of Production Research, 55(10): 2990–3007

Yu Y, Tang J F, Gong J, Yin Y, Kaku I (2014). Mathematical analysis and solutions for multi-objective line-cell conversion problem. European Journal of Operational Research, 236(2): 774–786

Yu Y, Tang J F, Sun W, Yin Y, Kaku I (2013a). Combining local search into non-dominated sorting for multi-objective line-cell conversion problem. International Journal of Computer Integrated Manufacturing, 26(4): 316–326

Yu Y, Tang J F, Sun W, Yin Y, Kaku I (2013b). Reducing worker(s) by converting assembly line into a pure cell system. International Journal of Production Economics, 145(2): 799–806

Yu Y, Tang J F, Yin Y, Kaku I (2015). Comparison of two typical scheduling rules of line-*seru* conversion problem. Asian Journal of Management Science and Applications, 2(2): 154–170

Yu Y, Wang J W, Ma K, Sun W (2018). *Seru* system balancing: Definition, formulation, and solution. Computers & Industrial Engineering, 122: 318–325

Yu Y, Wang S, Tang J F, Kaku I, Sun W (2016). Complexity of line-*seru* conversion for different scheduling rules and two improved exact algorithms for the multi-objective optimization. SpringerPlus, 5(1): 1–26

Zhang X L, Liu C G, Li W J, Evans S, Yin Y (2017). Effects of key enabling technologies for *seru*, production on sustainable performance. Omega, 66: 290–307