# Effects of key enabling technologies for *seru* production on sustainable performance

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**Abstract.** Demand uncertainty, economic globalization, and environmental deterioration force factories to innovate their manufacturing systems for achieving sustainable performance. *Seru* production, which is the latest manufacturing mode developed in Japan, attracts broad attention from both academia and practitioners. The overwhelming majority of existing works on *seru* production focus on economic performance unilaterally, while neglecting the environmental and social performance. This paper investigates the effects of key enabling technologies for *seru* production on sustainable performance. Firstly, four key enabling technologies for *seru* production are identified through systematic review, and an evaluation indicator system of sustainable performance in the context of *seru* production is developed. Then, the hypotheses about the effects of the identified key enabling technologies for *seru* production on sustainable performance are proposed on the basis of previous research achievements, theoretical analysis, and practical observations. Finally, the hypotheses are tested through structural equation modeling. Except for two hypotheses which are not supported and one which is indirectly supported, all other hypotheses are verified. The research results show that the four key enabling technologies for *seru* production have different effects on the three dimensions of sustainable performance. The achievements of this work are of significance to improve the comprehensive understanding of *seru* production, as well as to develop practical methods to implement sustainable operations.

**Keywords.** Work-cell-based manufacturing system; manufacturing innovation; structural equation modeling; sustainable manufacturing; sustainability

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## 1 Introduction

Nowadays, manufacturing factories are confronted with a more complex environment than ever before. First, demand uncertainty in volume and variety is expected to continuously increase because of more intense pricing competition, shorter product life-cycles, and less predictable behavior of consumers [1]. Second, economic globalization expands the fierce competition from the domestic to the international level, which forces factories to reduce their cost, an important determinant of the international competitiveness for manufacturing industries [2], without compromising on quality. Third, some emerging environmental problems such as global warming, energy crisis, and water resource depletion greatly challenge manufacturing factories, especially those having great impact on environment. In this case, manufacturing factories have to innovate their manufacturing systems to balance economic and environmental performance. *Seru* production, originally emerging at Sony in 1992 in Japan, is one of the most successful manufacturing innovations [3, 4]. It has been praised as a Double E (ecological and economic) manufacturing mode due to its excellent performance on both economic and environmental aspects [5, 6].

Previous research on *seru* production has achieved much, but a lot of problems have not been solved up to now. In the research on lean production, many enabling technologies have been successfully developed in the literature [7]. However, the enabling technologies for *seru* production have not been identified until now. A unified evaluation indicator system of sustainable performance in the context of *seru* production at the level of production system has not been established. Researchers and practitioners often indiscriminately use evaluation indicators at the levels of production system and entire factory in the performance evaluation of *seru* production. The existing literature rarely discusses *seru* production from an environment-friendly perspective although it is praised as a Double E production system.

In this work, we intend to identify the enabling technologies for *seru* production, develop a unified evaluation indicator system of sustainable performance in the context of *seru* production on the level of production system, and investigate the effects of enabling technologies for *seru* production on sustainable performance through structural equation modeling. Based on these investigations, we would like to answer the following questions.

1) What are the enabling technologies for *seru* production?

2) What indicators can be used to evaluate the sustainable performance of *seru* production?

3) Whether these enabling technologies affect the sustainable performance of *seru* production, and if any, to what degree does each technology do?

The rest of this paper is organized as follows. A literature review is expounded in Section 2. Then, the key enabling technologies for *seru* production are identified and the research hypotheses are proposed in Section 3. Section 4 gives a detailed description of the research methodology and data preparation. The data processing and hypotheses testing results are described in Section 5. The conclusions and discussions are presented in Section 6. The limitations of this work and further research along with this work are provided in Section 7.

## 2 Literature review

### 2.1 *Seru* production

*Seru* production is an advanced manufacturing mode generated in Japan in 1992. *Seru* is the Japanese pronunciation for 'cell'. For a long time, *seru* production has often been confused with cell production. Sakazume [8], Yin et al. [9], Stecke et al. [10], and Liu et al. [11] have made thorough comparisons between them from different perspectives. Their research results indicate that *seru* production and cell production are two different manufacturing systems.

The first academic literature on *seru* production can be traced back to 1995 to Shinohara [12]. Since then, a large number of papers on *seru* production have been published. Most of them provide the background of the generation of *seru* production, the conditions and procedures of *seru* production implementation, the types of *serus*, the advantages and achievements of *seru* production in practice, etc. For the implementation conditions, Sakazume [13] put forward three market conditions (changeable product mix, varying demand, need for small-lot multi-product production), three product conditions (short total assembly person-hours, small number of components, small products and components), and five process conditions (multi-skilled operators, few difficult operations, no need for expensive equipment, high use of shared equipment, small equipment).

Several works of research investigated the implementation procedures and framework of *seru* production. Yagyuu [5] divided the implementation procedure of *seru* production into eight steps; they are: selection of manufacturing system and product type, investigation and improvement of current manufacturing conditions, engineering design of the manufacturing system, operation planning, cross-training of operators, production balancing, redesign for low automation equipment, and stabilization work for production. Furthermore, he noted that some sub-systems such as delivery system and information system are also necessary. Iwamuro [14] provided a nine-step linear procedure which includes P-Q analysis, *seru* formation, multi-skilled workers' training and performance evaluation. Liu et al. [4] proposed a general implementation framework which mainly includes analysis on products and process features, cross-training, organizational design, engineering design, performance evaluation, and continuous improvement.

*Seru*, the most fundamental element of *seru* production systems, is an innovative manufacturing unit. In a *seru*, one (or several) worker (s) carries (carry) out all the operations of an assembly task [15]. In practice, there are three basic types of *serus*, namely, divisional *serus*, rotating *serus*, and *yatais* [4, 9–11, 16]. In a divisional *seru*, an operator moves back and forth between several specific workstations and several operators cooperate with each other to complete several discrete or successive tasks. In a rotating *seru*, every operator, moving from one workstation to another one by one in a fixed order, performs all tasks from start to finish. After a product is produced, the operator returns to the first workstation and begins a new round. Rotating *serus* require completely trained operators who have roughly the same skill level and proficiency in each task. In a *yatai*, only one operator who is completely cross-trained assembles a product from start to finish without aids. A *Yatai* requires operators with high proficiency levels.

Many works have shown the outstanding performance achieved by *seru* production. Kimura and Yoshita [17] concluded that *seru* production may reduce the space, workforce, work-in-process (WIP) inventories, lead-times and costs, and improve product quality. Increased profit [4, 10, 18], improved workers' morale, motivation, enthusiasm and satisfaction [4, 5, 8, 10, 11, 13, 19] are noted by a relatively large amount of literature. Sakazume [13] illustrated several advantages of *seru* production on the basis of a review of 107 papers, including reduction in capital investment, inventories, lead time, etc. Jonsson et al. [20] added ergonomics which is well known for its importance to people's health to assess *seru*'s special performance. Liu et al. [4] noted that *seru* production merges the flexibility of job shops, the efficiency of mass production and the environmentally friendly characteristics of sustainable manufacturing. More recently, Liu et al. [21, 22] investigated the production planning and operational decision-making in the context of *seru* production with the consideration of sustainable performance. For more details, please refer to Table 1. In view of these outstanding performances, Shinobu [23], Yin et al. [9] praised *seru* as "beyond lean", "the next generation of lean". Sakazume [8] considered *seru* to be one of the most powerful approaches to deal with the dynamic environment with high product variety and low product volume.

*Seru* production attracts more and more attention from both researchers and practitioners. Initially, one of Sony's video-camera factories obtained great achievements after the adoption of *seru* production [24–27]. From then on, many leading Japanese factories such as Canon, Panasonic, NEC, Fujitsu, Sharp, and Sanyo have reconfigured their conveyor lines into *serus* [18, 26, 28, 29]. Outside Japan, Samsung and LG Electronics [30] have managed to implement *seru* production. For more details of achievements in practice, please refer to Yin et al. [9], Sugano and Maeda [31], Liu et al. [11], and Nikkei [32]. Although plenty of factories have achieved huge benefits by implementing *seru* production, there are also many factories which failed to achieve expected results due to various factors.

From the existing literature on *seru* production, we can see that a lot of research achievements have been obtained in recent years. However, since the history of *seru* production is very short, lots of important issues in *seru* production remain to be investigated. Especially, the enabling technologies for *seru* production should be comprehensively identified and extensively investigated. Moreover, a unified evaluation indicator system of sustainable performance in the context of *seru* production at the level of production system should be developed.

### 2.2 Sustainable performance

"Sustainable development" was initially put forward by the Brundtland Commission in 1987. It was defined as a kind of development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" [33]. However, this macroeconomic definition is difficult for organizations to follow. To make this definition more microeconomic, many other concepts are proposed by massive organizations and researchers. The concept of "triple bottom line", firstly brought forward by Elkington in the book *Cannibals with forks-The triple bottom line of the 21th century* in 1997 [34], was widely acknowledged by academics and practitioners. It proposed a new, responsible approach to organizations that they should simultaneously consider and balance environmental, economic and social dimensions of sustainable development in practice.

Sustainable manufacturing is a special aspect of sustainable development for manufacturing systems. United States Department of Commerce defined sustainable manufacturing as "the creation of a manufacturing product with processes that have minimal negative impact on the environment, conserve energy and natural resources, are safe for employees and communities, and are economically sound" [86]. This definition is perfectly in line with "triple bottom line" and widely accepted. For sustainable manufacturing, economic sustainability usually incorporates financial and non-financial performance improvement [35], and is often operationalized as manufacturing costs [36]. Environmental sustainability refers to the use of energy and other resources and the footprint that factories leave behind as a result of their operations. It is related to waste reduction, pollution reduction, energy efficiency, emissions reduction, a decrease in the consumption of hazardous materials, a decrease in the frequency of environmental accidents, etc [37]. Social sustainability means that manufacturing factories provide equitable opportunities, encourage diversity, promote connectedness within and outside the community, ensure the quality of life and provide democratic processes and accountable governance structures [38].

An evaluation indictor system of sustainable performance is an important element to measure, assess, and enhance sustainability. For a manufacturing factory, in order to construct a valid and effective evaluation indictor system of sustainable performance, the manager should decide which indicators should be selected, and know the criteria to choose them. Rosen and Kishawy [39] pointed out four evaluation criteria for indicator selection including relevance, understandability, reliability, and assessability. The Sustainable Measures Group [87] added three more to this criteria; they are: measurability, timeliness, and long-term orientation.

In the literature, lots of key performance indictors for sustainability are developed by some international organizations, institutions, factories, and researchers. In most evaluation indictor systems of sustainable performance, three dimensions of economic, social, and environmental are included, e.g., Global Reporting Initiative [40, 41], the Dow Jones Sustainability Indexes [88], United Nations-Indicator of Sustainable Development [42], Ford Product Sustainability Index [89], and Amrina and Yosof's indicators [43]. In the sustainable performance evaluation indictor system of National Institute of Standards and Technology, two more dimensions including technological advancement and performance management are added [90].

These evaluation indictor systems of sustainable performance are established at different levels from a hierarchical view. These levels include operation, production systems, the entire factory, supply chain, region/country, and globe [44]. For example, the 2005 Environmental Sustainable Indicators [45], the European Environmental Agency Core Set of Indicators [46], the Dow Jones Sustainability Indexes [88], the International Organization for Standardization Environment Performance Evaluation standard (ISO 14031) [47], and United Nations-Indicator of Sustainable Development [42] focus on sustainable performance at the level of a region or a country. The Global Report Initiative [40] and Walmart Sustainability Product Index Questions [91] lay emphasis at the level of the entire factory. The OECD Toolkit [48], NIST's Sustainable Manufacturing Indicators Repository [90], and Ford Product Sustainability Index [89] focus on the level of production systems. Some researchers also showed that the evaluation indictor systems of sustainable performance can be classed into different types from a functional view, such as operational performance, marketing performance, and financial performance [49].

Recently, several industries such as mining and minerals industry [50] and automotive industry [43] have introduced sustainability into performance evaluation and built some evaluation indictor systems of sustainable performance. In the literature, the evaluation indictor systems of sustainable performance for supply chain management [51] and logistics management [52] are usually the topics investigated. For the implementation of evaluation indictor systems of sustainable performance, the World Business Council for Sustainable Development [53] and the Global Reporting Initiative [41] have built a foundation to some extent. Manufacturing factories may choose different indicators to form their own evaluation indictor systems of sustainable performance based on specific requirements. What's important is that a unified evaluation indicator system of sustainable performance should be established when we intend to compare the performance improvements among different factories. In the context of *seru* production, an evaluation indicator system of sustainable performance is not available and a unified one is pressingly needed.

## 3 The development of research hypotheses

### 3.1 The identification of key enabling technologies for *seru* production

Before proposing research hypotheses, we need to clarify the meaning of "enabling technology for *seru* production" first. In the literature, some researchers have mentioned some terms which are related to the enabling technologies for *seru* production. Yin et al. [9] noted that the understanding of *seru* production may be captured from two perspectives. One emphasizes infra-structural resources like people and equipment [12, 29, 54]. These resources play a fundamental role in developing critical capabilities for the manufacturing organization, and the acquisition, development, allocation, and usage of these resources need careful management [55]. The other focuses on "enablers" [5, 18], the key elements that make manufacturing organizations become high-performance [9]. In this work, we consider enabling technologies for *seru* production as the factors that help change *serus* into higher-performance manufacturing organizations. From this viewpoint, the enabling technologies for *seru* production in this work are closely related to the "enablers" in Yin et al.'s work.

With such an understanding of enabling technology for *seru* production, a systematic review on the published papers on *seru* production was conducted. These papers differ in methodologies ranging from analytical studies, mathematical modeling, simulation studies, to empirical and case studies. Some of them listed a series of enabling technologies for *seru* production while some deeply investigated on one or two. More detailed information about enabling technologies for *seru* production in the involved papers is presented in Table 1. In this table, the employed methodologies, possibly used performance measurements, as well as the general conclusions are presented.

**Table 1**

Systematic review of papers on *seru* production

| Paper | Methodologies | Operationalized enabling technologies | Performance indices | Conclusions/findings |
|---|---|---|---|---|
| Kaku et al. [15] (2008) | Mathematical modeling | Cross-training of workers, *kaizen*, conveyor line-*seru* conversion, making good communication environment. | Labor efficiency, motivation, cycle time, productivity, flexibility, effectiveness, inventory rate of products. | The largest contribution of the conversion is increasing not only the motivation but also the skill levels of workers to improve system performance in dynamic production environments. |
| Liu et al. [4] (2014) | Theoretical analysis | Line-*seru* conversion, cross-training, layout, P-Q analysis, continuous improvement, processing and transfer rules, *majime*, production balancing, JIT delivery system, small equipment, multi-skilled operators, dynamic production planning system, , *kanketsu*. | Flexibility, profit, quality, cost, delivery, lead-times, WIP inventory, job enrichment, job satisfaction, throughput time, carbon dioxide emission, proficiency, productivity, efficiency, sustainability, manpower requirements, shop-floor space. | Such an advanced production mode can achieve the integration of the flexibility of a job shop and the efficiency of mass production, as flexible manufacturing has done for machining. It also has some essential features of sustainable manufacturing. |
| Sakazume [8] (2005) | Empirical study (case) | U-shaped, multi-skilled workers, *kaizen*, line-*seru* conversion, configuration and layouts, multi-item small-sized production, simple equipment. | Productivity, capital investment, lead-times, manufacturing work space, flexibility, product quality, efficiency, delivery time, WIP/finished product inventory, cost, delivery time, capital investment, setup time, operator's sense of satisfaction and accomplishment. | Seven main advantages are: 1) easily adaptable to production volume changes; 2) frequent model changes; 3) multi-item small-sized products; 4) increased production; and 5) decrease in production cost; 6) improvement in product quality; 7) shortened delivery time. |
| Liu et al. [3] (2012) | Mathematical modeling | Skillful workers, equipment modification, tools and jigs, autonomous workers. | Setup time, flow time, makespan, processing time, production capacity, setup cost, inventory cost, waste. | Such a manufacturing system merges the considerable flexibility of the job shop and the high efficiency of the conveyor line to some extent. |
| Jonsson et al. [20] (2004) | Empirical study (case) | layout, multi-skilled workers, improved equipment, autonomous work groups. | Flexibility in production volume and variation, time to market, delivery time, throughput time, customized level, production costs, space utilization, man-hour, product quality, resources, health. | The man-hour productivity, product quality and ergonomics can be improved. |

**Table 1 (continues)**

Systematic review of papers on *seru* production

| Paper | Methodologies | Operationalized enabling technologies | Performance indices | Conclusions/findings |
|---|---|---|---|---|
| Stecke et al. [10] (2012) | Theoretical analysis | Human-centered, cross-trained workers, 5 whys, reconfiguration from line to *serus*, *kaizen*, low-automated equipment, *jidoka*, 5S, *kanketsu, jiritsu, majime, karakuri*, self-made equipment, compact lines, quick setup, JIT material, standing posture holding, learning organization. | Workforce, shop floor space, lead time, setup time, WIP inventories, cost, profits, finished product inventories, workforce motivation, product quality, career creations and enhancements, waste. | *Seru* is a more productive, efficient, and flexible system than Toyota Production System. |
| Liu et al. [11] (2010) | Theoretical analysis | Reconfiguration from line to *serus*, team empowerment, human-oriented design, redesign the big and heavy equipment, movable workstations, cross-trained workers, various layouts, learning organization, autonomy, multi-skilled workers. | Efficiency, flexibility, logistics cost, lead time, timely inspection and repair of defects, floor space, WIP inventory, finished product inventory, morale, worker's enthusiasm. | Japanese manufacturing factories have achieved great success with regards to *seru seisan.* |
| Sakazume [13] (2006) | Theoretical analysis | U-shaped, line-*seru* conversion, majime, multi-skilled workers, small-lot multi-kind production, small equipment. | Model changeover time, manufacturing space, efficiency, WIP/finished inventory, employee satisfaction and accomplishment, capital investment, productivity, lead/delivery time, quality, flexibility. | Assembly *serus* handel small-lot multi-kind production more efficiently than the line production system with the resultant advantages of a marked improvement in productivity, reduction in capital investment, shortened lead -times, saving of work space, improvement in product quality. |
| Isa and Tsuru [18] (2002) | Empirical study | Reconfiguration from line to *serus*, small 'right sized' equipment, low cost automation (LCA) equipment, multi-skilled workers, JIT delivery system, autonomy, multitasking, process improvement, workstation design. | Operation profit rates, efficiency, flexibility, line balance, man-hours and production lead time, WIP inventories, flexibility to adjust product mixes and volumes, setup time, quality, market share and status, maintenance workers number. | By and large, *seru* production has a positive effect on business performance, operating profit rates and ordinary profit rates, especially in pursuing small-lot production of a wide variety of products. |

**Table 1 (continues)**

Systematic review of papers on *seru* production

| Paper | Methodologies | Operationalized enabling technologies | Performance indices | Conclusions/findings |
|---|---|---|---|---|
| Kaku et al. [56] (2008) | Mathematical modeling | Line-*seru* conversion, human-centered, multi-skilled workers, *seru* formation, cross-training of workers, delivery method. | Setup time, total labor power (TLP), total throughput time (TTPT). | The best *seru* production system can achieve performance improvement in the TTPT and TLP to some extent under some constraints. |
| Kaku et al. [57] (2009) | Mathematical modeling | Line-*seru* conversion, delivery method, multi-skilled workers, *seru* formation cross-training of workers. | Total throughput time (TTPT), total labor power (TLP). | Converting conveyor assembly lines into *seru* production systems can achieve better system performance for both TTPT and TLP. |
| Villa and Taurino [58] (2013) | Mathematical modeling | Small batch transfer, *kaizen*, JIT system, *kanban*, movable workstations, layout, light equipment, flexible work force, production leveling standardization, cross-trained workers. | Setup time, stocks and WIP inventory, lead-times, quality, capacity utilization, flexibility. | Main advantage of *seru* production: 1)high flexibility; 2)low inventory; 3)short lead time; 4)good morale of workers. |
| Johnson [59] (2005) | Simulation study | Line-*seru* conversion, multi-skilled workers, cross training, organizational learning, handling equipment improvement. | Delivery lead times, flexibility, setup and move time, quality, cost, in-process waiting time, output, throughput time, WIP inventory, flow time, productivity, capacity, flexibility to quickly respond to customer demands. | Assembly *serus* have the ability to generate significant performance improvements over assembly lines. |
| Miyake [60] (2006) | Theoretical analysis | Work team empowerment, human-centered, simple-structured equipment, *kaizen*, autonomous work-*serus*, rapid reconfiguration, facility improvement, U-shaped layout, *majime*, materials flow control, *pokayoke*, multi-tasking, low-cost automation. | Cost, investment, WIP inventory, setup time, organization innovation, demand responsiveness to market demand, quality, man-hour productivity, flexibility, agility, floor occupation, throughput time, material loss. | Inheriting aspects of TPS and cellular manufacturing that embody leanness supporting abilities, *seru* production system renders great responsiveness and bolsters the manufacturing agility in fluctuated market. |
| Yin et al. [9] (2008) | Theoretical analysis | Human-centered, line-*seru* conversion, *jiritsu, kanketsu, majime, kaizen*, 5W1H, layout, cross-training, 5S, multi-skilled workers, learning organization, movable machines, self-made equipment. | Lead-times, WIP/finished inventory, quality, quick information feedback and detection. | *Seru* is able to evolve into a high-performance manufacturing organization (*yatai*) when all elements of *kanketsu*, *majime*, and *jiritsu* are present. |

The key enabling technologies for *seru* production are identified through the following procedures. First, different terms for enabling technologies in the papers mentioned in Table 1 are put together and given a uniform name by means of induction and categorization. For example, multi-skilled workers, flexible work force,and cross-trained workers are all human-related terms and describe the fact that workers in *serus* can perform more operations than those on conveyor lines. These terms are named uniformly as multi-skilled workers application (MWA). In the same way, several other enabling technologies are processed. They are line-*serus* conversion (LSC), equipment improvement (EQI), continuous improvement (COI), learning culture cultivation (LCC), suitable layout selection (SLS), delivery system optimization (DSO), as well as some hard-to-categorize enabling technologies such as standing posture holding, and *pokayoke* which means error and mistake proofing.

Then, a statistical analysis on the obtained enabling technologies for *seru* production is made and the result is presented in Table 2. Since the hard-to-categorize enabling technologies are only mentioned once or twice in the literature, they are omitted. It can be seen that such constructs as line-*serus* conversion (LSC), equipment improvement (EQI), and multi-skilled workers application (MWA) are most frequently mentioned and emphasized among the fifteen papers.

After that, four experts specialized in *seru* production and five practitioners from manufacturing factories were asked to select no more than four key enabling technologies from the obtained enabling technologies. Line-*serus* conversion (LSC), equipment improvement (EQI), and multi-skilled workers application (MWA) were ranked as the first three. Such results are largely in accordance with the above results of statistical analysis. Moreover, the construct of delivery system optimization (DSO) is not mentioned so many times in papers, but it is suggested to be an important enabling technology by experts. Following their suggestions, we selected delivery system optimization (DSO) as an important enabling technology for *seru* production to be further investigated in following sections.

Eventually, line-*serus* conversion (LSC), equipment improvement (EQI), multi-skilled workers application (MWA), and delivery system optimization (DSO) are identified as the key enabling technologies for *seru* production in this work. Detailed introduction for each one will be done in Section 3.2.

**Table 2**
Result of statistical analysis on enabling technologies for *seru* production

| Constructs | [15] | [4] | [8] | [9] | [10] | [11] | [13] | [20] | [18] | [56] | [57] | [58] | [59] | [60] | [3] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LSC | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | | ⋆ | ⋆ | ⋆ | | ⋆ | | ⋆ |
| EQI | | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | | | ⋆ | ⋆ | ⋆ | ⋆ |
| MWA | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ |
| DSO | | ⋆ | | | | | ⋆ | | ⋆ | ⋆ | ⋆ | ⋆ | | ⋆ | ⋆ |
| COI | ⋆ | ⋆ | ⋆ | ⋆ | ⋆ | | ⋆ | | | | | ⋆ | | ⋆ | |
| LCC | | | | ⋆ | ⋆ | ⋆ | | | | | | | ⋆ | | |
| SLS | | ⋆ | ⋆ | ⋆ | | ⋆ | | ⋆ | | | | ⋆ | | ⋆ | |

From Table 1, we can gain a finding that the implementation of the key enabling technologies for *seru* production contributes to performance improvement whether it is evaluated at the level of production system or entire factory. For example, Kaku et al. [56, 57] showed the significant effects of *seru* production on total throughput time and total labor power, while Isa and Tsuru [18] noted the performance improvement at the level of entire factory using measures such as market share. In this paper, we mainly focus on the effects of the key enabling technologies for *seru* production on sustainable performance at the level of production system. In the next section, we will propose our initial hypotheses and conceptual model from this perspective.

## 3.2 Hypotheses development

### 3.2.1 Hypotheses about the effects of line-*serus* conversion on sustainable performance

Line-*serus* conversion (LSC), clearly distinguished from job shop-cells conversion [10], describes the reconfiguration process from a conveyor line to *serus*. Sakazume called this change "*seru* division" [13] and summarized its three concrete manifestations as: 1) a decrease in the number of workers; 2) an increase in the number of *serus*; 3) the implementation of simple equipment in place of automated equipment [8]. Furthermore, he [8] drew seven main advantages of such a change and analyzed the mechanism behind them.

The adoption of line-*serus* conversion can bring some important environmental benefits. For a conveyor line that assembles multiple kinds of products, some workstations may not be necessary when a specific product is produced. Therefore, these extra workstations could be removed when multiple parallel *serus* are formed in which each *seru* is to process a specific product type. Following *majime* principle for layouts, considerable work space could be saved after the conversion. For example, Canon reconfigured conveyor lines of 20,000 meters in their 54 factories, and 720,000 square meters of work space was saved [9]; Sony saved 710,000 square meters of work space after reconfiguring conveyor lines of 35,000 meters [27]. Similarly, 53% of the work space was saved after the adoption of *seru* production in Fujitsu in 2003 [31]. Once the work space decreased, the carbon dioxide emission could also be lowered to some extent because of less need for heating and cooling equipment. Besides, the removal of automated equipment like robots might reduce relevant energy consumption and the consequent emission of green house gas. Given the above analysis and examples, we propose the following hypothesis:

**H1-1:** The line-*serus* conversion (LSC) has a significant positive effect on environmental performance (ENP).

Line-*serus* conversion also affects many aspects of economic performance. First, the removal of expensive robots and large conveyor belts decreases the equipment cost and related maintenance cost. Second, multiple *serus* that operate in parallel possess greater flexibility than a single production line [4, 10, 11]. Parallel *serus* make it possible to produce different kinds of products simultaneously. This avoids frequent change of products that happens often on conveyor lines when the variety of products is very large. Thus, larger variety, higher quality, and shorter throughput time may be ensured at the same time. For example, in Sony Kohda [61], the throughput time was reduced by as much as 53% after line-*serus* conversion (LSC). Meanwhile, multiple *serus* can produce the same kind of products concurrently. Even if defects, equipment failure, shortages or employee absence occur in one *seru*, other *serus* are not affected. Even though the fluctuation of demands grows drastically, the productivity and delivery time could be improved. Third, other benefits such as decrease of the number of front line workers in Sony Kohda [61], shorter lead time, lower inventories, and faster feedback of defective products were also achieved [9] after the conversion. Based on above analysis as well as the evidence in practice, we propose the next hypothesis:

**H1-2:** The line-*serus* conversion (LSC) has a significant positive effect on economic performance (ECP).

As stated above, when operators in parallel *serus* produce the same kind of products, the competition among *serus* can be stimulated. Apart from the pressure caused by peer competition, employees' motivation and upward mobility can be activated to a certain extent. When multiple *serus* produce different kinds of products, the diversified customer requirements can be better met. For example, the number of Sony Mexico's product types increased over 650% after the conversion from conveyor lines to *serus* [61], which naturally improves its customization level. In today's world, high customization level is typically an important factor to increase customer satisfaction. Besides, the removal of automated equipment reduces noises. Such a result is conducive to employees' health and improves both the internal work environment and the external community environment. Therefore, we propose the following hypothesis:

**H1-3:** The line-*serus* conversion (LSC) has a significant positive effect on social performance (SOP).

### 3.2.2 Hypotheses about the effects of equipment improvement on sustainable performance

Equipment improvement (EQI) in *seru* production represents a new trend of equipment development towards low-cost automation and specialization. It emphasizes the adoption of small, simplified, movable, self-made, less-automated, and low-cost equipment [62]. This trend of equipment improvement (EQI) is more popular in the manual manufacturing environment.

In most Japanese electronic factories that are implementing *seru* production, small, simplified, and movable equipment is usually used in place of big, complex, and fixed equipment. Small equipment takes less space. Simplified and movable equipment is arranged flexibly according to factory layout, which can save huge work space for factories. Moreover, small, simplified, and movable equipment usually has low setup time and energy consumption, which can save lots of power and reduce related carbon dioxide emission. Furthermore, self-made and specialized equipment does not contain the unnecessary parts compared to the general equipment, which partly avoids additional waste emission and energy consumption in *seru* production. Therefore, the following hypothesis is proposed.

**H2-1:** The equipment improvement (EQI) has a significant positive effect on environmental performance (ENP).

Compared with general equipment, self-made and specialized equipment removes the unnecessary parts and thus reduces the relevant costs to a certain extent, and usually has higher machining efficiency. The simplified equipment can be easily duplicated and modified at a low cost. Here are some examples. A factory of Stanley Electric located in Northern Japan, *karakuri-ed* (a Japanese term meaning "copy an expensive equipment into an inexpensive self-made equipment with the required functions") an expensive machine which costs 30 million yen into a simplified inexpensive one which costs 200 thousand yen, only 1/150 of the original price [28]. Canon *karakuri-ed* a 6 million yen inspection machine into a 500 thousand yen machine, only 8.33% of the original price [32]. Correspondingly, the depreciation cost and maintenance cost decline significantly compared with those on conveyor lines [8]. Liu et al. [11] pointed out that although the substitution of multipurpose industrial robots and long conveyor lines for multiple simplified equipment may raise associated costs, the overall investment in *seru* production declines because of remarkable savings in other aspects. Furthermore, some other economic benefits like the reconstruction time of the manufacturing system and delivery time of products can also be achieved in practice due to equipment improvement in *seru* production. Denso is a global automotive components manufacturer. Using movable equipment, Denso can reconstruct their *serus* within 30 seconds [10]. On the basis of above analysis, we propose the following hypothesis:

**H2-2:** The equipment improvement (EQI) has a significant positive effect on economic performance (ECP).

When large automated equipment is replaced with less-automated and removable equipment, a more participatory work environment is provided to workers. They can move the equipment easily and rearrange its position according to their needs, so that they can perform the tasks in a comfortable manner. Besides, self-made and specialized equipment itself is designed strictly according to operators' practical requirements. It does good to operators' health by taking ergonomics into consideration [20]. Thus, employees' health and satisfaction could be improved in a long run. In addition, the removal of large conveyor lines and robots eliminates the emanatory noise to some extent. This is good for creating a sound environment for employees and the community residents. In view of these arguments, we propose the following hypothesis:

**H2-3:** The equipment improvement (EQI) has a significant positive effect on social performance (SOP).

#### 3.2.3 Hypotheses about the effects of multi-skilled workers application on sustainable performance

Multi-skilled workers, in contrast to single-skilled workers on conveyor lines, are the precondition to successfully implement *seru* production [4]. They are requested to master not only multiple operation skills but also some management and decision-making skills. Multi-skilled workers application (MWA) is a technology of adopting workers with multiple skills and problem-solving abilities, assigning or transferring multi-skilled workers within or among *serus* [62]. It's an important and fundamental enabling technology for *seru* production and has been extensively investigated in the literature.

Although a lot of valuable research results concerning multi-skilled workers application have been obtained, no evidence can we find supporting its direct or significant effect on environmental improvement. In order to ascertain the potential relationship between multi-skilled workers application and environmental performance, an on-the-spot investigation was conducted in some nearby factories. Several managers have made a rough estimation on their relationship that a possibly positive effect may exist, because the decrease of product movements between workstations due to the application of multi-skilled workers contributes to environmental improvement. In the absence of sufficient evidence, we propose an exploratory hypothesis to be further tested by large samples.

**H3-1:** The multi-skilled workers application (MWA) has a significant positive effect on environmental performance (ENP).

Adopting multi-skilled workers in a *seru* can easily realize *shojinka* (a Japanese term which means using least-manpower to finish the assigned production). Only those workers with high efficiency are then reserved in *serus*, so that the productivity per capita improves significantly. For example, an S-class worker in Canon, who has the highest skill level in Canon's skill-level system including classes of 3, 2, 1, and S (S means super), can assemble a complicated multi-functional peripheral of 2,700 components within just two hours, or a luxury camera of 940 components within only four hours in a *seru* [24]. Moreover, a *seru* with fewer workers can easily achieve the production balance, which results in less adjustment between processes, less waiting, less stagnation, and less buffer inventory, and contributes to product quality improvement and some other performance improvements. Such *serus* with fewer or even one worker are more easily managed, saving relevant management cost. Therefore, we propose the following hypothesis:

**H3-2:** The multi-skilled workers application (MWA) has a significant positive effect on economic performance (ECP).

As described above, *shojinka* resulted from multi-skilled workers application is definitely an enabler of economic improvement. However, *shojinka* also raises some doubts about its little contribution to social employment. Sometimes the impacts in more than two dimensions strongly interact [63]. As far as what we observed in some manufacturing factories, when the workers with low efficiency are released from production line, they are not dismissed from factories but given retraining and assigned to some other positions which are more suitable to their abilities. This measure is widely taken by Japanese factories whose culture highly advocates lifelong employment. But how factories can deal with the trade-off between these two conflicting aspects needs further discussions from both researchers and practitioners.

Compared to single-skilled workers, multi-skilled workers application is more adaptable to the case of multi-product production. Workers with multiple skills can be regrouped and transferred within or among *serus* flexibly when the production schedule changes due to the fluctuation of customers' demands. Quick response helps win customers and improve their satisfaction. When each multi-skilled worker in a *seru* produces one entire product or most parts of it, his/her sense of achievement will be greatly encouraged. This will boost the morale and enhance the job satisfaction greatly. With clear responsibility, workers will be more careful and responsible when they produce products in *serus* than on conveyor lines, and defective products will be promptly detected and accurately traced. This is vital to improve products quality, as well as customer satisfaction. Based on the above analysis, we propose the following hypothesis:

**H3-3:** The multi-skilled workers application (MWA) has a significant positive effect on social performance (SOP).

### 3.2.4 Hypotheses about the effects of delivery system optimization on sustainable performance

In *seru* production, delivery system controls the storage, sorting, distribution of materials, the delivery of materials among *serus*, and the shipment of work-in-process and final products [4]. Delivery system optimization (DSO) is a technology to improve the delivery time, the delivery method, the delivery route, the delivery batch, and the delivery frequency and realize JIT delivery. Its aim is to smooth the material flow and facilitate production. When several *serus* are internally linked to process complex products composed of many modules, delivery system optimization (DSO) is more important to achieving high manufacturing performance [4].

Several aspects of delivery system optimization (DSO) could simultaneously contribute to the reduction of required space. First, corresponding to multi-variety and small-batch production, the delivery in small batch and high frequency is adopted in many factories. Small batch means that less space is needed on the workstations or within *serus*. Second, a small batch of materials and products can be delivered by small vehicles which take less space than large ones. Third, JIT delivery assures that the materials, work-in-process and finished products are input and output in a timely manner. It is not necessary to hold the extra space for putting them. Such a situation brings great benefits to manufacturing factories [64, 65]. Moreover, the reduction of required space can lower the carbon dioxide emission to some extent. Based on the above analysis, we propose the following hypothesis:

**H4-1:** The delivery system optimization (DSO) has a significant positive effect on environmental performance (ENP).

Small vehicles for the delivery in small batch as well as the specialized delivery vehicles require less investment and maintenance cost. The delivery in small batch and high frequency is much more flexible in dealing with abrupt changes in product requirements and production schedules. Corresponding to the delivery improvement, some suitable part transfer rules within *serus* are developed, including one-piece processing and one-piece transfer, one-piece processing and small-batch transfer, and small-batch processing and small-batch transfer [4, 14]. These measures help keep the production system running in a continuous manner, which naturally shortens the delivery time of products. In *seru* production, delivery workers, especially those released from production lines, are encouraged to master not only delivery technology but also production scheduling and management knowledge. The adoption of such delivery workers can help coordinate the production system and delivery system so as to improve production efficiency. Accordingly, the following hypothesis is proposed:

**H4-2:** The delivery system optimization (DSO) has a significant positive effect on economic performance (ECP).

The delivery operators who are released from production lines are familiar with production process. So they can communicate and coordinate closely with production workers in their work. This helps create a harmonious environment and a learning organization in which workers feel more comfortable. In *seru* production, delivery operators are empowered with more autonomy to make on-the-spot decisions based on their extensive experience and rich knowledge. Their job satisfaction and morale can be greatly improved. Moreover, delivery in small batches ensures the product quality and the optimized delivery system results in a shorter delivery time. These improved services result in increased customer satisfaction. Small vehicles for delivery make less noise than large ones, helping create a better community environment. Considering these analyses, we propose the following hypothesis:

**H4-3:** The delivery system optimization (DSO) has a significant positive effect on social performance (SOP).

#### 3.2.5 Holistic hypotheses

According to the statements of Shinohara [12], Kaku et al. [15], Isa and Tsuru [18], Liu et al. [3, 11], Nonaka and Katsumi [25], and Tsuru [54], *seru* production is a human-centered system, in which multi-skilled operators are regarded as the most important resources. The implementation of *seru* production largely depends on the multi-skilled workers application (MWA) [4]. This judgement was also indicated by the statistical analysis on enabling technologies in Table 2 since the enabling technology of multi-skilled workers application (MWA) is involved in all the literature. However, we did not find evidence to show the multi-skilled workers application (MWA) has a significantly positive effect on environmental performance as described above. Hence, we propose the following holistic hypothesis:

**H5:** Multi-skilled workers application (MWA) has the largest positive effects on economic or social performance.

All of the above hypotheses and our conceptual model are shown in Fig. 1. Shah and Goldstein [66] noted that it is necessary to evaluate the model fit in empirical studies. Following their suggestions, with the above analysis for providing the hypotheses about the effects of the key enabling technologies for *seru* production on sustainable performance, we propose another holistic hypothesis as follows:

**H0**: $S - \Sigma(\theta) = 0$,

where $S$ represents sample covariance matrix and $\Sigma(\theta)$ stands for model reproduced covariance matrix in structural equation modeling (SEM). The smaller the distance between $S$ and $\Sigma(\theta)$ is, the better the proposed model fits the observed data.

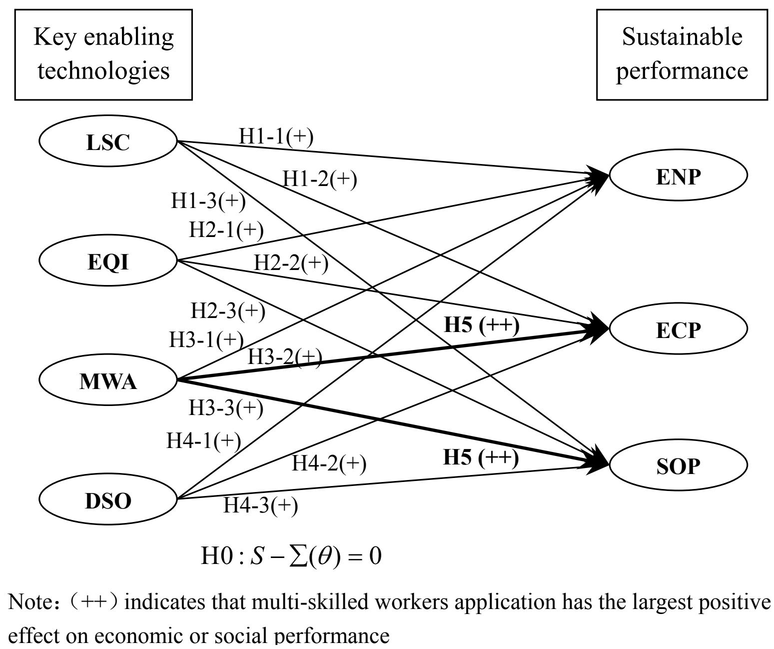



**Fig. 1.** Conceptual model of relationships between key enabling technologies for *seru* production and sustainable performance

## 4 Methodology

In this section, confirmatory factor analysis (CFA) is used to develop and test the constructs of key enabling technologies for *seru* production and sustainable performance in the context of *seru* production. In the next section, structural equation modeling (SEM) is used to examine the relationships between these constructs based on the survey data. This paper uses SPSS 20.0 to conduct the descriptive analysis and LISREL 187 to conduct the CFA and SEM.

### 4.1 Instrument development

To operationalize the key enabling technologies and sustainable performance for quantitatively testing the hypotheses, a survey instrument is developed (see Appendix A and Appendix B). 20 items belonging to the four identified key enabling technologies are included in our instrument of Appendix A, and a part of them come from the instrument developed by Li et al. [62]. Our instrument of Appendix B consists of 18 items which are classed into three groups to measure three dimensions of sustainable performance respectively.

Although our instrument of key enabling technologies for *seru* production is roughly similar to Li et al.'s instrument (see Appendix C), there are some differences between them. In establishing the instrument of key enabling technologies for *seru* production by referring to the items of Li et al.'s instrument, some modifications are made to better meet the demands of this work. The details of modifications are stated as follows.

To test whether a good environment for multi-skilled workers' development is provided in factories, MSW3 and MSW7 of Li et al.'s instrument are replaced. Five items of EQI of Li et al.'s instrument are reorganized in different expressions but with the same content. Just-in-time plan (DSO2) is added into delivery system optimization in place of DTM1 of Li et al.'s instrument which mainly depends on industry's practical situation. Line-*serus* conversion (LSC) is a newly established construct in which all the items are designed on the basis of previous research results [8, 13].

To develop the instrument of sustainable performance, we reviewed lots of available key performance indictors of sustainability which are designed at the level of production systems [40, 43, 89, 90]. It is widely advised to include "triple bottom line" in sustainable performance evaluation [39, 43, 89]. Joung et al. [85] also noted that, in constructing sustainability metrics, the specific requirements of research or business strategies should be considered. In this work, we construct an instrument of sustainable performance in the context of *seru* production by referring to the first three dimensions of Sustainable Manufacturing Indicator Repository (SMIR) of the National Institute of Standards and Technology [90] and the evaluation indicator system of sustainable performance developed by Amrina and Yusof [43]. The former includes many selectable indicators and the latter has been successfully applied in the automobile industry. The specific development procedures of our instrument of sustainable performance are as follows.

For environmental dimension, the items of energy and shop-floor space are selected from Amrina and Yusof's indicators and the items of green house gases and hazardous substance are chosen from NIST's. These four items subordinate to two subcategories of environmental dimension, namely, resource consumption and waste emissions. Since they largely determine the environmental influence of *seru* production, we included energy consumption, shop-floor occupation, green house gas emission, and hazardous substance into the dimension of environmental performance (ENP) eventually.

For economic dimension, NIST's indicators like profit and investment mainly reflect the economic performance at the organizational level. However, we focus on the performance at the level of production system. Therefore, we use Amrina and Yusof's [43] indicators and the performance indicators obtained from the systematic review in Section 3 as reference. In Amrina and Yusof's paper, quality, cost, delivery, and flexibility were recognized as more commonly used indicators than others like time, labor productivity, and efficiency. To enrich economic dimension, these indicators are all included into our instrument, and cost is further subdivided into inventory cost, and jigs and tools cost. As a result, eight items entered this dimension to jointly characterize the economic performance.

For social dimension, stakeholder theory is the most popular one to identify social responsibility objects [67]. A stakeholder is defined as an individual or a group affected by factories' action in the process of goal-achieving. Clarkson [68] classified primary stakeholders into five parties. Three parties of employees, customers, and the surrounding community in Clarkson's [68] classification are considered in both Amrina and Yusof's and NIST's instruments. We and many managers from factories think that such three parties of primary stakeholders also fit *seru* production well. Therefore, we measure social dimension by employee-related items, customer-related items, and community-related items. Employee-related items consist of occupational health and safety, and job satisfaction. Customer-related items include customization level and customer satisfaction. Community-related items are noise and community employment opportunity.

After all items of the instrument of key enabling technologies for *seru* production and sustainable performance were determined, we drafted a survey questionnaire. Then, 9 experts, among them 4 experts from academia specialized in *seru* production and 5 practitioners who are engaged in production management from 5 representative factories, were asked to review the draft questionnaire to evaluate whether the main aspects of key enabling technologies for *seru* production and sustainable performance had been covered. Some minor changes have been made according to their feedback in the questionnaire. Then, a pilot study including 30 samples was launched to make the statements more accurate and concise, and to validate the wording and intelligibility of questions and statements. Based on the achievements of pilot study, the questionnaire was further improved.

All the items were measured with a five-point Likert scale. For the items in Appendix A, respondents were asked to rate the extent to which they have implemented the enabling technologies according the real situation in their factories (1= no implementation, 2= little implementation, 3= some implementation, 4= extensive implementation, 5= complete implementation). For the items in Appendix B, respondents were asked to rate the extent to which they agree with the statements about the performance improvement after the implementation of *seru* production according the real situation in their factories (1= strongly disagree, 2= disagree, 3= neutral, 4= agree, 5= strongly agree).

### 4.2 Data collection and sample characteristics

*Seru* production has been successfully implemented in a large number of manufacturing factories, for example, Cannon, Samsung, and Foxconn. We selected hundreds of manufacturing factories that have implemented *seru* production. The selected factories in the pilot study were also included in the final sample. The questionnaires were delivered to the target factories by hand, letter, and e-mail. We requested that the questionnaires be completed by production managers as far as possible because they are much more familiar with the application situation.

In all 600 questionnaires, 98 questionnaires were not returned. The return ratio is 83.67%. Among the returned 502 questionnaires, 66 factories declined to cooperate because of business secret though we promised to keep their responses confidential. Moreover, based on the answers to some pre-designed lie-detection questions [69] and on the number of missing data in questionnaires, we can judge that 240 factories completed our questionnaires perfunctorily. Eventually, 196 effective and valid questionnaires were left. The effective response rate was 32.67%. The effective responses cover a wide range of manufacturing factories, they are personal computers (24), printers (27), copy machines (8), facsimile machines (12), cell phones (20), auto components (4), televisions (8), digital cameras (28), DVD players (22), washing machines (9), office equipment (8), module parts for digital electric equipment (10), and others (16). Table 3 shows more details of the respondents' characteristics.

**Table 3**
Distribution of respondent factories

| Classification | Total | Percentage |
|---|---|---|
| Size (employees) | | |
| $\geq$ 1000 | 15 | 7.7% |
| 500-999 | 88 | 44.9% |
| 300-499 | 60 | 30.6% |
| 100-299 | 26 | 13.3% |
| $\leq$ 99 | 7 | 3.5% |
| Total | 196 | 100% |
| Implementation years of *seru* production | | |
| $\geq$ 11 | 19 | 9.7% |
| 7-10 | 15 | 7.7% |
| 3-6 | 112 | 57.2% |
| $<$ 3 | 50 | 25.4% |
| Total | 196 | 100% |
| Types of *serus* | | |
| *Yatai* | 6 | 3.1% |
| Rotating | 38 | 19.4% |
| Divisional | 16 | 8.2% |
| Compound | 106 | 54.1% |
| Others | 30 | 15.2% |
| Total | 196 | 100% |

From Table 3, we can see that more than half of the respondent factories are relatively large ones with over 500 employees. Most factories adopted *seru* production less than six years. The number of factories adopting compound *serus* are 106, accounting for 54.1% of the total samples and ranking the first. This phenomenon indicates that three basic *seru* types are usually used together in practice.

## 4.3 Measures

### 4.3.1 Descriptive statistics

In this paper, the extrapolation method is used to test the potential non-response bias. This method is based on the assumption that subjects who respond less readily are more like non-respondents, where "less readily" was defined as answering later [70]. In order to use this method, the effective questionnaires were manually divided into two groups according to a given response time point. The first group, which represents the respondents, includes the effective questionnaires returned before the time point. The second group, which represents the non-respondents, contains those effective questionnaires returned after the time point. The two groups are compared on some key characteristics such as factory size and industry type through a series of Chi-square difference tests. No significant difference was found between the groups. This result indicates that non-response bias has no significant impact on the sample data.

In this work, the processing of missing data includes two stages, the missing value analysis and the missing value replacement. The missing value analysis is conducted for each of the 38 items in SPSS 20.0 in the first stage. The missing value replacement with series mean value is conducted in the second stage. No significant problem is shown in the whole process. Some other descriptive statistics such as mean value and standard deviation can be seen in Appendix A and Appendix B.

### 4.3.2 Common method variance

In collecting data, only one respondent is requested from each factory. Hence, the common method bias may arise [71]. Harmon's single-factor test is the most widely used method to evaluate the possibility of this kind of bias [71, 72]. When such a single-factor test is conducted, a high common method variance may exist if all factors come down to one single factor or a special factor accounts for the majority of total covariance over all variables. We subjected all the items into an exploratory factor analysis (EFA) with non-rotation method and got 8 factors with eigenvalues higher than 1, accounting for 64.92% of the total variance. The first factor accounts for only 30.52% of the variance. This indicates that common method variance does not have significant effects on this research.

### 4.3.3 Verification of reliability and validity of constructs

For a successful empirical research, constructs should have good reliability and validity. Reliability means the possibility of drawing the same result by applying the same observation method to the same object. It contains both internal and external consistency of the test results. Cronbach alpha, construct-reliability (CR, also known as composite reliability), and average variance extracted (AVE) are recommended by Garver and Mentzer to assess reliability [73]. Cronbach alpha is to measure the consistency of items within a latent construct and the consistency of the whole scale. Composite reliability is used to identify the extent that measureable items share the latent factor and to compensate the small sample bias of Cronbach alpha. Average variance extracted (AVE) is to investigate how much of the total variance of observable indice comes from the variance of latent construct. From Table 4, we can see that all the constructs' alpha and CR values exceed 0.7, and some AVE values are slightly below 0.5. For the values of Cronbach alpha and CR, 0.7 and 0.7 or greater are suggested to be acceptable respectively [73, 74]. For AVE value, Hair et al. [75] noted that 0.5 or greater is acceptable, but slightly below 0.5 is also used as an acceptable value in the literature [64].

Validity refers to the proximity of the measured value to the true value. It can be further divided into content validity and construct validity. Construct validity consists of convergent validity and discriminant validity. To ensure the content validity, an extensive literature review was conducted to define each construct and the measure items were developed based on the instruments due to Li et al. [62] , NIST [90], and Amrina and Yusof [43]. Their instruments were also formed based on extensive literature review and have been already tested.

Ahire et al. [76] recommended that the normed-fit index (NFI) coefficient can be used to evaluate convergent validity. NFI belongs to comparative fit index which is drawn by comparing the conceptual model with null model (the most constrained and worst fitting model). For NFI, the value of 0.9 or greater indicates strong validity [77]. All the NFI values in Table 4 exceed 0.9, which indicates strong validity. Bagozzi and Yi [74] noted that, in the same construct, if the factor loadings of all items are 0.5 or greater, the convergent validity is acceptable. Appendix A and Appendix B present the CFA results which include the specific factor loadings and their corresponding $t$ values of the measurement model. Considering all Std. loadings are greater than 0.5, we know that each item plays an important role in its affected construct and all the constructs show good convergent validity.

**Table 4**

Related fit indices for construct assessment

| Construct | Fit index | | | | Reliability coefficient | | | Validity |
|---|---|---|---|---|---|---|---|---|
| | GFI | NNFI | CFI | Normed$\chi^2$ | Alpha | CR | AVE | NFI |
| MWA | 0.96 | 0.98 | 0.99 | 1.96 | 0.864 | 0.87 | 0.48 | 0.97 |
| LSC | 0.98 | 0.98 | 0.99 | 1.60 | 0.783 | 0.78 | 0.47 | 0.99 |
| EQI | 0.98 | 0.97 | 0.99 | 1.88 | 0.794 | 0.80 | 0.45 | 0.97 |
| DSO | 0.99 | 1.00 | 1.00 | 1.03 | 0.781 | 0.79 | 0.48 | 0.99 |
| ENP | 0.99 | 0.96 | 0.99 | 3.18 | 0.804 | 0.82 | 0.53 | 0.99 |
| ECP | 0.93 | 0.95 | 0.97 | 2.95 | 0.836 | 0.89 | 0.50 | 0.95 |
| SOP | 0.96 | 0.96 | 0.98 | 2.81 | 0.832 | 0.83 | 0.50 | 0.96 |

In assessing discriminant validity, Joreskog [78], Anderson and Gerbing [79] suggested using Chi-square difference tests on the constrained and unconstrained models. If the Chi-square values of the constrained models were significantly larger than those of the unconstrained models for each group, then the discriminant validity can be considered good. From Table 5, we can see that all Chi-square values in the constrained model are larger than those in the unconstrained model. These results together show that all constructs have good discriminant validity.

**Table 5**

Descriminant validity analysis on key enabling technologies and sustainable performance constructs

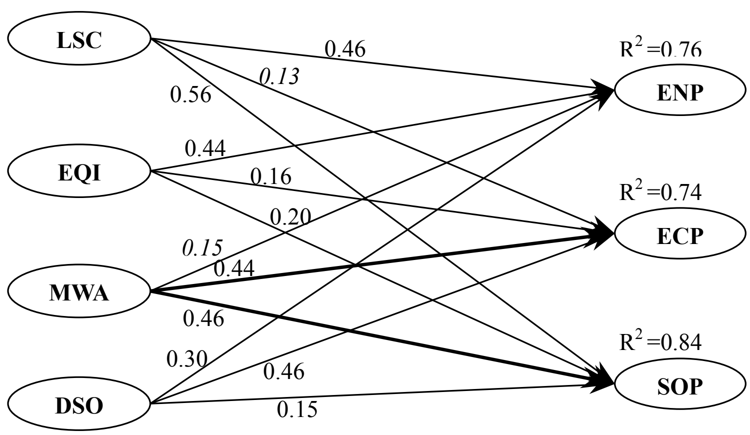
| Group | Models | Chi-square | df | Chi-square difference | Test |
|---|---|---|---|---|---|
| Group1 | Unconstrained model | 134.99 | 53 | — | |
| ($\rho$=1 between ENP and ECP) | Constrained model | 356.82 | 54 | 221.83 | 0$***$ |
| Group2 | Unconstrained model | 63.52 | 34 | — | |
| ($\rho$=1 between ENP and SOP) | Constrained model | 131.46 | 35 | 67.94 | 0$***$ |
| Group3 | Unconstrained model | 123.33 | 76 | — | |
| ($\rho$=1 between ECP and SOP) | Constrained model | 194.71 | 77 | 71.38 | 0$***$ |
| Group4 | Unconstrained model | 50.27 | 26 | — | |
| ($\rho$=1 between LSC and EQI) | Constrained model | 284.19 | 27 | 233.92 | 0$***$ |
| Group5 | Unconstrained model | 225.83 | 43 | — | |
| ($\rho$=1 between LSC and MWA) | Constrained model | 237.19 | 44 | 11.36 | 0$***$ |
| Group6 | Unconstrained model | 162.92 | 19 | — | |
| ($\rho$=1 between LSC and DSO) | Constrained model | 448.59 | 20 | 285.67 | 0$***$ |
| Group7 | Unconstrained model | 226.46 | 53 | — | |
| ($\rho$=1 between EQI and MWA) | Constrained model | 736.45 | 54 | 509.99 | 0$***$ |
| Group8 | Unconstrained model | 126.6 | 26 | — | |
| ($\rho$=1 between EQI and DSO) | Constrained model | 644.9 | 27 | 518.3 | 0$***$ |
| Group9 | Unconstrained model | 288.05 | 43 | — | |
| ($\rho$=1 between MWA and DSO) | Constrained model | 604.55 | 44 | 316.5 | 0$***$ |

Notation: $***$ Chi-square difference is significant at 0.001 level.

# 5 Analysis and results

## 5.1 An initial model

Based on the preparation work above, we put the covariance matrix of sample data into LISREL187 and tested the hypotheses using the maximum likelihood estimation. The preliminary results are shown in Fig. 2. The standardized coefficient of each path represents the corresponding effect of the key enabling technology for *seru* production on sustainable performance (SP). With regard to the disclosure of overall fit index, the debate on superiority or even appropriateness of one index over another has not reached a unified conclusion yet. Generally speaking, fit indices can be distinguished as absolute and incremental [80]. Absolute fit indices represent the degree to which the hypothesized model fits the sample data. Incremental fit indices measure the proportional improvement of fit when the hypothesized model is compared with a restricted and nested baseline model.




RMSEA=0.094, NNFI=0.89, CFI=0.90, IFI=0.90, Normed $\chi^2$ =2.71, df=647

**Fig. 2.** The results with respect to the initial model

For absolute measures, Root Mean Square Error of Approximation (RMSEA), Standardized Root Mean square Residual (SRMR), Goodness of Fit Index (GFI), and Adjusted Goodness of Fit Index (AGFI) are commonly used [66]; nevertheless, Hu and Bentler [80] advised against GFI and AGFI because these two methods are significantly influenced by the sample size and insufficiently sensitive to model misspecification. For incremental measures, Normed Fit Index (NFI), Non-Normed Fit Index (NNFI, also known as Tucker Lewis Index), Comparative-Fit Index (CFI), and Incremental Fit Index (IFI) are most popular [66]. However, Hu and Bentler [80] do not recommend NFI because of the same reason as above. According to Shah and Goldstein [66], multiple measures of fit should be reported so that readers may have the opportunity to know the underlying fit of the data to the model from multiple perspectives. In this work, we consider Hu and Bentler's and Shah and Goldstein's opinions comprehensively.

R-square is another important measure which represents the explained variance to endogenous variables for each structural equation. Although this index is often neglected in the literature, we also include it in this paper. Moreover, SRMR and RMSEA are two similar measures both reflecting the residual differences between the input and reproduced matrices. In this paper, we selected RMSEA. Eventually, we adopted such fit indices as the ratio of Chi-square to degrees of freedom (namely, Normed $\chi^2$), NNFI, CFI, IFI, R-square, and RMSEA to assess the overall model fit.

Normed $\chi^2$, the value of $\chi^2$ dividing by the degrees of freedom, can adjust the complexity of the misspecificated model. Joreskog's advice [81] that a good fit should be within the range of 1 to 3 is widely accepted. NNFI, CFI, and IFI are all comparative fit indices which have the range of 0 (the worst fit) to 1 (the best fit). Byrne [82] recommended 0.90 to be the minimum value of a good fit for them. Root Mean Square Error of Approximation (RMSEA) is an absolute index. It decreases as the goodness of fit increases, whose lower bound is 0 [83]. Garver and Mentzer [73] put forward the relatively acceptable upper bound 0.08 which has been extensively recognized. As for R-square, no definitive standard is accepted. But a good model fit should explain a significant amount of variation to endogenous variables [84].

In Fig. 2, the obtained values of fit indices are inconsistent to some extent. Compared with the criteria above, both CFI (0.90) and IFI (0.90) equal to the recommended level 0.90, and normed $\chi^2$ (2.71) falls into the recommended range of 1 to 3. These three fit indices show that the initial model fitting are acceptable. However, NNFI (0.89) is slightly below the lower bound 0.90, and RMSEA (0.094) exceeds the upper bound 0.08. These two fit indices do not show that the initial model fitting are acceptable. The inconsistent results represent a comparatively poor model fit to some extent. The three R-square values for endogenous constructs are 0.76, 0.74, and 0.84, respectively. The verification results of hypotheses with respect to the initial model are summarized in Table 6. $T$-statistics are calculated for all coefficients to test which path being statistically significant. Numbers in italics show that the path coefficient is statistically insignificant.

**Table 6**
The initial results for hypotheses testing

| Hypotheses | Path coefficient ($T$)/fit indices | Results |
|---|---|---|
| H0 | Relatively poor fit | Not Support |
| H1-1 | 0.46 (5.47) | Support |
| H1-2 | *0.13 (1.47)* | Not Support |
| H1-3 | 0.56 (6.48) | Support |
| H2-1 | 0.44 (5.78) | Support |
| H2-2 | 0.16 (2.56) | Support |
| H2-3 | 0.20 (4.38) | Support |
| H3-1 | *0.15 (1.84)* | Not Support |
| H3-2 | 0.44 (5.24) | Support |
| H3-3 | 0.46 (6.75) | Support |
| H4-1 | 0.30 (4.08) | Support |
| H4-2 | 0.46 (5.69) | Support |
| H4-3 | 0.15 (3.37) | Support |
| H5 | Neither 0.44 nor 0.46 is the largest | Not Support |

In Table 6, four out of fourteen hypotheses are not supported by the results. Relatively poor fit indices fail to support H0. H1-2 and H3-1 have insignificant $T$ values respectively. For H5, although the two path coefficients 0.44 and 0.46 are significant at 0.001 level, neither of them is the largest among all path coefficients. Therefore, H5 was not supported.

### 5.2 A modified model

The exploratory hypothesis H3-1 concerning the effect of multi-skilled workers application (MWA) on environmental performance (ENP) is not supported in the initial testing. This is not surprising because we could not find relatively sufficient evidence to support such a relationship when we proposed this hypothesis.

The result that H1-2 concerning the effect of line-*serus* conversion (LSC) on economic performance (ECP) is not supported is unexpected, since the effects between them seems strong in our field survey of several factories. Besides, previous literature also revealed that there is a good relationship between them [10, 59]. More evidence is needed to explain the reasons. This leads us to rethink whether there exist a nested or competing model [75].

Looking back to the items of constructs, we found that the construct of line-*serus* conversion (LSC) involves changes in both equipment and workers which are further described in the constructs of equipment improvement (EQI) and multi-skilled workers application (MWA). Generally speaking, items of the construct of line-*serus* conversion (LSC) are general and guiding expressions for the transformation. Only when line-*serus* conversion (LSC) is primarily and successfully formed can multi-skilled workers application (MWA) and equipment improvement (EQI) be further developed. This is in line with Sakazume's statements that the content of the changes can be broadly classified into changes in the method of the division of labor and changes in production equipment [6, 8]. Hence, from the theoretical perspective, it is feasible to set line-*serus* conversion (LSC) as the precedent of equipment improvement (EQI) and multi-skilled workers application (MWA).

From the statistical perspective, the correlation matrix of the constructs of four key enabling technologies (Table 7) clearly shows that line-*serus* conversion (LSC) is significantly related to multi-skilled workers application (MWA) and equipment improvement (EQI) simultaneously since the corresponding correlation coefficients are 0.58 and 0.32 respectively. This is a support for the above inference.

**Table 7**
Correlation matrix on key enabling technologies for *seru* production

| | LSC | EQI | MWA | DSO |
|---|---|---|---|---|
| LSC | - | | | |
| EQI | 0.32 | - | | |
| MWA | 0.58 | 0.00 | - | |
| DSO | 0.44 | 0.02 | 0.38 | - |

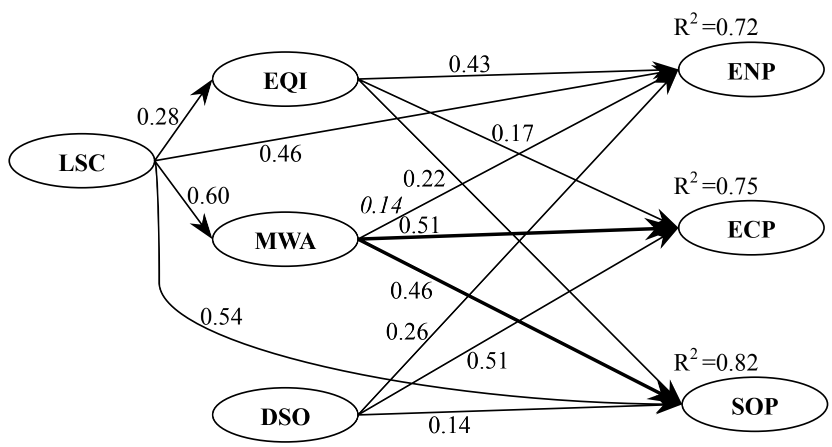
Note: All correlation coefficients are significant at 0.001 level.

A large amount of literature and relevant statistics about H5 were analyzed similarly to H1-2. The analysis results show that there is no significant evidence to support further adjusting any path of the model. However, we found some possible causes to attenuate the effects of multi-skilled workers application (MWA) which will be discussed in Section 6.

Moreover, we did a careful examination on other statistic results through structural equation modeling. Although some modification indices are high (the maximum is 32.16), we do not further adjust any paths since there is no theory indicating the necessity of adjustments.

Considering the analysis above and Hair et al.'s [75] recommendation on the competing model, we set line-*serus* conversion (LSC) as the precedent of multi-skilled workers application (MWA) and equipment improvement (EQI). This means that an indirect effect of line-*serus* conversion (LSC) on economic performance (ECP) is posited.

The modified model and the corresponding outputs through structural equation modeling are shown in Fig. 3. Compared with Fig. 2, there is not much variation in the path coefficients, but the overall model fit indices improve obviously and demonstrate a perfect fit. The value of RMSEA reduces to 0.066, which is evidently under the suggested range of 0.08 [73]. The value of Normed $\chi^2$ 1.85 is still within the range of 1 to 3 [81]. The values of NNFI, CFI, and IFI increase to 0.94, 0.94, and 0.95 respectively, which are significantly above 0.90 level. The three values of R-square are 0.72, 0.75, and 0.82, which indicates that the correspondingly explained variance for ENP, ECP, and SOP by the key enabling technologies are 72%, 75%, and 82% respectively. In addition, the modified model shows a little parsimony by increasing 4 (651-647) degrees of freedom which is negatively correlated with model complexity. All the indices indicate that the model fit is fairly good. So, H0 is strongly supported in the modified model.




RMSEA=0.066, NNFI=0.94, CFI=0.94, IFI=0.95, Normed $\chi^2$ =1.85, df=651

**Fig. 3.** The results with respect to the modified model

The modified model also provides favorable path coefficients which can be used to calculate the indirect effect of line-*serus* conversion (LSC) on economic performance (ECP). Although the coefficients of the path from line-*serus* conversion (LSC) to economic performance (ECP) via equipment improvement (EQI) are not as large as those of the path from line-*serus* conversion (LSC) to economic performance (ECP) via multi-skilled workers application (MWA), the aggregate value 0.35 (0.28*0.17+0.60*0.51=0.35, $P < 0.01$) is quite influential. As a result, H1-2 is indirectly verified, and H5 is not supported since neither 0.51 nor 0.46 is the largest coefficient. The exploratory hypothesis H3-1 is still not supported. The final results of hypotheses testing are shown in Table 8.

**Table 8**
The final results of hypotheses testing

| Hypotheses | Path coefficient (T)/fit indices | Results |
|---|---|---|
| H0 | very good fit | Support |
| H1-1 | 0.46 (5.47) | Support |
| H1-2 | 0.35 (∗∗) | Indirectly Support |
| H1-3 | 0.54 (5.85) | Support |
| H2-1 | 0.43 (5.37) | Support |
| H2-2 | 0.17 (2.83) | Support |
| H2-3 | 0.22 (4.40) | Support |
| H3-1 | *0.14 (1.72)* | Not Support |
| H3-2 | 0.51 (6.35) | Support |
| H3-3 | 0.46 (6.24) | Support |
| H4-1 | 0.26 (3.31) | Support |
| H4-2 | 0.51 (5.73) | Support |
| H4-3 | 0.14 (2.87) | Support |
| H5 | Neither 0.51 nor 0.46 is the largest | Not Support |

Note: ∗∗ Indirect path coefficient is significant at 0.01 level.

# 6 Conclusions and discussions

The analysis results through structural equation modeling show that the modified model is perfectly fitted and most hypotheses are supported by the collected data. The positive effects of the identified four key enabling technologies for *seru* production on sustainable performance (SP) were almost verified. However, not all the key enabling technologies have the same effect on sustainable performance (SP). For example, the path coefficient indicating the effect of line-*seru* conversion (LSC) on social performance (SOP) is as high as 0.54 while that for delivery system optimization (DSO) on social performance (SOP) is as low as 0.14. Even for a specific key enabling technology for *seru* production, the effects on different dimensions of sustainable performance vary. Most analysis results through structural equation modeling agree with the statements in the literature, while some results do not. In the following, we make a comprehensive discussion on them.

## 6.1 Effects of line-*serus* conversion on sustainable performance

The hypotheses H1-1 and H1-3 are strongly and significantly supported. For these two hypotheses, the corresponding path coefficients are 0.46 ($p < 0.001$) and 0.54 ($p < 0.001$), respectively. Especially, the path coefficient 0.54 ranks the first among all path coefficients. These results clearly demonstrate that line-*serus* conversion (LSC) has significantly positive effects on both environmental performance and social performance. Moreover, it is clear that the path coefficient presenting the indirect effect of line-*serus* conversion (LSC) on environmental performance (ENP) via equipment improvement (EQI) is 0.28*0.43=0.12 ($p < 0.001$); the path coefficient presenting the indirect effect of line-*serus* conversion (LSC) on social performance (SOP) via equipment improvement (EQI) and multi-skilled workers application (MWA) is 0.60*0.46+0.28*0.22=0.34 ($p < 0.01$). Taking the indirect effects into account, the effects of line-*serus* conversion (LSC) on both environmental performance and social performance will become larger since the corresponding path coefficients become 0.58 ($p < 0.001$) and 0.88 ($p < 0.01$), respectively.

The performance improvement reflected on these corresponding path coefficients coincides with the wide statements from the employees in the factories and the residents in the community. The surveys on the manufacturing factories indicate that employees are more satisfied and energetic in *seru* production systems than those on conveyor lines, and residents around the factories which are implementing *seru* production are more pleased with their community's residential environment. Moreover, the flexibility of *seru* formation facilitates the factories to fulfill customers' customization requirement, which improves the customers' satisfaction and loyalty to the products and service.

A direct effect of line-*serus* conversion (LSC) on economic performance (ECP) is not presented by the analysis results of the structural equation model. It was somewhat unexpected at the very beginning. After careful rethinking, we found that although the direct effect does not exist, it does not mean that line-*serus* conversion (LSC) has no effect on economic performance (ECP). The key enabling technology of line-*serus* conversion (LSC) indirectly improves economic performance (ECP) through other two key enabling technologies, namely, multi-skilled workers application (MWA) and equipment improvement (EQI). Such an indirect effect of line-*serus* conversion (LSC) on economic performance (ECP) is also verified in our modified model. In this paper, the calculated result 0.35 ($p < 0.01$) indicates that such an indirect effect is relatively strong.

The path coefficient 0.6 of the intermediate link between LSC and MWA demonstrates that line-*serus* conversion (LSC) largely depends on multi-skilled workers application (MWA). Compared with the improved equipment, multi-skilled workers have irreplaceable initiative and dynamism in dealing with various situations, especially in emergency cases. This largely confirms the previous judgement that *seru* production is a human-centered production mode [3, 11, 12, 15, 18, 25, 54].

### 6.2 Effects of equipment improvement on sustainable performance

Hypotheses H2-1, H2-2, and H2-3 are supported, where the corresponding path coefficients are 0.43 ($p < 0.001$), 0.17 ($p < 0.01$), and 0.22 ($p < 0.001$), respectively. These results indicate that the key enabling technology of equipment improvement (EQI) has positive effects on all three dimensions of sustainable performance. Clearly, the effect on environmental performance is the strongest among the three effects since the corresponding path coefficient is 0.43 which is bigger than 0.17 and 0.22. This is in line with the standpoint that *seru* production is with environmentally friendly characteristics of sustainable manufacturing [4].

From the path coefficient 0.17 ($p < 0.01$) of the link associated with Hypothesis H2-2, we can see that equipment improvement (EQI) has a weak but significant effect on economic performance (ECP). Moreover, some surveyed factories implementing *seru* production less than 7 years reported that the performance of equipment-based cost was not so expected. Several of them even claimed that there seemed to be a rise in equipment investment, especially at the preliminary phase of *seru* production implementation. These contradict previous findings that equipment improvement (EQI) can greatly improve economic performance, e.g., as high as 90% equipment cost decrease in NEC [61]. To find the factors that weaken the economic performance, we made an analysis on the initial questionnaires and related literature. Some possible evidence is found and described as below.

First, a higher capital investment is needed because more sets of tools and machines should be purchased for multiple *serus*, particularly when the inspection operation is conducted separately in each *seru*. This investment burden will be relieved once the initial investment on multi-*serus* formation is finished. After that, both the maintenance cost and the depreciation cost of the small and inexpensive equipment will be very low in daily management compared with that of the previous heavy and expensive equipment. Hence, in the long term, the equipment improvement (EQI) may have a positive effect on cost reduction.

Second, in the early stage of the implementation of *seru* production, the operators lack the knowledge or are not proficient enough to self-make the specialized equipment. Hence, the expensive general equipment has to be introduced from outside of the factory. The substantial introduction of general equipment results in low utilization of such equipment and high investment for the factory for a short while. This problem can be settled during the production process as the operators become more skilled. Managers should provide accessible training opportunities and create a supportive learning atmosphere to shorten the growth cycle of the operators. Therefore, this temporarily weak effect will not be a permanent obstacle on their way to fully implementing *seru* production.

### 6.3 Effects of multi-skilled workers application on sustainable performance

The final results from the structural equation model significantly and strongly support hypotheses H3-2 and H3-3, where the corresponding path coefficients are 0.51 ($p < 0.001$) and 0.46 ($p < 0.001$) respectively. Such results demonstrate that multi-skilled workers application (MWA) has positive effects on both economic and social performance. However, Hypothesis H3-1 is not supported since the path coefficient 0.14 ($p > 0.05$) of the link associated with it is insignificant. Such empirical result fails to verify the managers' estimation that a possibly positive effect may exist between multi-skilled workers application (MWA) and environmental performance (ENP). Hypothesis H5 is not supported either, because neither 0.51 nor 0.46 ranks the first among all the path coefficients. As for H5, two reasons may explain the results to some extent.

First, in *seru* production, multi-skilled operators are required to master not only basic operation skills but also management skills. The necessary cross-training may bring them more pressure and burden [4]. For example, operators in Sheet Metal Products [59] participating in the trial assembly cell project felt more tired at the end of the day than those did on the conveyor line. Under such circumstances, factories may even suffer resistance to the formation of *serus* from operators, especially those with less desire for career development, not to mention performance improvement. In this case, managers should take various measures like merit pay system, superior welfare, and regular occupational guidance to stimulate employees to realize their individual value so as to further improve the organizational performance. At the same time, managers should provide various channels such as psychological counseling both online and offline and available gymnasiums for operators to release their mental and physical pressure.

Second, the continuous training cost may weaken the effects of multi-skilled workers application (MWA) on economic performance (ECP) and social performance (SOP). In order to respond to market changes and customers' demands rapidly, operators must be trained to master the latest technologies or skills. Accordingly, managers should arrange the complex training programmes in a comprehensive way as early as possible [4]. What skills, what objectives, what methods, which employees, and what forms of their composition, should be taken into account before real training starts. During the training process, managers need to adjust the training content based on an ever-changing environment rather than follow a fixed plan. And after training, it is necessary to check whether the workers have reached the expected skill level. This procedure is usually done through theoretical and practical tests. If the workers do not reach the expected skill level, they need to be retrained till they are fully qualified. As a result, the huge input of training time, money, and energy becomes a disadvantage for multi-skilled workers application (MWA) [24].

In the application of multi-skilled workers, managers should also be aware that production efficiency and product quality may not reach the expected level in the early phase of operation because of unfamiliarity with new operations and carelessness of operators [4]. Such a problem is somewhat similar to that arising in equipment improvement (EQI). Although the effects of multi-skilled workers application (MWA) on sustainable performance (SP) could sometimes be weakened, it really plays an important role in performance improvement in manufacturing factories. Managers who are facing these problems should deal with them properly, and managers who are not encountering such problems should be fully prepared for early prevention.

### 6.4 Effects of delivery system optimization on sustainable performance

The hypotheses H4-1, H4-2, and H4-3 are supported, where the corresponding path coefficient are 0.26 ($p < 0.001$), 0.51 ($p < 0.001$), and 0.14 ($p < 0.01$), respectively. These results imply that delivery system optimization (DSO) for *seru* production has positive effects on all three dimensions of sustainable performance. This nicely supports the experts' statements that the delivery system works well in *seru* production with high performance.

Obviously, the effect of delivery system optimization (DSO) on environmental performance (ENP) is weaker than that on economic performance (ECP) since the corresponding path coefficients are 0.26 and 0.51, respectively. This finding indicates that some measures of delivery system optimization (DSO) have less contribution to environmental improvement. For example, both JIT delivery and delivery in small batches can result in higher frequency than delivery in large quantities. The higher delivery frequency may lead to the increase of the consumed energy and the emitted green house gas, especially when the transportation facilities are energy-intensive. Therefore, to eliminate the unfavorable influence on environment, the delivery and transportation facilities should be improved as well. Managers need to pay attention to equipment improvement (EQI) on all related equipment rather than just on manufacturing and assembly equipment whenever a JIT delivery method is used.

## 7 Limitations and future research

In this paper, four key enabling technologies for *seru* production were identified and an evaluation indicator system of sustainable performance in the context of *seru* production was developed. Then, this work proposed several hypotheses about the effects of the identified key enabling technologies on sustainable performance (SP), and investigated the effects through structural equation modeling. The achievements of this work help to improve the comprehensive understanding of *suru* production, as well as to develop practical methods to improve sustainable performance of manufacturing factories.

The findings of this work that the key enabling technologies for *seru* production have positive effects on sustainable performance, except that multi-skilled workers application has insignificant effect on environmental performance, largely agree with the results in previous literature. However, in production practice, it should be noted that different manufacturing factories may not achieve the similarly high sustainable performance by adopting the same enabling technologies [19]. Context factors such as industry types, operation years, and corporate culture play an active role in the highly sophisticated influence mechanism of technology-performance. Managers should also keep in mind that enabling technologies for *seru* production are sometimes a double-edged sword. For example, on one hand, multi-skilled workers application can undoubtedly reduce the manpower requirement and increase job satisfaction. But on the other hand, it inevitably raises the training cost due to the continuous training programme, as well as increases employees' work pressure because of the job enlargement. In order to improve the sustainable performance, a variety of effective measures should be taken to make full use of the advantages and avoid the disadvantages of enabling technologies.

Although many research results were achieved, there are still some limitations in this paper. The main limitations can be summarized as follows. First, as statements due to Yin et al. [9], the high performance of *seru* production is based on an organic integral system of all enabling technologies rather than one or some enabling technologies. In this paper, we only discussed four key enabling technologies for *seru* production. These four key enabling technologies can characterize *seru* production to some extent, but can not show all aspects of *seru* production. Other enabling technologies, such as standing gestures, *kanketsu* [4, 10], and continuous improvement, should be investigated in future research to extend and optimize the model proposed in this paper. More challenges will emerge as more enabling technologies are added to the model.

Second, four key enabling technologies for *seru* production are identified in this paper, but an intensive and comprehensive research on each of them has not been conducted. Especially, the research on the key enabling technologies of equipment improvement (EQI) and delivery system optimization (DSO) is far from enough. A thorough research on each of them is needed. The advantages and disadvantages of each key enabling technology, and the interactive relationships with others should be investigated both in depth and in width. The comprehensive research on each enabling technology for *seru* production helps factories to make better use of them.

Third, there is still much room to improve the instrument of evaluation indicator system of sustainable performance in the context of *seru* production. In order to promote the quantitative evaluation, the instrument needs to be quantified more scientifically and rationally. The measurement and industrial standards for relevant items should be established so that factories may clearly understand their status and improvement from both horizontal and longitudinal perspectives. Moreover, to ensure the adaptability of the instrument, further testing needs to be done by using data collected from more manufacturing factories.

Finally, for manufacturing factories, the sustainable performance can be evaluated at different organisational levels, such as the level of operation, the level of production system, the level of the entire factory, the level of supply chain [85]. In this paper, sustainable performance is restricted to the level of production system. In the future, researchers may develop a more complete model which includes sustainable performance at both the level of production system and the level of the entire factory.

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**Appendix A**

Items of key enabling technologies for *seru* production from literature and practice. (mainly adapted from Li et al.'s instrument)

| Factor | Number of items | Code | Definition | Mean | Std. Deviation | Std.loadings | T |
|---|---|---|---|---|---|---|---|
| Line-*serus* Conversion (LSC) $\alpha$=0.783 | 4 | LSC1 | We reconfigure long conveyor assembly lines into parallel *serus* with respect to various product types | 3.91 | 0.732 | 0.62 | a |
| | | LSC2 | We remove expensive and automated equipment like robots from factories | 3.90 | 0.755 | 0.74 | 7.33 |
| | | LSC3 | Multiple *serus* are laid out in *majime* | 3.91 | 0.722 | 0.68 | 7.04 |
| | | LSC4 | One or several multi-skilled or even full-skilled workers are in charge of a *seru* | 3.98 | 0.671 | 0.71 | 7.21 |
| Equipment improvement (EQI) $\alpha$=0.794 | 5 | EQI1 | We use less automated equipment | 3.98 | 0.774 | 0.66 | a |
| | | EQI2 | We use small and simplified equipment with similar functions as large equipment holds | 3.97 | 0.698 | 0.55 | 6.48 |
| | | EQI3 | We use self-made and specialized equipment | 4.03 | 0.705 | 0.61 | 7.12 |
| | | EQI4 | The equipment in a *seru* is removable | 3.93 | 0.761 | 0.84 | 8.60 |
| | | EQI5 | Our reconstructed equipment can be easily duplicated and modified at a low cost | 4.05 | 0.692 | 0.64 | 7.42 |
| Multi-skilled workers application (MSW) $\alpha$=0.864 | 7 | MSW1 | Cross-training for multi-skilled workers are often organized | 4.01 | 0.723 | 0.74 | a |
| | | MSW2 | Multi-skilled workers are widely adopted | 4.06 | 0.666 | 0.69 | 9.03 |
| | | MSW3 | Workers are motivated to realize self-values and pursue career developments | 4.10 | 0.713 | 0.66 | 8.59 |
| | | MSW4 | Workers are empowered to make production decisions | 4.02 | 0.764 | 0.70 | 9.16 |
| | | MSW5 | Learning atmosphere is cultivated among workers | 3.98 | 0.716 | 0.74 | 9.68 |
| | | MSW6 | Workers are trained to handle production schedule and performance evaluation | 3.99 | 0.748 | 0.69 | 9.01 |
| | | MSW7 | Multiple workers can be transferred within or among *serus* according to the fluctuations of customer demand | 4.01 | 0.672 | 0.62 | 8.19 |
| Delivery system optimization (DSO) $\alpha$=0.781 | 4 | DSO1 | Our delivery is usually done in small batches and high frequency | 3.93 | 0.752 | 0.65 | a |
| | | DSO2 | We adopt a just-in-time materials delivery system | 3.91 | 0.763 | 0.85 | 8.08 |
| | | DSO3 | Our delivery workers have good knowledge of scheduling and management | 3.97 | 0.750 | 0.64 | 7.25 |
| | | DSO4 | Materials, parts or products between operations are input and output timely | 3.94 | 0.661 | 0.62 | 7.03 |

Notation: a – reference variable.

**Appendix B**

Items of the evaluation indictor system of sustainable performance. (mainly adapted from NIST's and Amrina and Yusof's instruments)

| Factor | Number of items | Code | Definition | Mean | Std. Deviation | Std. loadings | T |
|---|---|---|---|---|---|---|---|
| Environmental | 4 | ENP1 | The consuming energy per unit product was reduced | 4.42 | 0.655 | 0.66 | a |
| performance | | ENP2 | The occupied shop-floor space was reduced | 4.20 | 0.782 | 0.73 | 7.59 |
| (ENP) | | ENP3 | The green house gas emission was reduced | 4.00 | 0.894 | 0.73 | 7.47 |
| $\alpha$=0.866 | | ENP4 | The hazardous substance was reduced | 4.26 | 0.795 | 0.78 | 7.77 |
| Economic | 8 | ECP1 | Production efficiency was improved | 4.11 | 0.644 | 0.74 | a |
| Performance | | ECP2 | Production flexibility was improved | 4.14 | 0.621 | 0.75 | 10.17 |
| (ECP) | | ECP3 | Setup time was reduced | 4.17 | 0.649 | 0.61 | 8.20 |
| $\alpha$=0.836 | | ECP4 | Inventory cost was reduced | 4.10 | 0.701 | 0.72 | 9.88 |
| | | ECP5 | Labor productivity was improved | 4.07 | 0.652 | 0.71 | 9.68 |
| | | ECP6 | The cost of jigs and tools was reduced | 4.07 | 0.683 | 0.70 | 9.58 |
| | | ECP7 | Finished product first-past quality yield was raised | 4.04 | 0.639 | 0.64 | 8.73 |
| | | ECP8 | The delivery time was reduced | 4.21 | 0.636 | 0.75 | 10.27 |
| Social | 6 | SOP1 | Occupational health and safety of employee were increased | 4.10 | 0.607 | 0.57 | a |
| Performance | | SOP2 | Employee's job satisfaction was increased | 4.06 | 0.673 | 0.67 | 6.91 |
| (SOP) | | SOP3 | Customization level was improved | 3.97 | 0.708 | 0.67 | 6.89 |
| $\alpha$=0.832 | | SOP4 | Customer's satisfaction level was increased | 4.08 | 0.708 | 0.71 | 7.15 |
| | | SOP5 | Community employment rate was increased | 4.19 | 0.656 | 0.75 | 7.36 |
| | | SOP6 | The generated noise to the community was reduced | 4.07 | 0.633 | 0.67 | 6.91 |

Notation: a – reference variable.

**Appendix C**

A part of Li et al.'s instrument.

| Items codes | Label |
|---|---|
| Equipment improvement | |
| EQI1 | Movable equipment is used. |
| EQI2 | Equipment is simplified. |
| EQI3 | Self-made specialized equipment is applied. |
| EQI4 | Equipment is designed with a less-automated and low-cost orientation. |
| EQI5 | Small equipment is applied. |
| Multi-skilled workers application | |
| MSW1 | Training for multi-skilled workers is often organized. |
| MSW2 | Multi-skilled workers are widely adopted. |
| MSW3 | Several multi-skilled workers are assigned to the same *seru* in case of a large demand. |
| MSW5 | Workers are empowered to make production decisions. |
| MSW7 | Workers are trained for on-site management skills. |
| MSW6 | Workers are trained and encouraged to handel product schedule and performance review. |
| MSW8 | Multiple workers can be transferred within or among *serus* according to the fluctuations in demand. |
| *MSW4* | *Workers are not encouraged for learning multiple skills (reverse coded).* |
| Suitable delivery plan and transfer rules development | |
| DTM1 | Deliver plan is designed based on variable production conditions including *seru* types. |
| DTM2 | Small-batch frequent delivery plan is used for raw materials. |
| DTM3 | Reasonable transfer rule is selected to shift products or parts between processes. |
| DTM4 | Delivery operators have good knowledge of scheduling and management. |

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