Hindawi
Mathematical Problems in Engineering
Volume 2019, Article ID 4036794, 13 pages
https://doi.org/10.1155/2019/4036794

Research Article

Analysis of the Effect of the Line-*Seru* Conversion on the Waiting Time with Batch Arrival

Hui Ren [1] **and Dongyu Wang** [2]

[1] *School of Economics and Management, Xi'an University of Technology, Xi'an 710054, China*
[2] *School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China*

Correspondence should be addressed to Hui Ren; ren1987@qq.com

Received 10 March 2019; Accepted 14 April 2019; Published 26 May 2019

Academic Editor: Frederico Cruz

The conveyor assembly line has been widely used in manufacturing industries to produce standard products with low costs. However, due to lack of flexibility, this production method has not been conducive to multivariety and small-batch production. In this situation, *seru* production formed by converting conveyor assembly lines has been a successful innovation in the Japanese manufacturing industry. Most of the existing literature has studied the benefits of this line-*seru* conversion from the perspective of the enterprises themselves, but this paper studies the effect of the line-*seru* conversion on the waiting time from the perspective of the customer. First, the change in the average waiting queue length caused by the line-*seru* conversion is proposed as an evaluation index. Second, with the consideration of the practical situation of random batch arrivals, the average waiting queue length formulas for the conveyor assembly line and *seru* production are established based on the assumption that the arrival is a Poisson process. Then, under two scenarios, we investigate the relationship between the average waiting queue length changed by the line-*seru* conversion and other parameters and find that the conversion can reduce the average waiting queue length in multivariety and small-batch production. Finally, under other potential scenarios, the equations for determining the average waiting queue length resulting from a change to line-*seru* conversion are derived.

1. Introduction

With an increasingly diversified customer demand and shortened product life cycle, manufacturing enterprises are gradually facing a multivariety and small-batch production environment. In such an environment, the conveyor assembly line, which is suitable for mass production, has to be adjusted frequently, resulting in manufacturing companies not being able to take full advantage of its unique efficiency. At the same time, demand fluctuations often lead to over- or underproduction; hence, the fatal weakness of low flexibility is completely exposed [1]. To face such a turbulent markets environment, manufacturing factories started to look for new production organization forms with low costs and high flexibility. In various organizational innovations, Sony made huge profits by successfully implementing the dismantling of its conveyor assembly line and converting to *Seru Seisan* [1]. At Sony Kohda, a total of 710,000 square meters of workshop space was reduced [2] and the throughput time was reduced by 53%. At Canon, the number of required workers was reduced by 35,976, an amount equal to 25% of Canon's previous total workforce [2]. Thus, *seru* production has attracted considerable attention in manufacturing industry.

Each *seru* in *seru* production is a small and compact production organization that consists of some equipment and one or more workers that produce one or more products [3]. There are three types of *seru* in production practice: divisional, rotating, and *yatai*. When the conveyor assembly line is reconfigured, the *serus* formed first are the divisional *serus*, in which tasks are divided into different sections and each section is in charge of one or more partially cross-trained workers. A rotating *seru* is often organized in a U-shaped layout with several completely cross-trained workers who can assemble an entire product. As partially cross-trained workers are trained to become completely cross-trained workers, divisional *serus* can evolve into rotating *serus*. *Yatai* is a *seru* with only one completely cross-trained worker. In this paper, we only analyze *yatais*.

At present, most scholars have analyzed the benefits of converting a conveyor assembly line to *seru* production in a changeable market environment from the perspective of the enterprises themselves, but there is little analysis of this conversion from the perspective of the customers' perception. However, in the process of manufacturing and service, it is difficult to obtain the customers' satisfaction without considering the customers' perception. This paper compares these two production organization forms, conveyor assembly line and *seru* production, based on the customers' waiting time. In this paper, the conversion of the conveyor assembly line into *seru* production is called line-*seru* conversion.

The remainder of this paper is organized as follows. The following section is literature review. Section 3 describes the research problems and constructs the average waiting queue length formula changed by the line-*seru* conversion. Section 4 mainly investigates the relationship between the average waiting queue length changed by the line-*seru* conversion and other parameters under two conversion scenarios. Finally, the conclusions are drawn in Section 5.

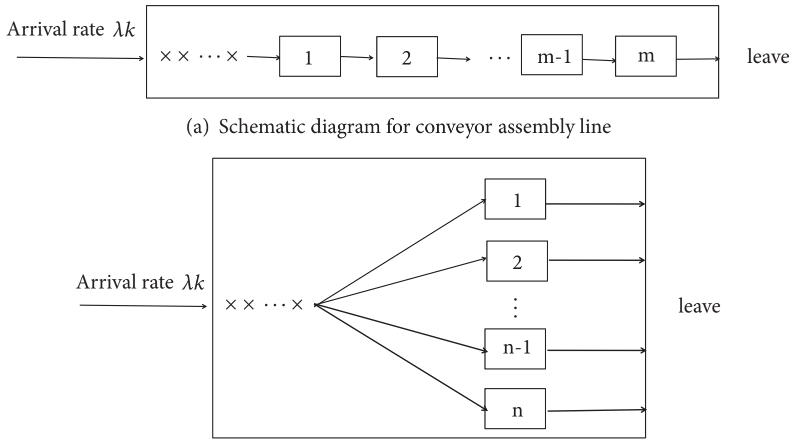
2. Literature Review

Because line-*seru* conversion in Japanese industry has been able to improve system performance in a changing market environment, for production organizations, it has been regarded as an innovation, for which many scholars have conducted theoretical research. For example, Kaku et al. [4] defined the line-*seru* conversion problem and constructed a mathematical model to describe it. As the total throughput time and the total labor power are applied to evaluate system performance, this model can be used as an evaluation tool to decide whether manufacturing factories should convert their production system. Then, Liu et al. [1] investigated the problem of how to convert the conveyor assembly line to *serus*. They built a comprehensive mathematical model to solve two issues, namely, how many *serus* should be established and how many workers should be assigned to each *seru*. Compared with Kaku's model, their model is more suitable for analyzing the problem of the reconfiguration of the assembly line to *serus*. Actually, multiobjective decision-making is often used in the line-*seru* conversion problem. Although Yu et al. [5] also discussed how to implement this type of line-*seru* conversion, they constructed a two-objective line-*seru* conversion model that minimizes the total throughput time (TTPT) and the total labor hours (TLH). Yu et al. [6] also proposed a multiobjective optimization model to investigate the following two performances of line-*seru* conversion: the total throughput time and the total labor hours. Then, Yu et al. [7] further developed a more efficient algorithm to solve large-scale problems within a reasonable time. Yu et al. [8] formulated several main models of line-hybrid *seru* system conversion and clarified the complexity and properties of line-hybrid *seru* system conversion. Yu et al. [9] formulated a line-*seru* conversion towards reducing worker(s) without increasing makespan.

Since *seru* production is a human-centered assembly system, the performance improvement resulting from the line-*seru* conversion is heavily dependent on the cross-trained workers. For converting a conveyor assembly line to *seru* production, Kaku et al. [10] constructed theoretical models to analyze the human task-related performances, which included the possible added operational tasks, the skill level, and the cross training of workers. Liu et al. [11] investigated the workers' training and assignment problem in the line-*seru* conversion. They formulated a two-objective model to minimize the total training cost and to balance the total processing times among the cross-trained workers in each *seru*. Yu et al. [12] presented a multiobjective line-*seru* conversion model, with the goals of reducing worker(s) and simultaneously increasing productivity, and performed several numerical simulation experiments to illustrate that the line-*seru* conversion can be used to reduce both worker(s) and the total throughput time. Ying and Tsai [13] discussed how to minimize total cost for training and assigning multiskilled workers in *seru* production systems. Lian et al. [14] studied a multiskilled worker assignment problem in *seru* production systems considering the worker heterogeneity.

Although a line-*seru* conversion can improve system performance, not all enterprises can successfully implement it due to lack of theoretical guidance. Therefore, based on a systematical analysis of many experiences involving the implementation of *seru* production in Japanese manufacturing factories, Liu et al. [15], for practitioners from a practical perspective, provided a general framework and some basic principles that should be followed while implementing *seru* production. Through the analysis of the profit function of the *seru* system, Yin et al. [3] explained why the implementation of *seru* production with respect to an uncertain market could produce higher profits with a smaller workforce. Further, Yin et al. [16] studied how two electronics giants, Sony and Canon, had applied *seru* to improve productivity, quality, and flexibility in ways that have enabled them to remain competitive. Yu et al. [17] focused on the fundamental principles of *seru* system balancing in order to reduce makespan, labor hours, and manpower.

In addition, Liu et al. [18] systematically summarized the advantages of *seru* production relative to that of a conveyor assembly line: these advantages included reducing lead time, setup time, WIP inventories, finished-product inventories, cost, required workforce, and shop floor space. Additionally, they found that *seru* production also positively influences profits, product quality, and workforce motivation. Lately, Zhang et al. [19] pointed out the sustainability of *seru* production. Throughout the research of the line-*seru* conversion, most of the studies have analyzed the improvement of system performance from the perspective of the enterprise. However, this paper takes the waiting time as an index to analyze the line-*seru* conversion from the perspective of the customers' perception. Most of the existing literature studied the related problems of a single product randomly arriving at a production system. For example, Uday et al. [20] used queuing theory to compare the waiting time performance with single arrivals for the production line and the case manager approach. However, in an actual production system,



(a) Schematic diagram for conveyor assembly line

(b) Schematic diagram for cellular manufacturing

Figure 1: A comparison of conveyor assembly line and cellular manufacturing.

a business is not a retailer, and most of the customer orders are random batch arrival orders, with the batch size different for different customers. Therefore, unlike the previous literature, this article focuses on the conveyor assembly line and *seru* production with batch arrivals. Next, a review of the relevant research on batch arrival processes in the manufacturing and service systems is presented.

First, scholars have studied queuing systems with batch arrivals at a single service window, namely, the production system with only one workstation. In the early 1960s, Suzuk [21] and Takacs [22] conducted research on the queuing model in the basic form $M^x/G/1$ and obtained some queuing indexes. Subsequently, Chaudhry [23] pointed out the advantages of the supplementary variable method and used it to study the $M^x/G/1$ queue model. Later, the supplementary variable method became an important tool to study the batch arrival queuing model. By using the inverse transformation of Laplace-Stieltjes to solve the supplementary variable, Briere and Chaudhry [24] provided easy access with the exact numerical solution of the $M^x/G/1$ model. Before that, in one sense, this type of queuing model was only partially solved. In this paper, we also use the inverse transformation of Laplace-Stieltjes to solve the supplementary variable and then obtain the average waiting queue length of a *seru* production system. The difference is that we study a multiserver batch arrival queuing system, where the conveyor assembly line consists of multiple workstations in a series and in which the *seru* production system consists of multiple parallel workstations, as shown in Figures 1(a) and 1(b).

Next, we review the researches related to multiserver batch arrival queuing systems. Hideaki and Wu [24] considered multiple servers with a semi-Markov batch arrival process queuing system. Based on the theory of a piecewise Markov process, they obtained the waiting time distribution. The arrival process of the queuing system in their research is different from the batch arrival process with *seru* production in this paper. Güllü [25] analyzed a $M/G/\infty$ queue with batch arrivals, in which the number of jobs in the system was characterized as a compound Poisson random variable. Differing from this paper, they assumed that the same batch of products must be processed by the same server. Bara and Jeongsim [26] considered a multiserver $M^x/M/c$ queue with impatient customers and used the customers' loss probability to measure the quality of service in such a system. The biggest difference between the queuing system in their study and the one utilized in the *seru* production situation in this paper is that they assumed a customer was only willing to wait in the queue for a fixed time.

Furthermore, Wu [27] classified the batch queuing models for manufacturing systems. For batch arrivals, he took the cycle time as an index and only studied the performance of two queuing models: single job processing and serial batch processing. According to Wu's classification, the systems studied in this paper are batch arrivals with serial batch processing and batch arrivals with parallel batch processing. In this paper, however, the average waiting queue length under a stable state is regarded as the index by which these two queuing systems are measured.

3. The Effect of the Line-*Seru* Conversion on the Average Waiting Queue Length

Under multivariety and small-batch production, many manufacturing factories convert their conveyor assembly line into *seru* production to overcome the low flexibility of the conveyor assembly line. However, whether the line-*seru* conversion can improve the waiting time performance from the perspective of the customers' perception remains to be further studied. According to Little' Law, the average waiting queue length is positively correlated with the average waiting time and is more intuitive. Therefore, we analyze the change in the average waiting queue length resulting from the line-*seru* conversion with random batch arrivals. Let ΔL_q denote the difference between the average waiting queue length of the conveyor assembly line $L_q(A)$ and the average waiting queue length of the *seru* production $L_q(C)$; then

$$\Delta L_q = L_q(A) - L_q(C). \tag{1}$$

When the value of $\Delta L_q > 0$, it indicates that the line-*seru* conversion reduces the average waiting queue length and further shows that the conversion can improve the customers' waiting time performance. When the value of $\Delta L_q = 0$, it indicates that the line-*seru* conversion does not change the average waiting queue length and further shows that the conversion cannot improve the waiting time performance. When the value of $\Delta L_q < 0$, it indicates that the line-*seru* conversion increases the average waiting queue length and further shows that the conversion increases the waiting time. Formula (1) shows that the average waiting queue length changed by the line-*seru* conversion can be obtained only when the average waiting queue lengths of the conveyor assembly line and the *seru* production methods are obtained.

3.1. The Batch Arrival Queuing Model for a Conveyor Assembly Line. On the basis of a queuing system with batch arrivals and a single server window, namely, a $M^x/M/1$ queuing model, the number of workstations is increased in a series to form a queuing system of a conveyor assembly line with batch arrivals, as shown in Figure 1(a), in which the number of workstations is m. A worker is assigned to one workstation to perform one operation. We assume that the product arrival process is a Poisson flow with parameter λ [25, 26] and has batch arrival of which the mean of the batch size is k. The operating characteristics of the first operation in the conveyor assembly line are defined as a $M^x/M/1$ queuing model with the arrival rate of λk and the service rate of μ. Using Burke's theorem [20], the steady-state output completed by the first worker is also a Poisson process with parameter λk. The output of the first operation serves as the input of the second operation. Repeating the above logic, the conveyor assembly line essentially consists of m decomposable $M^x/M/1$ queuing models. Note that when the conveyor assembly line is in a stable state, the arrival rate λk must be less than the service rate μ.

When any batch of x products arrives at the conveyor assembly line simultaneously, there are m' products in the system, and $m' > m$. Therefore, the conveyor assembly line starts processing this batch of products when $(m' - m + 1)$ products are completed. According to Little's Law, the average queue length can be obtained by the average sojourn time of each product in the conveyor assembly line, and then the average waiting queue length can be obtained. The average sojourn time of each product in any batch consists of two parts. The first part is the time that any batch of products waits for the completion of $(m' - m + 1)$ products. The second part is the average time spent on each product during the production of any batch of products. It is noteworthy that the average time spent on each product includes not only the production time of each product, but also the waiting time of each product during the production of this batch of products.

As the mean of batch size is k, $E[x] = k$; the average time spent on each product during the production of any batch of products on the conveyor assembly line is shown as follows:

$$E\left[\sum_{i=1}^{x}\left(\frac{m}{\mu}+\frac{i-1}{\mu}\right)P\right] = E\left[\frac{m}{\mu}+\frac{x-1}{2\mu}\right] = \frac{2m+k-1}{2\mu} \tag{2}$$

where P is the probability that this product ranks *ith* in x products and $P = 1/x$. m/μ is the processing time for each product. $(i-1)/\mu$ is the waiting time for the *ith* product.

The average sojourn time of each product in the conveyor assembly line is

$$\begin{aligned} W_s(A) &= \sum_{m'=0}^{\infty} E p_{m'} \\ &= \sum_{m'=0}^{\infty}\left(\frac{m'-m+1}{\mu}+\frac{2m+k-1}{2\mu}\right)p_{m'} \\ &= \frac{L_s(A)}{\mu}+\frac{k+1}{2\mu} \end{aligned} \tag{3}$$

where E is the sojourn time when the product arrives at the conveyor assembly line with m' products and $p_{m'}$ is the probability of m' products on the conveyor assembly line. Furthermore, $\sum_{m'=0}^{\infty} m' p_{m'} = L_s(A)$, and $L_s(A)$ is the average queue length of the conveyor assembly line, which represents the average of products (waiting and processing products) in this system.

Therefore, the average waiting queue length in the conveyor assembly line, $L_q(A)$, is as follows.

$$L_q(A) = L_s(A) - \frac{m\lambda k}{\mu} = \frac{\lambda k(k+1)}{2(\mu-\lambda k)} - \frac{m\lambda k}{\mu} \tag{4}$$

3.2. The Batch Arrival Queuing Model for Seru Production. This paper studies a *seru* production system containing several *yatais*, which were formed by converting the conveyor assembly line, and in which one completely cross-trained worker is responsible for all the operations at one *seru*. We assume that the number of *serus* is n $(n \le m)$ and that the number of completely cross-trained workers in the system is also n. The arrival process is the same as that of the conveyor assembly line, and the products are processed in a first-in-first-out manner. The service time of each *seru* also follows a negative exponential distribution, but the service rate, which is different from that of the conveyor assembly line, is set at μ'. Therefore, the *seru* production system with batch arrivals belongs to a $M^x/M/n$ queuing model, as shown in Figure 1(b). Although a $M^x/M/n$ queuing system has not been studied in depth, it is similar to a $M/M/n$ queuing system [28], except that the arrival process is different. Based on the study of a $M/M/n$ queuing system, we explore the average waiting queue length of a $M^x/M/n$ queuing system.

This paper studies the number of products already in the system when any batch of products arrives at the system, namely, the average queue length, to obtain the average waiting queue length formula. Through the analysis of the whole process from product arrival to departure, it is found that the number of products already in the system of any batch of products arrival is closely related to the number of products that may be served by the system within the products arrival interval. Next, this paper will analyze the relationship between these two quantities in detail.

Since the arrival process is a Poisson flow with the parameter λk, the interval time of the batch arrivals is a

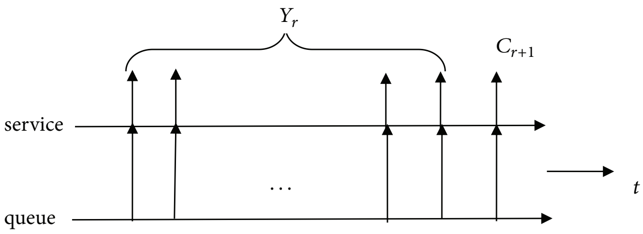


Figure 2: $M^x \mid M \mid n$ queuing model.

negative exponential distribution with the parameter λk, and its distribution density is $g(t) = (\lambda k)e^{-(\lambda k)t}$. C_r represents the rth batch of arrival products, and t_r represents the arrival moment of the rth batch of products; $\{t_r,\ r > 1\}$ is called an embedded point column. We assume that X_r is the number of products already in the system when the rth batch of products arrives at the system, and it is only related to the system state at the $t_r - 0$ moment. $\{X_r,\ r > 1\}$ has proved to be a homogeneous Markov chain in theory [28]. Let $T_r = t_r - t_{r-1}$ $(r > 1)$ be the rth time arrival interval and Y_r be the number of products that may be served by *n serus* within the rth time arrival interval T_r, as shown in Figure 2.

If there are X_r products in the system at the arrival moment of the rth batch of products, and the number of the rth batch of products is set as the mean of the batch size k, the system has X_{r+k} products when the next batch of products arrives at the system. Therefore, there are the following.

$$X_{r+k} = \begin{cases} X_r + k - Y_r, & Y_r < X_r + k \\ 0, & Y_r \geq X_r + k \end{cases} \tag{5}$$

Lemma 1. *Since the service time is a negative exponential distribution, the number of finished products Y_r follows a Poisson distribution, under the condition of a known rth time arrival interval T_r. For a Markov chain $\{X_r,\ r \geq 1\}$, the one-step transition matrix is as follows.*

$$\begin{aligned} p_{ij} &= P\left(X_{r+k} = j \mid X_r = i\right) \\ &= \begin{cases} P\left(Y_r = i + k - j\right), & j \leq i + k \\ 0, & j > i + k \end{cases} \end{aligned} \tag{6}$$

Theorem 2. *When seru production is in a steady state, namely, $n \leq j \leq i + k$,*

$$p_{ij} = \int_0^\infty \frac{\left(n\mu' t\right)^{i+k-j}}{(i+k-j)!} e^{-n\mu' t} g(t)\, dt. \tag{7}$$

Proof of Theorem 2. When $n \leq j \leq i + k$, *n serus* are all busy in the period of T_r, so when the *n serus* are fully occupied, the output stream is actually the superposition of n independent Poisson processes with the parameter μ', namely, a Poisson stream with the parameter $n\mu'$. Thus, within this time length of $T_r = t$, the conditional probability of outputting $i + k - j$ products is $((n\mu' t)^{i+k-j}/(i + k - j)!)e^{-n\mu' t}$; hence,

$$p_{ij} = \int_0^\infty \frac{\left(n\mu' t\right)^{i+k-j}}{(i+k-j)!} e^{-n\mu' t} g(t)\, dt. \tag{8}$$

□

When $\lambda k / n\mu' < 1$, it can be theoretically proved that this Markov chain must have a stationary distribution denoted as $\{\overline{p}_j\}$; namely, it is the distribution of X_r when the system is stable, and it satisfies the following equation.

$$\overline{p}_j = \sum_{i=0}^{\infty} p_{ij} \overline{p}_i = \sum_{i=j-k}^{\infty} p_{ij} \overline{p}_i, \quad j \geq 0, \tag{9}$$

Let

$$\beta_l = \int_0^\infty \frac{\left(n\mu' t\right)^l}{l!} e^{-n\mu' t} g(t)\, dt; \tag{10}$$

thus, when $n \leq j \leq i + k$, according to Theorem 2, there is

$$p_{ij} = \beta_{i+k-j} \tag{11}$$

and, then, when $j \geq n - 1$, formula (11) is also true. Thus, by formula (9) and formula (11), we can obtain the following.

$$\overline{p}_{j+k} = \sum_{i=0}^{\infty} \overline{p}_i p_{i,j+k} = \sum_{i=0}^{\infty} \overline{p}_i \beta_{i-j} \tag{12}$$

Let

$$\begin{gathered} \overline{p}_j = C_1 \alpha^j, \\ \overline{p}_{j+k} = C_1 \alpha^{j+1} \\ \left(j \geq n - 1,\ \alpha < 1\right) \end{gathered} \tag{13}$$

where α is a supplementary variable and C_1 is a constant. Formula (13) is substituted into formula (12); then, we can obtain

$$\alpha = G^*\left(n\mu' - n\mu'\alpha\right) \tag{14}$$

where $G^*(x) = \mathscr{L}[g(t)]$, namely, the Laplace transformation of $g(t)$. Formula (14) has a unique solution in the unit circle; that is, there is $0 < \alpha < 1$. Therefore, the stationary solution is

$$\begin{aligned} \overline{\mathbf{P}} &= \left(\overline{p}_0, \overline{p}_1, \ldots, \overline{p}_{n-2}, C_1\alpha^{n-1}, C_1\alpha^n, \ldots\right) \\ &= C\left(\gamma_0, \gamma_1, \ldots, \gamma_{n-2}, 1, \alpha, \alpha^2, \ldots\right) \end{aligned} \tag{15}$$

where $C = C_1 \alpha^{n-1}$.

Then, $g(t) = \lambda k e^{-\lambda k t}$ is substituted into formula (14); hence, $\alpha = \lambda k / n\mu'$ is gained. When the system is stable, $\lambda k / n\mu' < 1$.

The average waiting queue length formula in *seru* production is

$$\begin{aligned} L_q(C) &= \sum_{j=n}^{\infty} (j - n)\, \overline{p}_j = \sum_{j=n}^{\infty} (j - n)\, C\alpha^{j-n+1} \\ &= \frac{C\lambda^2 k^2}{\left(n\mu' - \lambda k\right)^2} \end{aligned} \tag{16}$$

where C is obtained by formula (15) and $0 < C < 1$.

4. Numerical Analysis of Conversion Scenarios

To save costs, the line-*seru* conversion may be accompanied by downsizing and reducing the number of workstations. In *seru* production system containing several *yatais*, there is a one-to-one correspondence between cross-trained workers and *serus*. Let l represent the number of workers downsized. The number of cross-trained workers and the number of *serus* are $(m - l)$: $m > l$ and $l \geq 0$. Thus n in $L_q(C)$ can be replaced by $(m - l)$. As the cross-trained workers perform all the operations of a product, they usually reintegrate manufacturing processes, which may reduce certain non-value-added operations. Let s represent the reduced number of operations. A product may only take $(m - s)$ operations, and $m > s$; $s \geq 0$. In general, s will be very small, but it may increase with the increase of m in some cases. Because the cross-trained worker is no longer specialized in a single operation, his efficiency may be lower than that of specialized workers in the conveyor assembly line [29]. Let ε, where $0 < \varepsilon \leq 1$, denote the relative efficiency of the cross-trained worker as compared with that of the specialized worker. This means that the processing time of each operation for a product in *seru* production follows an exponential distribution with a mean of $1/\varepsilon\mu$. Hence, the average processing time for a product is $(m - s)/\varepsilon\mu$, and the service rate is $\varepsilon\mu/(m - s)$, which can replace μ' in $L_q(C)$. Therefore, the average waiting queue length changed by the line-*seru* conversion is

$$\Delta L_q = L_q(A) - L_q(C) = \frac{\rho(k+1)}{2(1-\rho)} - m\rho - \frac{C\rho^2(m-s)^2}{\left[\varepsilon(m-l) - (m-s)\rho\right]^2} \tag{17}$$

where $\rho = \lambda k/\mu$ is the system utilization rate of the conveyor assembly line. To avoid confusion, the term "system utilization rate" will be used consistently in this paper to denote "the system utilization rate of the conveyor assembly line".

In the multivariety and small-batch production environment, the conveyor assembly line has to reconfigure equipment and personnel frequently, so the system utilization rate is necessarily low. We mainly focus on the effect of the line-*seru* conversion on the average waiting queue length with respect to a low system utilization rate. Based on a practical line-*seru* conversion under different conversion scenarios, the input parameters in (17) are determined to obtain meaningful management insights. Specifically, to generate different scenarios, three factors are considered, namely, downsizing, the reduced number of operations, and worker efficiency. With two possibilities for each factor, a total of eight scenarios are generated. To clarify the relative performance of *seru* production, two scenarios will be analyzed: (1) the simplest scenario, where there is no reduction in operations and no downsizing, and the efficiency of cross-trained workers is equal to that of specialized workers, and (2) the most general scenario, where there is a reduction in operations, downsizing, and less efficient cross-trained workers. Then, the mean of the batch size and the number of workstations are selected to analyze the sensitivity of the average waiting queue length changed by the line-*seru* conversion in these two scenarios. Finally, the production conditions of the line-*seru* conversion are obtained.

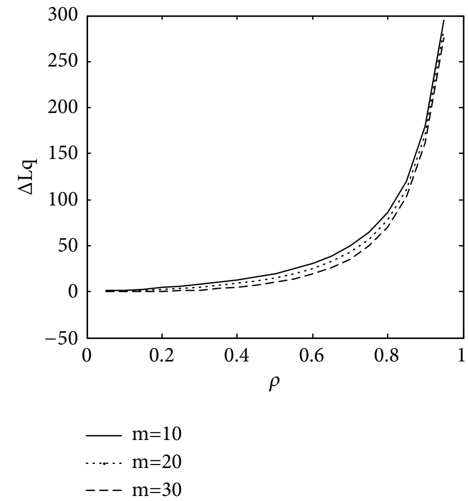


Figure 3: The average waiting queue length changed by the line-cell conversion, under different number of workstations in Scenario 1.

Scenario 1. When the conveyor assembly line is dismantled into *seru* production, there is no downsizing and no reduction in operation. Additionally, we assume that the cross-trained workers in *seru* production and the specialized workers in the conveyor assembly line have the same efficiency. By substituting $s = l = 0$, $\varepsilon = 1$ into (17), we can find the following.

$$\Delta L_q = L_q(A) - L_q(C) = \frac{\rho(k+1)(1-\rho) - 2C\rho^2}{2(1-\rho)^2} - m\rho \tag{18}$$

Because $0 < C < 1$, $0 < 2C < 2$. When $(k+1) \gg 2$, the value of C does not affect the sign of ΔL_q. For the convenience of calculation, let $C = 0.5$; therefore, ΔL_q can be simplified.

$$\Delta L_q = \frac{\rho(k+1)(1-\rho) - \rho^2}{2(1-\rho)^2} - m\rho \tag{19}$$

Figure 3 illustrates the effect of the change in the number of workstations on the average waiting queue length changed by the line-*seru* conversion in Scenario 1. On the assumption that the mean of the batch size $k = 50$, the line-*seru* conversion reduces the average waiting queue length, and the reduced queue length increases with the decrease of the number of workstations and with the increase of the system utilization rate. This shows that when the mean of the batch size is greater than the number of workstations, the line-*seru* conversion should be implemented under Scenario 1. For the conveyor assembly line, if the number of workstations increases, the waiting queues will naturally reduce. Since the utilization rate of these two system is the same in Scenario 1, the standard deviation of the total processing time performed

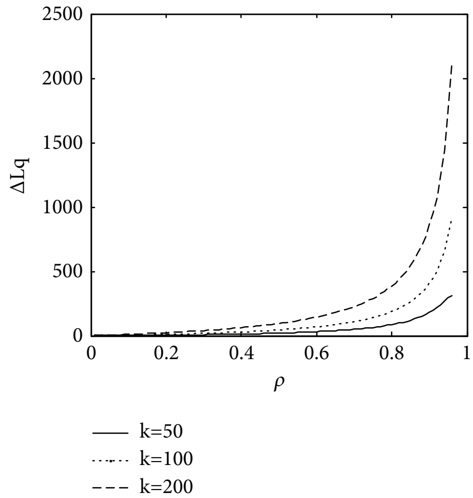


FIGURE 4: The average waiting queue length changed by the line-cell conversion, under different batch size means in Scenario 1.

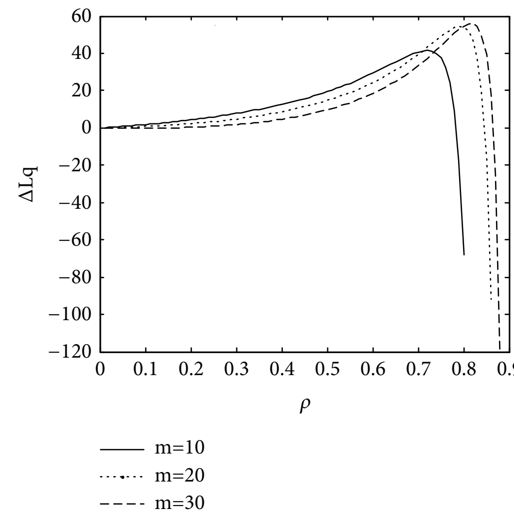


FIGURE 5: The average waiting queue length changed by the line-cell conversion, under different number of workstations in Scenario 2 (downsizing and the reduced operations are fixed).

by one cross-trained worker in *seru* production will be less than the sum of the standard deviations of the processing times of all workstations in the conveyor assembly line. The above conclusions are summarized as follows.

Corollary 3. *For Scenario 1, when the mean of the batch size is greater than the number of workstations in the conveyor assembly line, and the conveyor assembly line has at least two workstations (production operations)* ($m \geq 2$)*, the line-seru conversion will reduce the average waiting queue length* ($\Delta L_q > 0$)*, and the reduced queue length will increase with the decrease of the number of workstations m and with the increase of the system utilization rate* ρ *(*ΔL_q *is inversely related to m and is positively related to* ρ*).*

Corollary 4. *For a modified Scenario 1, when the number of staff downsized is equal to the reduced number of operations (i.e.,* $s = l \geq 1$*) and other parameters remain unchanged, the conclusion of the Corollary 3 can also be drawn.*

Figure 4 illustrates the effect of the change in the mean of the batch size on the average waiting queue length changed by the line-*seru* conversion in Scenario 1. On the assumption that $m = 10$ represents the number of workstations in the conveyor assembly line, when the mean of the batch size is greater than the number of workstations in the conveyor assembly line, the line-*seru* conversion will reduce the average waiting queue length, and the reduced queue length will increase with the increase of the mean of the batch size and the system utilization rate. This is because the system utilization rate of *seru* production is the same as that of the conveyor assembly line in Scenario 1. Even if the mean of the batch size is large, the efficiency of *seru* production is higher than that of the conveyor assembly line. Hence, the conveyor assembly line should be converted to *seru* production in Scenario 1. These conclusions are further summarized as follows.

Corollary 5. *For Scenario 1, when the mean of the batch size is greater than the number of workstations and the conveyor assembly line has at least two workstations* ($m \geq 2$)*, the line-seru conversion will reduce the average waiting queue length* ($\Delta L_q > 0$)*, and the reduced queue length will increase with an increase of the mean of the batch size k and with an increase of the system utilization rate* ρ *(i.e.,* ΔL_q *is positively related to k and* ρ*).*

Corollary 6. *For a modified Scenario 1, when the number of staff downsized is equal to the reduced number of operations (i.e.,* $s = l \geq 1$*) and other parameters remain unchanged, the conclusion of the Corollary 5 can also be drawn.*

Scenario 2. When the conveyor assembly line is dismantled into *seru* production, the factory implements downsizing and cross-trains relatively inefficient workers. Meanwhile, the cross-trained workers reintegrate manufacturing processes to reduce operations.

This most general scenario is downsizing in the process of conversion, which makes the number of *serus* less than that of workstations in the conveyor assembly line. According to the practical situation, the number of workers downsized and the reduced number of operations can be roughly divided into two cases: (1) they are fixed and do not change with the number of workstations (operations); (2) they increase with the increase of the number of workstations. For Scenario 2, these two systems do not have the same number of staff, the same number of service windows, and the same service rate; thus, they do not have the same system utilization rates, and the system utilization rate of *seru* production is $((m-s)/\varepsilon(m-l))\rho < 1$, which leads to the system utilization rate of the conveyor assembly line, $\rho < \varepsilon(m-l)/(m-s)$.

Based on (17), Figures 5, 6, 7, and 8 illustrate how the average waiting queue length changed from the line-*seru* conversion is affected by the change in the number of workstations, which, under Scenario 2, is related to the number of staff downsized and the reduced number of operations.

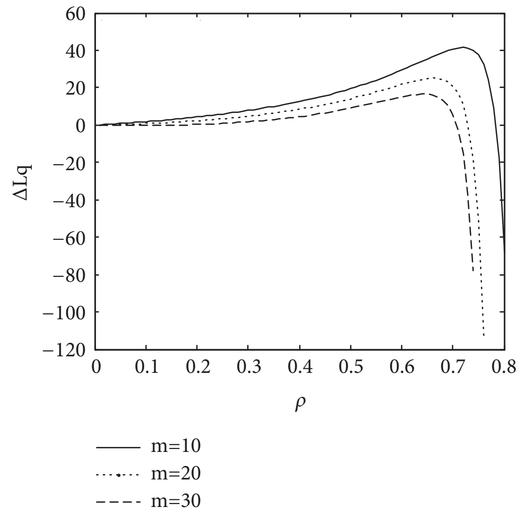


Figure 6: The average waiting queue length changed by the line-cell conversion, under different number of workstations in Scenario 2 (the reduced operations are fixed but downsizing is changed).

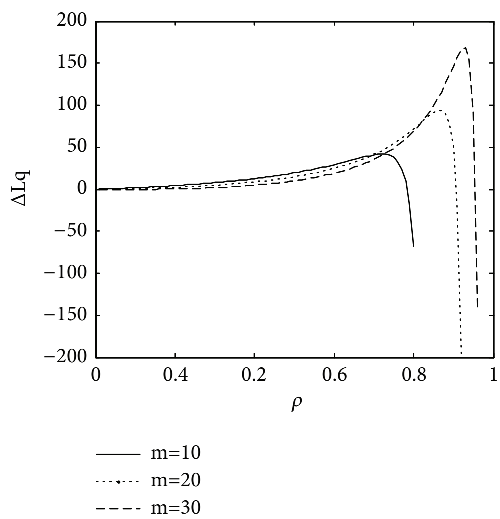


Figure 7: The average waiting queue length changed by the line-cell conversion, under a different number of workstations in Scenario 2 (downsizing is fixed but the reduced operations are changed).

Figure 5 shows that the number of staff downsized and the reduced number of operations are fixed, $l = 2, s = 1$. Figure 6 shows that the reduced number of operations is fixed, $s = 1$, but the number of staff downsized increases with the increase in the number of workstations as follows: when $m = 10, l = 2$; when $m = 20, l = 4$; and when $m = 30, l = 6$. Figure 7 shows that the number of staff downsized is fixed, $l = 2$, but the reduced number of operations increases with the increase in the number of workstations as follows: when $m = 10$, $s = 1$; when $m = 20$, $s = 2$; and when $m = 30$, $s = 3$. Figure 8 shows that the number of staff downsized and the reduced number of operations increase with the increase of the number of workstations as follows: when $m = 10, l = 2, s = 1$; when $m = 20, l = 4, s = 2$; and when $m = 30, l = 6, s = 3$.

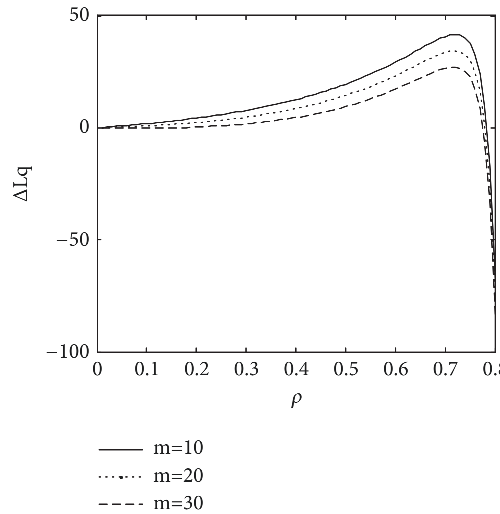


Figure 8: The average waiting queue length changed by the line-cell conversion, under a different number of workstations in Scenario 2 (downsizing and the reduced operations are changed).

Under the condition in which the mean of the batch size $k = 50$ and the relative efficiency of the cross-trained worker $\varepsilon = 0.95$, the average waiting queue length changed by the line-*seru* conversion in these four cases is first reduced and then increased with the increase of the system utilization rate. This shows that when the system utilization rate is not high, the line-*seru* conversion should be implemented. Meanwhile, when the system utilization rate is less than a certain value, the reduction of the average waiting queue length increases gradually with the decrease of the number of workstations. This differences among the four cases are as follows: in Figures 5 and 7, as the system utilization rate increases, the curve with the minimum number of workstations firstly begins to decline and turns until it extends below 0; in Figure 6, as the system utilization rate increases, the curve with the maximum number of workstations firstly begins to decline and turns until it extends below 0; in Figure 8, as the system utilization rate increases, the three curves simultaneously begin to decline until reaching below 0.

Corollary 7. *For Scenario 2, when the mean of the batch size is greater than the number of workstations in the conveyor assembly line and $m \geq 2$, the average waiting queue length changed by the line-seru conversion is first reduced and then increased with the increase of the system utilization rate ρ. When the system utilization rate is less than a certain value, the reduction of the average waiting queue length increases gradually with the decrease of the number of workstations m. This shows that when the system utilization rate is not high, the line-seru conversion should be implemented ($\Delta L_q > 0$), and ΔL_q is inversely related to m.*

On the basis of (17), Figure 9 illustrates the effect of the change in the mean of batch size on the average waiting queue length changed by the line-*seru* conversion in Scenario 2. On the assumption that $m = 10, l = 2, s = 1, \varepsilon = 0.95$, with the increase of the system utilization rate, the line-*seru*

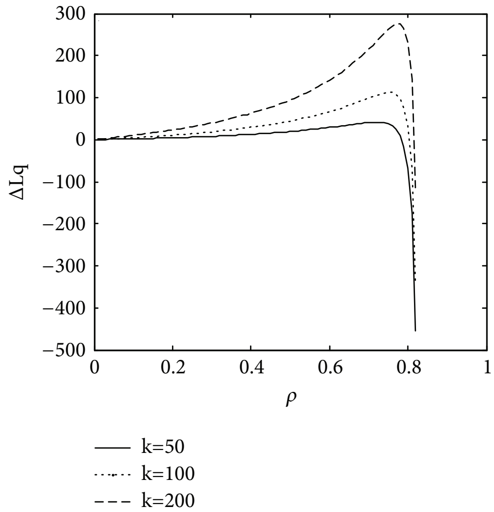


FIGURE 9: The average waiting queue length changed by the line-cell conversion, under different batch size means in Scenario 2.

conversion first reduces the average waiting queue length until the reduction reaches the highest value, and then the reduction begins to decrease gradually until it is less than 0. Meanwhile, when the system utilization rate is less than a certain value, the reduction of the average waiting queue length increases gradually with the increase of the mean of the batch size.

Corollary 8. *For Scenario 2, when the mean of the batch size is greater than the number of workstations in the conveyor assembly line and $m \geq 2$, the average waiting queue length changed by the line-seru conversion is first reduced and then increased with the increase of the system utilization rate ρ. When the system utilization rate is less than a certain value, the reduction of the average waiting queue length increases gradually with the increase of the mean of the batch size k. This shows that when the system utilization rate is not high, the line-seru conversion should be implemented ($\Delta L_q > 0$), and ΔL_q is positively related to k.*

From Figures 5–9, depending on the values of parameters m, s, l, k, and ρ, the line-*seru* conversion may reduce, increase, or not change the average waiting queue length. According to formula (17), this relationship can be captured in the form of an equation to answer when to use (or not to use) *seru* production or the conveyor assembly line. The relationship is stated as the following corollary.

Corollary 9. *For Scenario 2, when*

$$\begin{gathered}\frac{k+1}{2(1-\rho)} - m - \frac{\rho(m-s)^2}{2\left[\varepsilon(m-l)-(m-s)\rho\right]^2} > 0 \\ 0 < \frac{m-s}{\varepsilon(m-l)}\rho < 1\end{gathered} \tag{20}$$

the line-seru conversion will reduce the average waiting queue length. Since the number of staff downsized and the reduced number of operations in Figures 6–8 are related to the number of workstations, it is impossible to perform the "break-even" analysis of the number of workstations and the system utilization rate. Therefore, we only give the results of this "break-even" analysis for Figures 5 and 9 in Scenario 2, as follows.

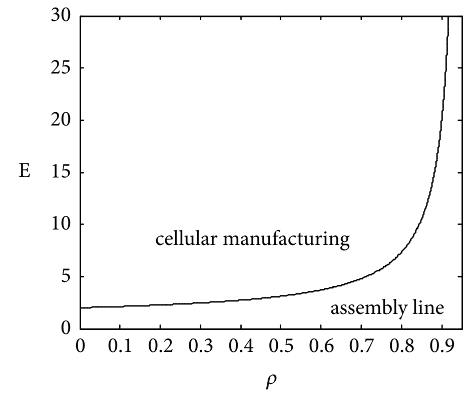


FIGURE 10: Decision diagram for choosing the system, under different number of workstations and system utilization rate in Scenario 2.

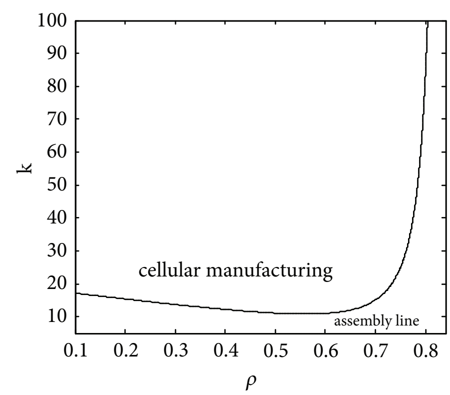


FIGURE 11: Decision diagram for choosing the system, under different batch size means and system utilization rates in Scenario 2.

(1) Given the parameters $k = 50$, $s = 1$, $l = 2$, $\varepsilon = 0.95$ for (20), the break-even relationship between the number of workstations m and the system utilization rate ρ is considered, as shown in Figure 10. As seen from Figure 10, the break-even curve divides the space into two regions, where one is suitable for *seru* production (due to a shorter queue length) and the other is suitable for the conveyor assembly line. Break-even curves drawn for alternate values of k, l, s, ε show a pattern similar to that of Figure 10. These break-even curves indicate that when the system utilization rate is not high and the number of workstations is larger than a certain value, the line-*seru* conversion should be implemented.

(2) Given the parameters $m = 10$, $s = 1$, $l = 2$, $\varepsilon = 0.95$ for (20), the break-even relationship between the mean of batch size k and the system utilization rate ρ is considered, as shown in Figure 11. The break-even curve also divides the space into two regions, which correspond to *seru* production and the conveyor assembly line. Break-even curves drawn for alternate values of m, s, l, ε show a pattern similar to that of Figure 11. These break-even curves indicate that when the

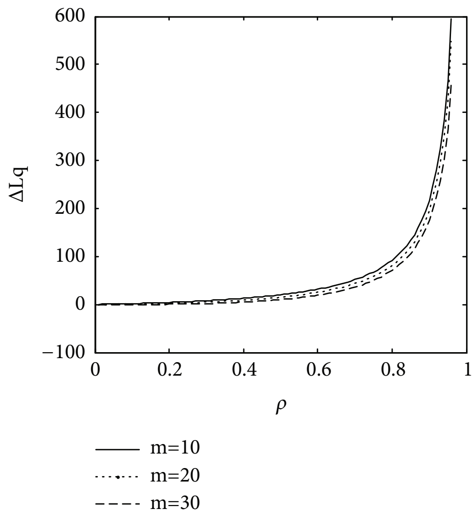


Figure 12: The average waiting queue length changed by the line-cell conversion under different number of workstations in Scenario 2 ($s = 3, l = 1$).

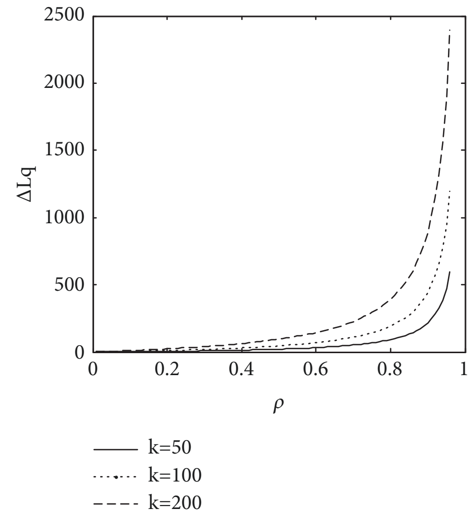


Figure 13: The average waiting queue length changed by the line-cell conversion under different batch size means in Scenario 2 ($s = 3, l = 1$).

system utilization rate is not high and the mean of batch size is larger than a certain value, the line-*seru* conversion should be implemented.

Figures 10 and 11 have important practical implications, and it can help managers to decide whether or not the conveyor assembly line should be converted into *seru* production from the perspective of the waiting queue length. For example, for a batch arrival Poisson flow with a mean of 60, when the system utilization rate of the conveyor assembly line with 20 workstations reaches 0.6, should it be converted into *seru* production? In the conversion process, the number of staff downsized is 2 and the reduced number of operations is 1. The line-*seru* conversion can also reduce the average waiting queue length, even if the efficiency of the cross-trained workers is only 90% of that of the conveyor assembly line worker ($\varepsilon = 0.90$). Therefore, the conveyor assembly line should be converted into *seru* production in this case.

For Scenario 2, the system utilization rate of *seru* production is $((m - s)/\varepsilon(m - l))\rho$. According to the parameters of five examples mentioned above, it is found that the system utilization rate of the conveyor assembly line for these five examples is less than that of *seru* production. Next, for Scenario 2, we reset the parameters so that the system utilization rate of the conveyor assembly line is greater than that of *seru* production, and then analyze the effect of the line-*seru* conversion under this condition on the average waiting queue length.

First, on the assumption of $k = 50$, $\varepsilon = 0.95$, we analyze the effect of the number of workstations on the average waiting queue length changed by the line-*seru* conversion based on formula (17). Figure 12 describes the impact situation that the number of staff downsized and the reduced number of operations are fixed, where $l = 1, s = 3$. For the example of the number of workstations related to the number of staff downsized and the reduced number of operations, numerical analysis shows that the effect of the number of workstations on the average waiting queue length is similar to that of Figure 12, so there is no need to enumerate the results one by one. From Figure 12, we find that for Scenario 2, where the system utilization rate of the conveyor assembly line is greater than that of *seru* production, the line-*seru* conversion will reduce the average waiting length, and the reduction will gradually increase with the increase of the system utilization rate and the decrease of the number of workstations.

Second, on the assumption of $m = 10$, $l = 2$, $s = 1$, $\varepsilon = 0.95$, we analyze the effect of the mean of batch size on the average waiting queue length changed by the line-*seru* conversion based on formula (17), and Figure 13 describes the specific situation. From Figure 13, we find that for Scenario 2, where the system utilization rate of the conveyor assembly line is greater than that of *seru* production, the line-*seru* conversion will reduce the average waiting length, and the reduction will gradually increase with the increase of the system utilization rate and the mean of batch size. These conclusions are further summarized in Corollary 10.

Corollary 10. *For Scenario 2, where the system utilization rate of the conveyor assembly line is greater than that of seru production, the line-seru conversion will reduce the average waiting length ($\Delta L_q > 0$), and the reduced queue length will increase with an increase of the mean of the batch size k, an increase of the system utilization rate ρ, and a decrease of the number of workstations m (i.e., ΔL_q is positively related to k and ρ and is inversely related to m).*

From the perspective of the waiting time performance, this paper mainly analyzes the effect of the line-*seru* conversion under the two scenarios on the average waiting queue length. By setting the appropriate parameters in (17), the average waiting queue length changed by the line-*seru* conversion for other potential scenarios can also be obtained, and the resultant formulas are shown in Table 1.

Table 1: The formulas of average waiting queue length changed by the line-cell conversion under each scenario.

$l = 0$		$l > 0$		
$\varepsilon = 1$	$\varepsilon < 1$	$\varepsilon = 1$	$\varepsilon < 1$	
$\dfrac{\rho(k+1)(1-\rho)-\rho^2}{2(1-\rho)^2} - m\rho$	$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2 m^2}{2(\varepsilon m - m\rho)^2}$	$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2 m^2}{2(m-l-m\rho)^2}$	$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2 m^2}{2[\varepsilon(m-l)-m\rho]^2}$	$s = 0$
$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2(m-s)^2}{2[m-(m-s)\rho]^2}$	$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2(m-s)^2}{2[\varepsilon m-(m-s)\rho]^2}$	$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2(m-s)^2}{2[(m-l)-(m-s)\rho]^2}$	$\dfrac{\rho(k+1)}{2(1-\rho)} - m\rho - \dfrac{\rho^2(m-s)^2}{2[\varepsilon(m-l)-(m-s)\rho]^2}$	$s > 0$

5. Conclusions

In multivariety and small-batch production, the efficiency of the conveyor assembly line could not be fully realized. Therefore, the factory began to experiment with the reform of the production organization form and eventually found that the line-*seru* conversion can be adapted to such a production environment. Later, scholars studied the various issues in the line-*seru* conversion from different degrees, and most of the research results analyzed the advantages of line-*seru* conversion from the perspective of the enterprises themselves. However, this paper analyzes the effect of the line-*seru* conversion on waiting time from the perspective of the customer.

First, the average waiting queue length changed by the line-*seru* conversion is used as the evaluation index. Second, queuing theory is used to establish the average waiting queue length formulas with random batch arrivals of the conveyor assembly line and *seru* production. Then, under two typical scenarios, we explore the relationship between the average waiting queue length changed by the line-*seru* conversion and other parameters, such as the mean of the batch size, the number of workstations, and the system utilization rate. In summary, the line-*seru* conversion should be implemented in most cases; only when the system utilization rate of the conveyor assembly line is less than that of *seru* production and the system utilization rate is high, the conveyor assembly line should be continued. In the multivariety and small-batch production environment, the system utilization rate of the conveyor assembly line is not less than that of *seru* production, so the line-*seru* conversion should be implemented. Finally, we also present the formulas of the average waiting queue length changed by the line-*seru* conversion under the other potential six scenarios.

In the process of formulation establishment, the service time is assumed to follow a negative exponential distribution according to the actual condition, but there is no hypothesis test. Meanwhile, we believe that the arriving products are processed in the first-in-first-out manner. In fact, however, the service manner may be many forms or even mixed. Therefore, for further research, the average waiting queue length formula can be constructed more realistically. At the same time, there remain several important yet unanswered questions, such as the following: (1) Is the construction cost of *seru* production higher or lower than that of a conveyor assembly line? (2) Although some studies have shown that the line-*seru* conversion will save space cost, as the organizational change of conversion process still requires a certain amount of investment, will a line-*seru* conversion reduce or increase manufacturing costs? (3) Will the labor costs be higher (due to a higher levels of required skills) or lower (because of downsizing and reducing related costs)?

Data Availability

The parameters required in the numerical analysis are assumed according to the actual scenarios of the line-cell conversion. In each scenario, the specific parameters are given, and there is no other unpublished data.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

We sincerely thank Dr. Jie Lian for her help in paper writing. We also acknowledge the support of the National Natural Science Foundation of China (Grant: 71171161, 71371153).

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