International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tprs20

How to carry out assembly line-cell conversion? A discussion based on factor analysis of system performance improvements

Yang Yu [a], Jun Gong [a], Jiafu Tang [a], Yong Yin [b] & Ikou Kaku [c]

[a] Institute of Systems Engineering, State Key Laboratory of Synthetic Automation for Process Industries, Northeastern University, Shenyang, P.R. China

[b] Yamagata University, Yamagata, Japan and Xi'an University of Technology, Xi'an, Shaanxi Province, P.R. China

[c] Tokyo City University, Yokohama, Japan

Published online: 12 Jul 2012.

To cite this article: Yang Yu, Jun Gong, Jiafu Tang, Yong Yin & Ikou Kaku (2012) How to carry out assembly line-cell conversion? A discussion based on factor analysis of system performance improvements, International Journal of Production Research, 50:18, 5259-5280, DOI: 10.1080/00207543.2012.693642

To link to this article: http://dx.doi.org/10.1080/00207543.2012.693642

International Journal of Production Research
Vol. 50, No. 18, 15 September 2012, 5259–5280

How to carry out assembly line–cell conversion? A discussion based on factor analysis of system performance improvements

Yang Yu[a], Jun Gong[a], Jiafu Tang[a], Yong Yin[b] and Ikou Kaku[c*]

[a]*Institute of Systems Engineering, State Key Laboratory of Synthetic Automation for Process Industries, Northeastern University, Shenyang, P.R. China;* [b]*Yamagata University, Yamagata, Japan and Xi'an University of Technology, Xi'an, Shaanxi Province, P.R. China;* [c]*Tokyo City University, Yokohama, Japan*

(*Received 9 May 2011; final version received 18 April 2012*)

The line–cell (or line–*seru*) conversion is an innovation of assembly systems that has received less attention. Its essence is dismantling an assembly conveyor line and adopting a mini-assembly unit, called *seru* (or cell). In this paper, we discuss how to do such line–cell conversions, especially focusing on assembly cell formation (ACF) and assembly cell loading (ACL). We perform 64 arrays of full factorial experiment analysis that incorporate three factors: work stations, product types, and product lot sizes. We construct a two-objective line–cell conversion model that minimises the total throughput time (TTPT) and the total labour hours (TLH). Three non-dominated solutions obtained from the two-objective model are used to evaluate the performance of the line–cell conversion. By investigating the experimental results of the ACF and the ACL, we summarise several managerial insights that could be used to help successful line–cell conversions.

Keywords: seru; factor analysis; line–cell conversion; assembly cell formation; assembly cell loading; multi-objective optimisation

1. Introduction

The line–cell conversion is an innovation of the assembly system developed in Japan. Its essence is tearing out the traditional assembly conveyor lines and adopting a mini-assembly unit, called *seru*, a Japanese word for cellular organism. A *seru* is an old-fashioned workshop where a craftsperson, including a jack-of-all-trades worker, assembles an entire product from start to finish by her/himself. This compact assembly organisation is similar to assembly cells, a widely adopted assembly system in Western industries. A detailed introduction of the *seru* system and its managerial mechanism can be found in Yin *et al*. (2008) and Stecke *et al*. (2012). There are three *seru* types: divisional *seru*, rotating *seru*, and *yatai*. A divisional *seru* is a short line staffed with several partially cross-trained workers. Tasks within a divisional *seru* are divided into different sections. Each section is operated by one or more workers. On the other hand, workers within rotating *serus* and *yatais* are completely cross-trained. A rotating *seru* is often organised in a U-shaped layout with several workers. Each worker assembles an entire product from start to finish without disruption. The assembly tasks are performed on fixed stations, so workers walk from station to station. A *yatai* is a single worker *seru*, the smallest production organisation. So a *yatai* owner does all operational and managerial tasks by her/himself. For example, a Canon S-class (the highest class in Canon's skill hierarchy) worker can assemble a complicated multi-functional peripheral of 2700 components in just two hours, or a luxury camera of 940 components in only four hours (Kimura and Yoshita 2004, Stecke *et al*. 2012). Canon, NEC and Sony are big Japanese companies leading to Japanese electronic industry. A NEC completely cross-trained worker can assemble a word processor of 120 components in 18 minutes (Shinohara 1995, Yamada and Kataoka 2001, Stecke *et al*. 2012). In this paper, we only analyse rotating *serus* and *yatais*, and leave the analysis of divisional *serus* as a future research topic.

A *seru* production system, which integrates lean and agile production paradigms (Yin *et al*. 2012), has many benefits. According to the literature (Takeuchi 2006, Stecke *et al*. 2012), it can reduce throughput time, setup time, required labour hours, work in process inventories, finished product inventories, cost, and shop floor space. This paper analyses two *seru* performances: reductions in throughput time and required labour hours. Some amazing

*Corresponding author. Email: kakuikou@tcu.ac.jp

ISSN 0020–7543 print/ISSN 1366–588X online

http://dx.doi.org/10.1080/00207543.2012.693642
http://www.tandfonline.com

cases related to these two *seru* performances are that the throughput time was reduced by 53% at Sony Kohda; and 35,976 required workers, equal to 25% of Canon's previous total workforce, have been saved (Yin *et al.* 2012).

Seru has also been adopted in the US (Williams 1994), Europe and Korea (Yin 2006), China (Cao 2008), and other countries (Yin *et al.* 2011). One substantial difference between a *seru* and an assembly cell is that equipment such as machines are less important for a *seru*. Most assembly tasks within a *seru* are manual so need only simple and cheap equipment, such as hand tools and workbenches. Duplicating this kind of equipment for multiple *serus* is usually not costly. Owing to its differences from an assembly cell, Western journalists have named it the "neo-craft workshop" (Williams 1994), and Western researchers have called it "a specific application of assembly cells" (Sengupta and Jacobs 2004). In China and Korea, researchers used "Japanese assembly cell" to distinguish it from traditional assembly cells (Yin 2006, Liu *et al.* 2010). Despite of these differences, a *seru* is very similar to an assembly cell. To be consistent with previous research (Kaku *et al.* 2009), we use "assembly cell" in this paper to represent the *seru* and call the conversion from assembly lines to *serus* "line–cell conversion".

The purpose of the line–cell conversion is to increase the productivity and competitive advantages. After dismantling an assembly line, managers need to decide how many cells are to be formed and how to assign workers and product batches to the appropriate cells. The improved performance of assembly system should also be evaluated. These decision problems were defined as line–cell conversion problems by the previous studies (Kaku *et al.* 2008a, 2008b, 2009).

Several papers have analysed cell performance by using operational factors. By analysing empirical data with a simulation model, Johnson (2005) investigated the influences of several operational factors in the line–cell conversion. He also reviewed cellular manufacturing and line–cell conversion literature, and summarised that the loss of worker specialisation could increase operational time. The conversion performance improvement was strongly dependent on the degree of reducing this increased operational time. Several researchers reported the advantages and disadvantages of the line–cell conversion (Tsuru 1998, Isa and Tsuru 1999, Sakazume 2005, Miyake 2006). Other studies and empirical cases presented the performance improvement from the line–cell conversion (for example, Burbidge 1989, Levin 1994, Feare 1995, Bukchin *et al.* 1997, Johnson 2005). However, these previous simulations or empirical studies cannot analyse in depth the line–cell conversion problems. An analytical model is required to analyse the line–cell conversion problem. Unfortunately, analytical research on line–cell conversion is relatively scarce. To the best of our knowledge, the only analytical model to date has been developed by Kaku *et al.* (2009).

By using a multi-objective mathematical model, Kaku *et al.* (2009) investigated several operational factors. Applying a multi-objective model is reasonable, because managers have to evaluate multiple operational factors. However, there are two things lacking in Kaku *et al.*'s research. First, an enumeration for a single-objective, but not non-dominated method was used to analyse Kaku *et al.*'s multi-objective model. Second, it is important to identify how an operational factor influences each objective. Unfortunately, the numerical results of Kaku *et al.* (2009) could only show partial behaviours of various operational factors, and could not reveal relationships among these factors. The reason is that when a factor was changing, their method fixed other factors.

To overcome the first shortcoming, we have clarified the mathematical insights of line–cell conversion problem in the paper (Yu *et al.* 2011). Kaku *et al.* (2009) considered three different assembly systems: a pure cell system, a pure assembly line, and a hybrid system that consists of several cells and an assembly line. Without loss of generality, we simplified their model into a simple case in which an assembly conveyer line is converted into a pure cell system.

Then we solved a two-objective optimisation problem that minimises the total throughput time (TTPT) and the total labour hours (TLH), by using a non-dominated sorting genetic algorithm. We also applied several numerical examples to illustrate the usefulness of our approach. The main outcomes of Yu *et al.* (2011) will be summarised in the next two sections.

Based on the framework of Kaku *et al.* (2009) and the results of our previous research (Yu *et al.* 2011), this paper tries to resolve the second shortcoming described above. We develop a 64-array experiment to investigate which operational factors may influence the performance improvements in the line–cell conversion. Three factors, that is to say product type, batch size, and the number of stations, are used to evaluate the line–cell conversion. Each factor has four levels. We also statistically investigate the relationships among these factors. All experimental data of factors is from the non-dominated solutions of the multi-objective line–cell conversion problem. When line–cell conversion is considered as a multi-objective optimisation problem, there may be many Pareto-optimal (non-dominated) solutions. It is meaningless to use all of the solutions for doing such investigations, so we propose three non-dominated solutions. The first one has the minimum TTPT, the second one has the minimum TLH, and the

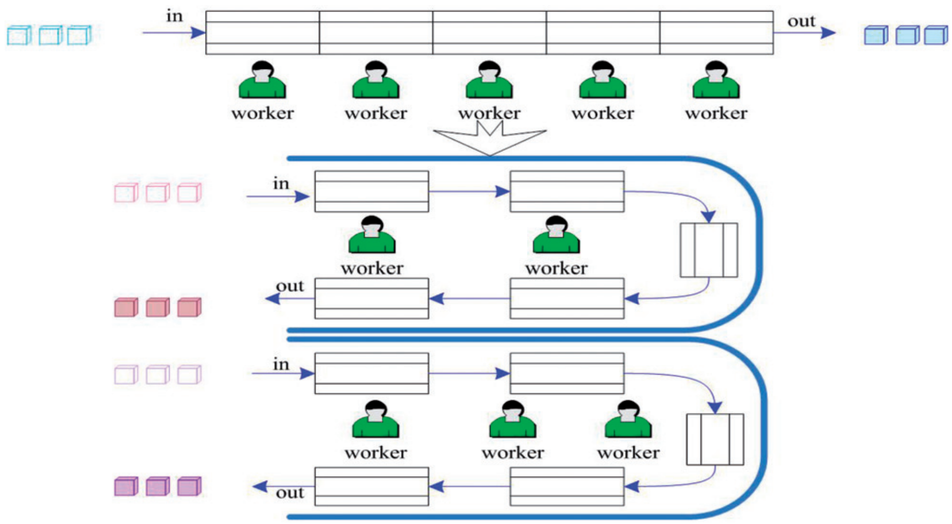

Figure 1. Converting an assembly line to pure cell system (assembly cell formation).

third one has the nearest distance to the average value of all non-dominated solutions. These statistical analyses can measure the influence degree of operational factors to performance improvements. Furthermore, our investigative results are helpful for decision problems: (1) how many cells should be formed; (2) how should workers be assigned to cells; and (3) how should product batches be allocated to cells.

The paper is organised as follows. The modified line–cell conversion model is presented in the second section. The Pareto-optimal front's feature of the multi-objective line–cell conversion model is summarised in the third section. A 64-array full factorial experiment with three factors and four levels is designed and executed in the fourth section, also the results of influence factor analyses are presented. Several insights on how to form cells and load cells are proposed in the fifth section. In the last section conclusions and future research directions are given.

2. Modified model of the line–cell conversion problem

2.1 *Problem description*

In this paper, we consider a case in which a traditional assembly conveyor line is converted to a pure cell system shown in Figure 1. All workers are assigned to cells (we call it "assembly cell formation") according to their assembly skill levels.

Figure 2 shows an assembly cell loading example with six batches and two cells. The length of rectangle charts in Figure 2 is the flow time of a product batch. We adopt a first come first serve (FCFS) principle. An arriving product batch is assigned to the empty cell with the smallest cell number. If all cells are occupied, the product batch is assigned to the cell with the earliest finish time.

As introduced in Section 1, we evaluate two line–cell conversion performances: throughput time and required labour hours, which have been reduced dramatically by *seru* users (for example, 53% throughput time at Sony, 25% required workforce at Canon, respectively). Therefore, our problem is to decide how many cells should be formed, how to assign workers and product batches to appropriate cells to minimise two objectives: the total throughput time and the total labour hours.

2.2 *Assumptions*

(1) The types and batches of products are known in advance. There are N product types that are divided into M product batches. Each batch contains a single product type.

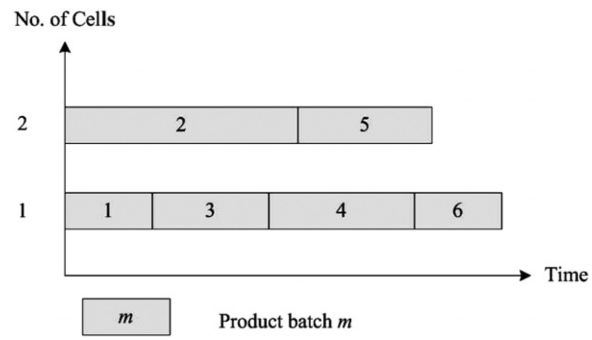

Figure 2. An example of FCFS scheduling rule in cell systems (assembly cell loading).

(2) In the line–cell conversion process, the cost of duplicating equipment is ignored. Because most tasks will be completed by simple and cheap equipment in the converted serus, mulitple equipment may be used in different *serus* but duplicating them is not costly (Stecke *et al*. 2012, Yin *et al*. 2012).
(3) A product batch needs to be assembled entirely within a single cell. In other words, a batch cannot be shared by cells.
(4) All product types have the same assembly tasks (if tasks of products are unique, we assume the task time for these unique tasks is zero so that we can treat the products with different assembly tasks).
(5) The assembly tasks within each cell are the same as the ones within the assembly line.
(6) A worker only performs a single assembly task in the assembly line (a specialist). In contrast, since the cells studied in this paper are rotating *serus* and *yatais*, a cell worker needs to perform all assembly tasks, and assembles the entire product from start to finish (a jack-of-all-trades), and there is no disruption or delay between adjacent tasks.
(7) In the assembly line, each task (or station) is operated by a single worker.
(8) The number of workers within each cell may be different, but no more than the total number of workers.
(9) The setup time is considered when two different product types are assembled consecutively; otherwise the setup time is zero.

2.3 *Notations*

We define the following terms:

Indices

i Index of workers ($i = 1, 2, \ldots, W$).
j Index of cells ($j = 1, 2, \ldots, J$).
n Index of product types ($n = 1, 2, \ldots, N$).
m Index of product batches ($m = 1, 2, \ldots, M$).
k Index of the sequence of product batches in a cell ($k = 1, 2, \ldots, M$).

Parameters

$$V_{mn} = \begin{cases} 1, & \text{if product type of product batch } m \text{ is } n \\ 0, & \text{otherwise} \end{cases}$$

B_m Size of product batch m.
T_n Cycle time of product type n in the assembly line.
SL_n Setup time of product type n in the assembly line.
SCP_n Setup time of product type n in a cell.
η_i Upper bound on the number of tasks for worker i in a cell. If the number of tasks assigned to worker i is more than η_i, worker i's average task time within a cell will be longer than her or his task time within the original assembly line.
C_i Coefficient of variation of worker i's increased task time after the line–cell conversion, that is, from a specialist to a completely cross-trained worker.

ε_i Worker *i's* coefficient of influencing level of doing multiple assembly tasks.
β_{ni} Skill level of worker i for each task of product type n.

Decision variables

$$Xij = \begin{cases} 1, & \text{if worker } i \text{ is assigned to cell } j \\ 0, & \text{otherwise} \end{cases}$$

$$Zmjk = \begin{cases} 1, & \text{if product batch } m \text{ is assigned to cell } j \text{ in sequence } k \\ 0, & \text{otherwise} \end{cases}$$. In addition, if $k = 0$, $Z_{mjk} = 0$.

Variables

SC_m Setup time of product batch m in a cell.
TC_m Assembly task time of product batch m per station in a cell.
FC_m Flow time of product batch m in a cell.
FCB_m Begin time of product batch m in a cell.

2.4 *Problem formulation*

We consider an assembly planning with N product types which are divided into M product batches. W workers are assigned to assembly cells after the line–cell conversion. The batches are assigned to cells with an FCFS principle. We define the total throughput time of the cell system following this FCFS principle.

First, the cross-training process can be represented as a V-shaped learning curve. In other words, in the early period of the line–cell conversion, workers often spend more time on tasks they are not familiar with (Yin *et al.* 2012). So it is reasonable to assume that a worker's skill level varies with the number of tasks assigned to her or him. In this paper, we assume that if the number of worker i's tasks within a cell is over her or his upper bound η_i, that is to say $W > \eta_i$, then the worker will spend more task time than her or his task time within the original assembly line. The details are given in Equation (1).

$$C_i = \begin{cases} 1 + \varepsilon_i(W - \eta_i), & W > \eta_i \\ 1, & W \le \eta_i \end{cases}, \quad \forall i \tag{1}$$

Second, the task time of a product varies with workers' skill levels. Therefore, for a cell, the task time of a product is calculated by average task time of workers in the cell. The task time of product batch m per station in a cell can be represented by the following equation.

$$TC_m = \frac{\sum_{n=1}^{N} \sum_{i=1}^{W} \sum_{j=1}^{J} \sum_{k=1}^{M} V_{mn} T_n \beta_{ni} C_i X_{ij} Z_{mjk}}{\sum_{i=1}^{W} \sum_{j=1}^{J} \sum_{k=1}^{M} X_{ij} Z_{mjk}} \tag{2}$$

Finally, the setup time SC_m, the flow time FC_m and the begin time FCB_m of product batch m are represented as below.

$$SC_m = \sum_{n=1}^{N} SCP_n V_{mn} \left(1 - \sum_{m'=1}^{M} V_{m'n} Z_{m'j(k-1)}\right), (j,k) \big| Z_{mjk} = 1, \quad \forall j, k \tag{3}$$

$$FC_m = \frac{B_m TC_m W}{\sum_{i=1}^{W} \sum_{j=1}^{J} \sum_{k=1}^{M} X_{ij} Z_{mjk}} \tag{4}$$

$$FCB_m = \sum_{s=1}^{m-1} \sum_{j=1}^{J} \sum_{k=1}^{m} (FC_s + SC_s) Z_{mjk} Z_{sj(k-1)} \tag{5}$$

Equation (3) states the setup time of product batch m. The setup time is considered when two different types of products are processed consecutively; otherwise the setup time is zero. This is a real-life consideration. One of the authors visited three companies' (Omron, Yamaha, and Fujitsu) assembly cell factories recently and observed the above case. Equation (4) states the flow time of product batch m within a cell. Equation (5) states the begin time of each product batch. There is no waiting time between two product batches so that the begin time of a product batch is the aggregation of flow time and setup time of all of the previous product batches that are assembled in the same cell.

The multi-objective mathematical model is given in Equations (6)–(12).

Objective functions:

$$TTPT = \text{Min}\left\{\underset{m}{\text{Max}}(FCB_m + FC_m + SC_m)\right\} \tag{6}$$

$$TLH = \text{Min}\sum_{m=1}^{M}\sum_{i=1}^{W}\left(\sum_{j=1}^{J}\sum_{k=1}^{M} FC_m X_{ij} Z_{mjk}\right) \tag{7}$$

Subject to:

$$\sum_{i=1}^{W} X_{ij} \leq W \quad \forall j. \tag{8}$$

$$\sum_{j=1}^{J} X_{ij} \leq 1 \quad \forall i \tag{9}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{M} Z_{mjk} = 1 \quad \forall m \tag{10}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{M} Z_{mjk} = 0 \qquad \left\{ j \,\middle|\, \sum_{i=1}^{W} X_{ij} = 0, \quad \forall j \right\} \tag{11}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{M} Z_{mjk} \leq \sum_{j'=1}^{J}\sum_{k'=1}^{M} Z_{(m-1)j'k'} \quad m = 2, 3, \ldots, M \tag{12}$$

where Equation (6) states the objective to minimise the total throughput time (TTPT) of all product batches. The TTPT is the finish time of the last completed product batch. Equation (7) states the objective to minimise the total labour hours (TLH) of all product batches. The TLH is the cumulative working time of all workers in the cell system. Equation (8) is the number constraint because the number of workers within a cell cannot exceed the total number of available workers (W). Equation (9) is the worker assignment rule, namely, each worker should be assigned to one and only one cell. Equation (10) is the product batch assignment rule, namely, each batch should be assign to one and only one cell. Equation (11) ensures that a product batch cannot be assigned to an empty cell. Equation (12) means that product batches must be assigned sequentially.

Generally speaking, even if we simplify the line–cell conversion model developed by Kaku *et al.* (2009), the resulting problem is still difficult. We show that the line–cell conversion problem is NP-hard.

Theorem 1: *The line–cell conversion problem is NP-hard.*

Proof: The line–cell conversion includes the assembly cell formation (ACF) problem and the assembly cell loading (ACL) problem. The ACF is to partition W workers of an assembly line into pairwise disjoint nonempty cells. We show that the ACF is an exact cover problem, which is NP-complete and is one of Karp's 21 NP-complete problems (Karp 1972).

In mathematics, given collection S of nonempty subsets of a set X, an exact cover of X is a subcollection S^* of S that satisfies the following two conditions: (1) the sets in S^* are pairwise disjoint; and (2) the union of the sets in S^* covers X.

Table 1. The parameters of the experiment.

Factor	Value
Batches	20
η_i	8
ε_i	N(0.01, 0.005)
SL_n	2.2
SCP_n	1.0
T_n	1.8

N(0.01, 0.005): Normal distribution ($\mu = 0.01$, $\sigma = 0.005$)

Let X stand for the set of all workers, so the cardinality of X, $|X| = W$ (the number of workers). Let P stand for an arbitrary solution of the ACF problem, so P is a set whose elements are nonempty cells, i.e., $P = \{x|xX\}$. The cardinality of P, $|P| = 1, 2, \ldots, W$ (the number of cells). We have two cases.

Case 1: $|P| = 1$.

This case means that all workers are assigned to the same cell, that is, $P = X$. In mathematical words, set X is an exact cover of itself.

Case 2: $2 \leq |P| \leq W$.

Suppose $A \in P$, $B \in P$ and $A \neq B$. Then $A \cap B = \emptyset$ (because cells are pairwise disjoint). Let y stand for an arbitrary worker, that is to say, $y \in X$. Since all workers are assigned to cells, we can find a cell $C \in P$ such that $y \in C$. Since y is an arbitrary worker, obviously we can get $^*P = \{y|\exists C(C \in P \wedge y \in C\} = X$, which means that υP covers all of X. Both A and B are arbitrary cells of P, they are non-overlapping and non-empty, and υP covers all of X, we can conclude that P is an exact cover of X.

Take Cases 1 and 2 together, we can conclude that P is an exact cover of X. Since P is an arbitrary solution of the ACF, this means that the ACF is an exact cover problem, which is NP-complete (Karp 1972).

Similarly, Yin *et al.* (2011) have proven that even a simple ACL (they use another term: "just-in-time organisation system") problem is NP-hard. Therefore, we can conclude that the line–cell conversion problem that consists of the ACF and ACL problems is NP-hard.

We show the detailed result of the workers partition in an example of the assembly cell formation. Consider an assembly line with three workers labelled as 1, 2, and 3, all the feasible nonempty cells are the following: {1}, {2}, {3}, {1,2}, {1,3}, {2,3}, and {1,2,3}. Then all feasible solutions of the assembly cell formation are following: {{1}, {2}, {3}}(this means three cells are constructed in which Worker 1 is in Cell 1, Worker 2 is in Cell 2, and so on.), {{1,2}, {3}}, {{1,3}, {2}}, {{2,3}, {1}} and {1,2,3}. Obviously, this is an exact cover of X {1, 2, 3}.

Theorem 1 means that the model described in this paper is, in general, computationally intractable. For small-sized problems with no more than eight workers, we used enumeration to obtain the non-dominated solutions (that is to say, exact Pareto-optimal solutions). For large-sized problems, however, there is no efficient algorithm for solving the problem to optimality, unless P = NP. Therefore, it is only natural to seek approximation algorithms that compute near-optimal solutions to the large-sized problems. In another research (Yu *et al.* 2011), we develop an approximation algorithm, that is, a non-dominated sorting genetic algorithm, to obtain the non-dominated solutions.

The purpose of this paper is to compare the performance of an assembly cell system with an assembly line, by using the non-dominated solutions obtained by the algorithms.

3. Pareto-optimal front of the multi-objective line–cell conversion model

3.1 *Data description*

The experimental data are described in Tables 1–5, respectively.

Table 1 shows the parameters of the experiment. Table 2 shows the distribution of coefficient of influencing level of doing multiple assembly tasks for each worker (ε_i) is N(0.01,0.005). The detailed data of ε_i are given in Table 2.

Table 2. Worker's coefficient of influencing level of doing multiple-assembly tasks (ε_i).

Worker	1	2	3	4	5	6	7	8
ε_i	0.012	0.006	0.007	0.009	0.009	0.014	0.022	0.009
Worker	9	10	11	12	13	14	15	16
ε_i	0.005	0.013	0.005	0.012	0.003	0.016	0.013	0.012

Table 3. The mean worker skill level for each task of product type n (β_{ni}).

Product type	1	2	3	4	5	6	7	8
μ	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08
Product type	9	10	11	12	13	14	15	
μ	1.09	1.10	1.11	1.12	1.13	1.14	1.15	

Table 4. Detailed data of each worker's skill level (β_{ni}).

Worker \ Product	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1.09	1.08	0.94	1.01	1.11	1.05	1.09	1.08	1.18	1.05	1.17	1.1	1.09
2	1.05	1.07	1	1.06	1.1	1.06	0.98	1.17	1.05	1.07	1.1	1.16	1.14	1.11	1.15
3	1	1.07	1.04	1.07	1.12	1.04	1.08	1.09	1.14	1.03	1.08	1.14	1.09	1.11	1.1
4	0.96	1.02	1.07	1.1	0.98	1.03	1.07	1.07	1.04	1.05	1.11	1.1	1.15	1.16	1.15
5	1.03	1.03	1.09	1.01	1.05	1.09	1.06	1.06	1.11	1.06	1.03	1.14	1.1	1.2	1.19
6	1	0.91	1.05	0.97	1.09	1.01	1	1.06	1.1	1.16	1.13	1.17	1.14	1.14	1.2
7	0.98	0.98	1	1.05	0.99	1.16	1.12	1.12	1.15	1.14	1.13	1.13	0.99	1.15	1.14
8	1	0.98	1.02	1.06	1.08	1	1.17	1.08	1.08	1.1	1.1	1.14	1.19	1.08	1.17
9	1.06	0.97	1.1	1.09	1.08	1.05	1	1.03	1.01	1.01	1.15	1.14	1.13	1.29	1.15
10	1.05	1.04	0.97	1.08	1	0.98	1.05	1.1	1.17	1.16	1.18	1.14	1.12	1.13	1.07
11	0.96	1.13	0.97	1.01	1.07	1.16	1.08	1	1.16	1.14	1.14	1.16	1.2	1.11	1.23
12	1.06	1.03	1.01	0.99	1.05	1.03	1.06	1.12	1.17	1.14	1.09	1.08	1.13	1.1	1.18
13	0.97	0.99	1.09	0.97	1.07	1.02	1.04	1.11	1.06	1.12	1.08	1.11	1.28	1.24	1.16
14	1.01	1.01	0.99	1.05	1.09	1.1	1.17	1.1	1.05	1.15	1.12	1.1	1.07	1.07	1.24
15	1	1	0.94	1.01	1.06	1.16	1.08	1.07	1.09	1.11	1.1	1.09	1.13	1.12	1.14
16	1.07	1.06	1.04	1.04	1.05	1.11	1.06	1.05	1.03	1.06	1.07	1.08	1.12	1.15	1.11

Table 3 shows that the mean skill level of workers for product type n has a range from 1.01 to 1.15. We fix the standard deviation as 0.05. For example, in the first column $\mu = 1.01$ represents the distribution of skill level of each worker for product type 1 is N ($\mu = 1.01$, $\sigma = 0.05$).

In Table 4, the smaller β_{ni} is, the better the assembly skill of worker i is for product n according to Equation (2).

In Table 5, there are five product types divided into 20 batches, and the mean of each batch's lot size is 50. For example, for the first batch, its product type is 1 and lot size is 43.

For the instance with W workers, five product types, and mean lot sizes 50, we use the following data set from Tables 1–5: the entire Table 1, the first W rows of Table 2, the first five rows of Table 3, the first W rows and the first five columns of Table 4, and the entire Table 5.

3.2 *Pareto-optimal front of the multi-objective line–cell conversion model*

All Pareto-optimal solutions construct Pareto-optimal front. Since an enumeration algorithm is used, non-dominated solutions in Figures 3 and 4 are Pareto-optimal. Figure 3 shows the Pareto-optimal front for the

Table 5. The data of 20 batches with five product types and lot sizes (50).

Batches	Product type	Lot size (B_m)
1	1	43
2	4	57
3	3	47
4	5	43
5	3	39
6	2	49
7	3	37
8	1	49
9	4	57
10	5	46
11	1	63
12	5	57
13	2	55
14	3	52
15	5	53
16	3	52
17	2	43
18	4	55
19	2	52
20	1	55

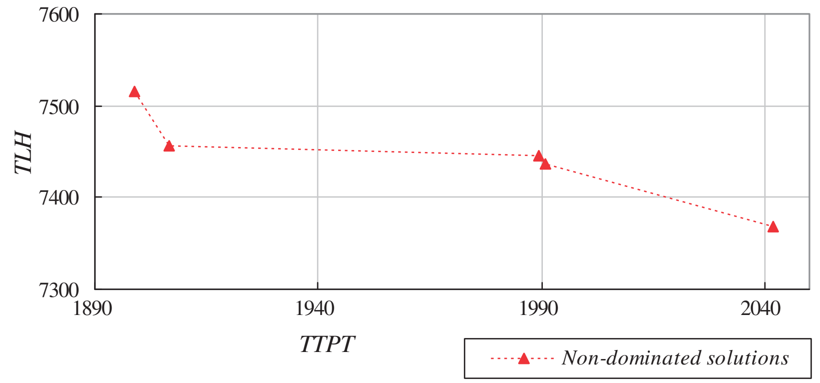

Figure 3. Pareto–optimal front for the example with four workers, five product types, and lot sizes (50).

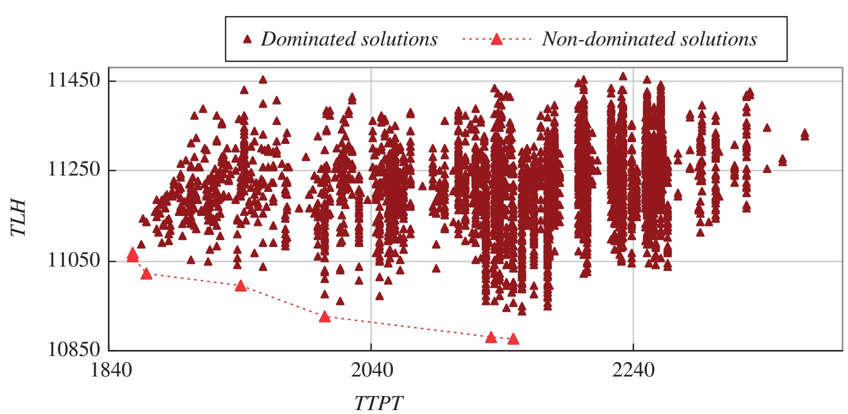

Figure 4. Pareto–optimal front for the example with six workers, five product types and lot sizes (50).

example with four workers, four product types and lot sizes (50). Figure 4 shows the Pareto-optimal front and their dominated solutions for the example with six workers, five product types and lot sizes (50).

From the graphs of non-dominated solutions in Figure 3 and Figure 4, it is easy to prove that the Pareto-optimal front of the multi-objective line–cell conversion is non-convex (for example, in Figure 3, the line connecting points #2 and #5 is located below points #3 and #4), so we cannot convert multiple objectives into a single objective by the weighted sum of objectives (Goicoechea *et al.* 1982) to analyse the influencing factor of the line–cell conversion. Moreover, 5 and 7 non-dominated solutions in Figure 3 and Figure 4 respectively mean the number of non-dominated solutions in different instances is not constant, so we cannot use all non-dominated solutions to analyse the influencing factor. Fortunately, there are always three non-dominated solutions in any instance. We discuss them in the following section.

3.3 *Three non-dominated solutions*

Definition 1: *mTTPT* is the non-dominated solution with the minimum TTPT.

Definition 2: *mTLH* is the non-dominated solution with the minimum TLH.

Definition 3: *aveNDSolution* is the non-dominated solution with the minimum distance to the average value of all of non-dominated solutions.

For example, the average TTPT of all non-dominated solutions is expressed as below.

$$ave\ TTPT = \frac{\sum_{S_i \in ND} TTPT\ of\ S_i}{|ND|} \tag{13}$$

where ND is the non-dominated solutions set and $|ND|$ is the number of non-dominated solutions. The average TLH (*aveTLH*) of all non-dominated solutions can be calculated in the same way.

In addition, the *aveNDSolution* can be obtained by calculating the minimum Euclidean distance as below.

$$aveNDSolution = \min_{S_i \in ND} \sqrt{(TTPT\ of\ S_i - ave\ TTPT)^2 + (TLH\ of\ S_i - ave\ TLH)^2} \tag{14}$$

Note that even if the number of non-dominated solutions in some instances is less than three, the above-defined three non-dominated solutions (*mTTPT*, *mTLH*, and *aveNDSolution*) still exist. For example, if there is only one non-dominated solution, then *mTTPT*, *mTLH*, and *aveNDSolution* still exist but are the same; if there are only two non-dominated solutions (which must be *mTTPT* and *mTLH*), then *mTTPT*, *mTLH*, and *aveNDSolution* (set as *mTTPT*) also exist. Therefore, there always exist the above-defined three non-dominated solutions in any instance, but two or all of them may be the same.

3.4 *Evaluation of performance improvements*

We also define the following index P including P_TTPT and P_TLH, which represent the performance improvements by the line–cell conversion:

$$P\_TTPT = \frac{TTPT \text{ of } CAL - TTPT \text{ of } PCM}{TTPT\ of\ CAL} \tag{15}$$

$$P\_TLH = \frac{TLH \text{ of } CAL - TLH \text{ of } PCM}{TLH\ of\ CAL} \tag{16}$$

where CAL represents the conveyor assembly line and PCM represents the pure cell type manufacturing system. A positive value of P shows the superiority of the assembly cell system over the assembly line, and vice versa.

We compute P_TTPT and P_TLH of *mTTPT*, *mTLH* and *aveNDSolution* in each experiment to analyse the factors that influence the system performance improvements in the line–cell conversion.

Table 6. Experiment factors design.

Factors	Level 1	Level 2	Level 3	Level 4
Stations A	4	8	12	16
Product types B	1	5	10	15
Lot sizes C	10	30	50	70

Table 7. The data of 20 batches with product type (B) in the experiment.

	Product type (B)			
Batches	1	5	10	15
1	1	1	5	1
2	1	4	6	12
3	1	3	10	8
4	1	5	8	2
5	1	3	1	11
6	1	2	5	4
7	1	3	9	13
8	1	1	4	1
9	1	4	7	5
10	1	5	2	7
11	1	1	9	6
12	1	5	3	14
13	1	2	4	9
14	1	3	2	10
15	1	5	7	5
16	1	3	10	14
17	1	2	8	3
18	1	4	3	6
19	1	2	1	15
20	1	1	6	9

Table 8. The data of 20 batches with lot sizes (C) in the experiment.

	Lot sizes (C)			
Batches	10	30	50	70
1	6	27	43	68
2	3	33	57	73
3	13	32	47	71
4	11	33	43	71
5	16	26	39	69
6	9	30	49	79
7	18	35	37	72
8	13	32	49	70
9	7	27	57	68
10	15	33	46	73
11	7	29	63	74
12	15	31	57	75
13	5	33	55	69
14	11	33	52	70
15	13	27	53	67
16	14	31	52	65
17	11	21	43	69
18	5	36	55	77
19	18	31	52	77
20	16	32	55	74

4. Analysis of operating factors with full factorial experiment

4.1 *The full factorial experiment design*

We designed a full factorial experiment to determine which factors may affect the degree of the system performance improvements of the line–cell conversion. Table 6 shows three factors that are used to represent the complex production environment: the number of work stations (workers or tasks), multiple types of the product, and lot (batch) sizes. The first factor represents the inside influence and the last two factors represent the outside influences. Each factor has four levels.

Table 7 and Table 8 show the data of 20 batches with product types (B), and with lot sizes (C), respectively. We provide a large batch number (20 batches) to test a lot of possibilities. In Table 7, product types of 20 batches are produced as random integers from one of the following four intervals: [1,1], [1,5], [1,10], and [1,15]. The elements in Table 8 are produced by fixing the standard deviation to 5, and using one of the following four means: 10, 30, 50, and 70. For example, the first column of Table 8 follows $N(10, 5)$.

For the experiment with W stations (workers), N product types, and lot sizes (L), we use the following data set from Tables 1–8: the entire Table 1, the first W rows of Table 2, the first W rows and the first N columns of Table 4, the N's column of Table 7, and the L's column of Table 8.

4.2 *Results of full factorial experiment*

Based on the above design, we have performed 64 experiments. The results are in Appendix 1. Note that the full factorial experiment was executed sequentially.

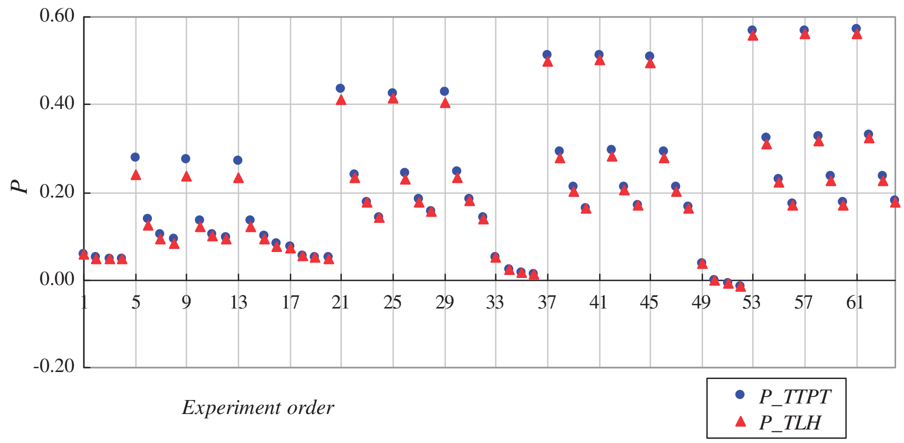

Figure 5. *P_TTPT* and *P_TLH* of *mTTPT* in 64 experiments.

Figures 5, 6 and 7 show the experiment results, where the horizontal axis represents the experiment order and the vertical axis represents the value of *P* (including *P_TTPT* and *P_TLH*) of *mTTPT*, *mTLH*, and *aveNDSolution*, respectively in each experiment.

Figure 5 shows the results of *P_TTPT* and *P_TLH* of *mTTPT*. The assembly cell system surpassed the assembly line in 61 experiments for both *TTPT* and *TLH*. So the line–cell conversion can be used to improve an assembly system's TTPT performance.

Figure 6 shows the results of *P_TTPT* and *P_TLH* of *mTLH*. All cases show that for TLH the cell system surpassed the assembly line. However, 27 experiments show that for TTPT the assembly line surpassed the cell system. The worst TTPT values of the cell system are in Experiments 49, 50, 51, and 52. So if we want to improve the TLH performance, we need to balance the trade-off between TTPT and TLH.

Figure 7 shows the results of *P_TTPT* and *P_TLH* in *aveNDSolution*. Sixty-one experiments show that the cell system surpassed the assembly line for TLH. Ten experiments, however, show that the assembly line surpassed the cell system for TTPT. So the line–cell conversion can always improve the TLH performance, but cannot improve the TTPT performance under some conditions.

From Figures 5 and 6, we can observe the TTPT improvement. For example, P_TTPT decreases with the increase of lot sizes (lot size is defined from 10 to 70 where numbered by point 1 to 4, . . . ,61 to 64 in Figure 5), and increases with the increase of product types (product type is defined from 1 to 5 where numbered by point 1,5,9,13,17. . . in Figure 5), and increases with the increase of stations (station is defined from 4 to 16 where numbered by point 1,17,33,49. . . in Figure 5). A detailed discussion on the influence of these factors and their interactions to TTPT and TLH performance is presented in the next Subsections 4.3 and 4.4, respectively.

From Figures 5, 6, and 7, we can conclude that the line–cell conversion can always be used to improve the TLH performance. For example, Figure 5 and Figure 6 show that even if we improve the TTPT or TLH performance alone, the TLH performance is always improved. Moreover, Figure 7 shows that if we improve the TTPT and TLH performances simultaneously, again, the TLH performance is always improved. However, sometimes the TTPT of the cell system is worse than that of the assembly line like in Figure 6 and Figure 7.

4.3 *Influencing factor analysis for minimum TTPT*

The effects of factors and two-factor interactions for the minimum TTPT are estimated by using the analysis of variance (ANOVA) shown in Table 9. The effect of product types (B), lot sizes (C), stations (A), $B \times C$, $A \times B$ and $A \times C$ are 39%, 35%, 9%, 9%, 6% and 2%, respectively.

To identify the tendency of influenced factors, Figure 8 shows the calculated results of each factor in different levels respectively. Figure 9 shows the specific two-factor interactions ($A \times B$, $A \times C$, $B \times C$). From Figure 9, it can be observed that the curves are not parallel with each other, which means the specific two-factor interactions should not be ignored.

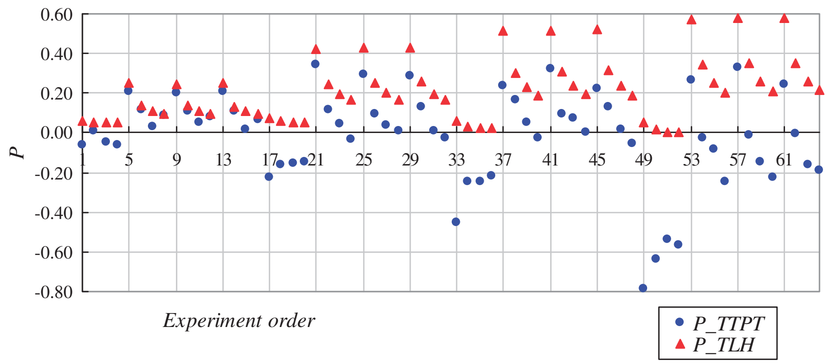

Figure 6. *P_TTPT* and *P_TLH* of *mTLH* in 64 experiments.

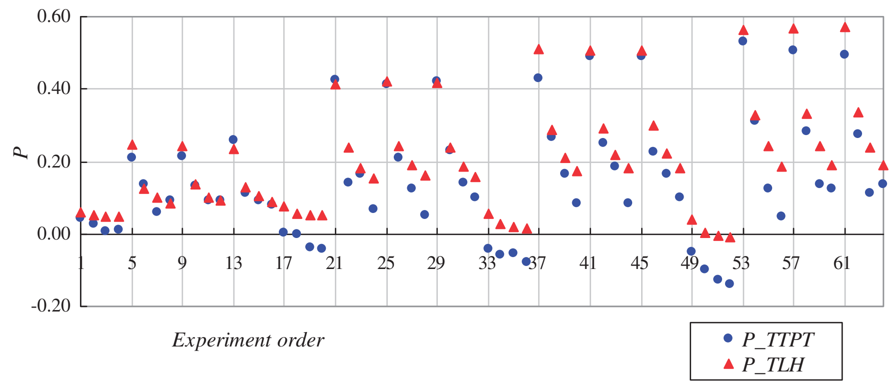

Figure 7. *P_TTPT* and *P_TLH* of *aveNDSolution* in 64 experiments.

Table 9. ANOVA results of minimum TTPT.

Factor	Sum of squares	Df	Mean square	F	Significance
A (stations)	0.134094	3	0.044698	171.33	0.000
B (product types)	0.586590	3	0.19553	749.47	0.000
C (lot sizes)	0.519603	3	0.173201	663.89	0.000
A × B	0.084744	9	0.009416	36.09	0.000
A × C	0.035576	9	0.003953	15.15	0.000
B × C	0.128656	9	0.014295	54.79	0.000
Residual	0.007044	27	0.000261		
Total	1.496308	63			

The regression formula of the minimum TTPT shows as Equation (17) and its significance level is 5%. According to Equation (17), to improve the TTPT performance, especially under the conditions of many stations (A), many product types (B), and small lot sizes (C), the line–cell conversion should be executed.

$$\begin{aligned} P\_TTPT \text{ in } mTTPT = {} & -0.005 + 0.0267\ \mathrm{A} + 0.0735\ \mathrm{B} + 0.0348\ \mathrm{C} \\ & + 0.0230\ \mathrm{A} \times \mathrm{B} - 0.0182\ \mathrm{A} \times \mathrm{C} - 0.0258\ \mathrm{B} \times \mathrm{C} \end{aligned} \tag{17}$$

4.4 *Influencing factor analysis for minimum TLH*

The effects of factors and two-factor interactions for the minimum TLH are shown in Table 10. The effect of product types, lot sizes, stations, B × C, A × B, and A × C are 40%, 30%, 13%, 7%, 6%, and 3%, respectively.

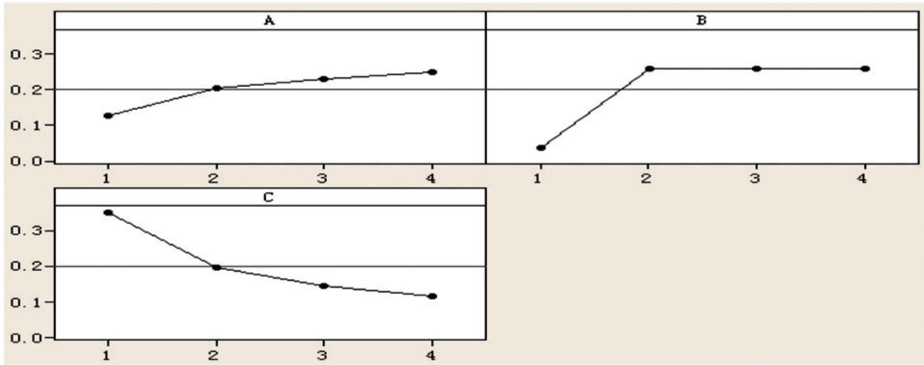

Figure 8. The influence tendency of factors of minimum TTPT.

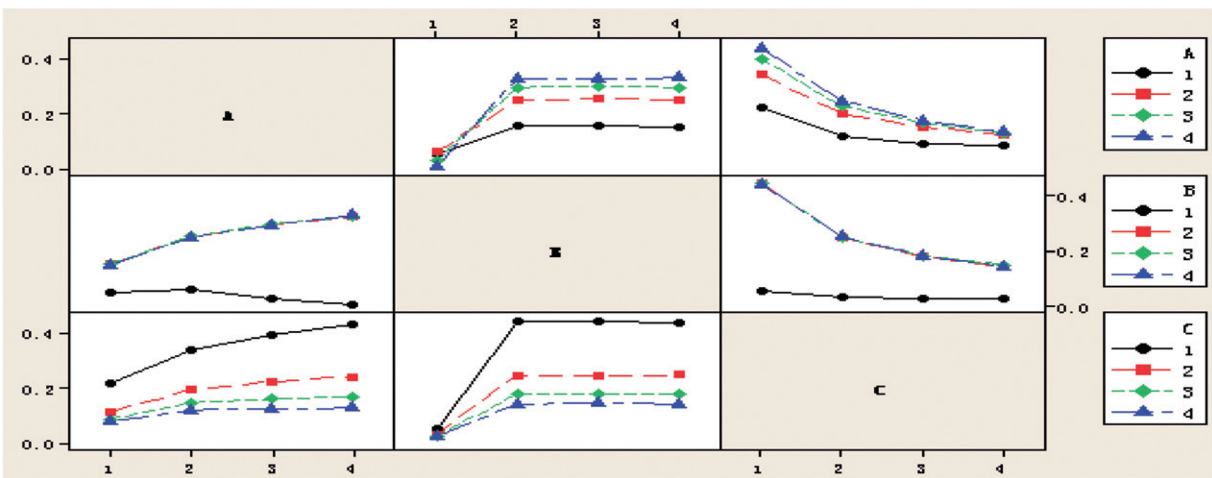

Figure 9. The two-factor interactions of minimum TTPT.

Figure 10 shows the calculated results of each factor in different levels respectively. Figure 11 shows the specific two-factor interactions.

The regression formula of the minimum TLH can be expressed as Equation (18) and its significance level is 5%.

$$\begin{aligned} P\_TLH \text{ in } mTLH = & -0.014 + 0.0313 \text{ A} + 0.0671 \text{ B} + 0.0367 \text{ C} \\ & + 0.0244 \text{ A} \times \text{B} - 0.0186 \text{ A} \times \text{C} - 0.0238 \text{ B} \times \text{C} \end{aligned} \tag{18}$$

4.5 *Discussion*

Several observations on the performance improvements of the line–cell conversion obtained from the full factorial experiment are remarked upon as follows.

Remark 1: By observing Figures 5–7, all of stations, product types, and lot sizes are significant for the TTPT or TLH performances, and the effects of product types and lot sizes are stronger. The more product types or the less lot sizes, the better the performances of TTPT and TLH may improve by the line–cell conversion. This is similar to the suggestions proposed by Kaku *et al.* (2009).

Table 10. ANOVA results of minimum TLH.

Factor	Sum of squares	Df	Mean square	F	Significance
A (stations)	0.185061	3	0.061687	223.68	0.000
B (product types)	0.606234	3	0.202078	732.73	0.000
C (lot sizes)	0.442659	3	0.147553	535.03	0.000
A × B	0.094165	9	0.010462778	37.94	0.000
A × C	0.038481	9	0.004275667	15.50	0.000
B × C	0.106431	9	0.011825667	42.88	0.000
Residual	0.007446	27	0.000275778		
Total	1.480477	63			

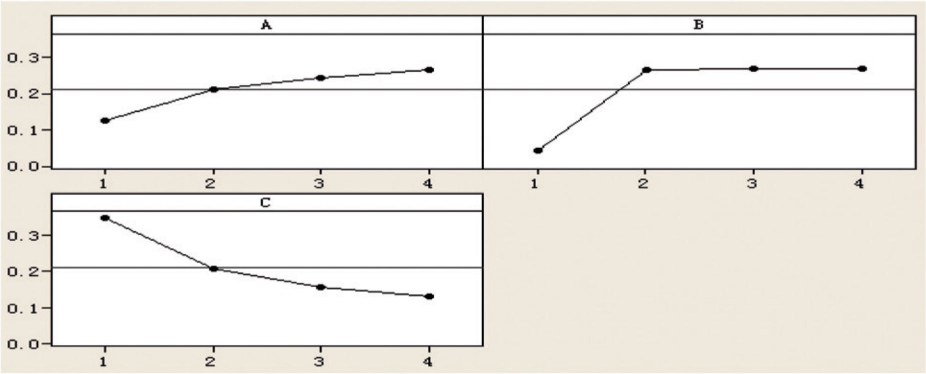

Figure 10. The influence tendency of factors of minimum TLH.

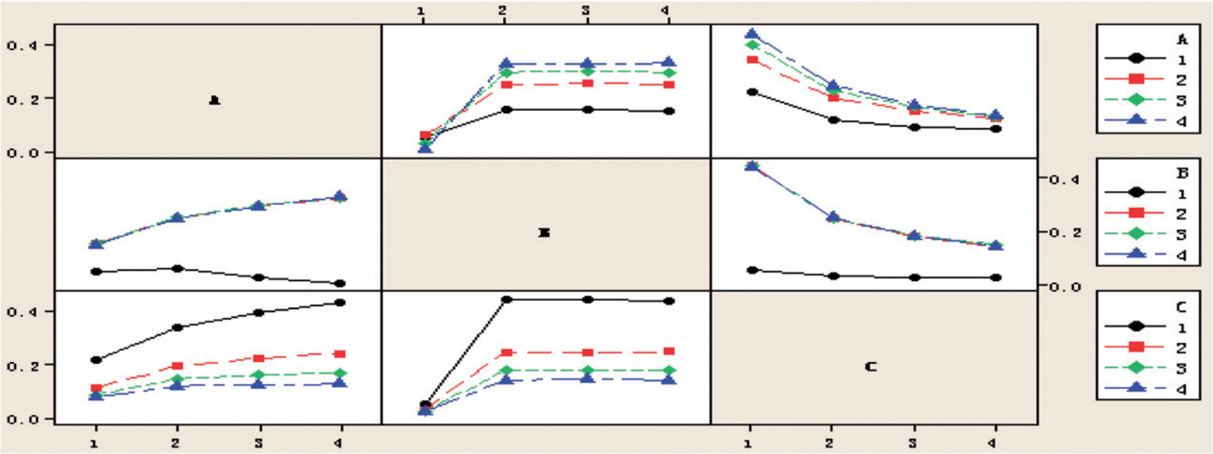

Figure 11. The two-factor interactions of minimum TLH.

Remark 2: In this paper, if the number of stations increases, the line–cell conversion can improve the performances of TTPT and TLH. However, according to Equation (1), the increase of the number of tasks (stations) of each worker may increase her or his task times, which hinders further performance improvements. So there exists a turning point at which the cell system performance will stop improving and begin getting worse (Kaku *et al.* 2009). Since ε_i is small in this study (N(0.01,0.005)), there is no such turning point in our result. We will study the effect of ε_i in the future.

Remark 3: All of the three specific two-factor interactions (A $\times$ B, A $\times$ C, and B $\times$ C) are significant for the minimum TTPT or TLH. The effect of B $\times$ C is more significant than others. So if the number of product types is high, and lot sizes are small, the line–cell conversion should be considered.

Remark 4: The regression formulas of the factors and the performance improvements show that the line–cell conversion could be used to improve the TTPT and TLH performances under the conditions with more product types, less lot sizes, and more stations.

Remark 5: From the pairwise comparisons among Figures 5, 6, and 7, to improve TTPT and TLH simultaneously, *mTTPT* is better than *aveNDSolution*, and *aveNDSolution* is better than *mTLH*. Therefore, if *mTTPT* is the solution of the line–cell conversion, we may not only reduce the solution space of the multi-objective line–cell conversion but also obtain good performance improvements.

5. Several insights on the assembly cell formation and the assembly cell loading

According to the above experimental results, the line–cell conversion can improve the performances of TTPT and TLH. In this section, we discuss the assembly cell formation and the assembly cell loading problems that relate to the line–cell conversion process.

5.1 *On the assembly cell formation*

As shown in Figure 1, after dismantling an assembly line, the assembly cell formation is to decide how many cells to be formed and how to assign workers to cells. ACF is one of most important problems in the line–cell conversion process.

Figure 12 represents the numbers of cells for *mTTPT* and *mTLH* in the 64 experiments. Figure 13 shows the ratios of the number of cells to the number of stations (workers) for *mTTPT* and *mTLH* in the 64 experiments.

5.1.1 *ACF for the minimum TTPT*

For *mTTPT*, Figure 12 shows that the numbers of cells are very small, and Figure 13 shows that the ratios of the number of cells to the number of stations (workers) are almost smaller than 0.5. This means that we should create fewer cells to improve the TTPT performance.

Property 1: Suppose that there is only one product type and the number of stations is smaller than η_i, if we create a cell system that consists of a single cell, then the TTPT performance of the single cell is higher than that of the original assembly line.

Explanation: For one product type, TTPT is the sum of setup time and the task time times the lot sizes of product. From Table 1, the setup time of the cell (1.0) is less than that of the line (2.2). In addition, the task time of the line is equal to the task time of the bottleneck worker, that is to say the slowest worker whose task time is the longest among all workers, but the task time of the cell is the average task times of all workers as Equation (2). In the situation that there is only one product type and the number of stations is smaller than η_i, the task time of the cell is always less than that of the line according to Equations (1) and (2), and the lot sizes are the same. Therefore the TTPT of the cell is shorter than that of the line.

In Figure 12, 14 cases show that the ACF for *mTTPT* only has one cell, especially in the situation of one product type and a smaller number of stations. This is consistent with Property 1. Also other cases with more product types and more stations show that fewer cells should be constructed to improve the TTPT performance.

Another important problem in the ACF is to assign workers to cells. From the 64 experiments, we found that the workers with similar assembly skill levels should be assigned to the same cell to improve the TTPT performance. We use the twenty-second experiment (see Table 11) to illustrate this observation.

Experiment 22 has eight stations, five product types, and lot sizes (30) (see Appendix 1). The solution for *mTTPT* is {{1,4,7}, {2,3,5,6,8}} (that is, two cells are formed, in which Workers 1, 4, and 7 are assigned to Cell 1, and Workers 2, 3, 5, 6, and 8 are assigned to Cell 2). Elements in Table 11 are cells' and workers' skill levels for the

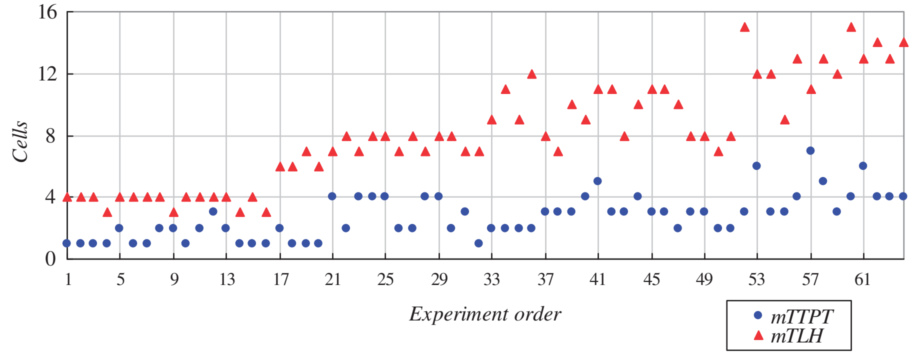

Figure 12. The numbers of cells for *mTTPT* and *mTLH* in the 64 experiments.

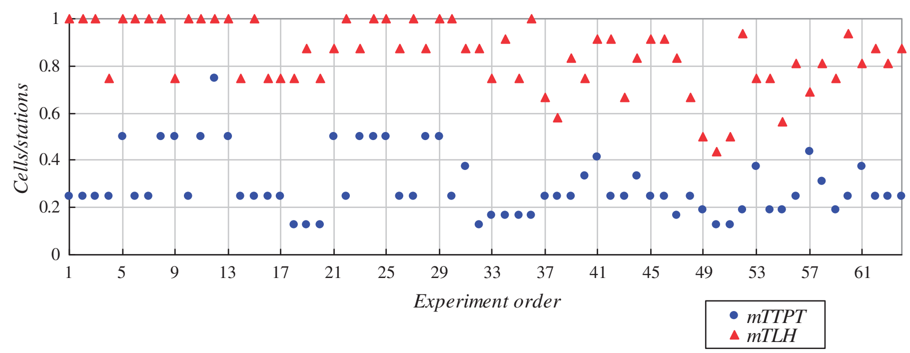

Figure 13. The ratios of the number of cells to the number of stations in the 64 experiments.

Table 11. Cells' and workers' skill levels for the five product types in Experiment 22 for *mTTPT*.

	Skill level										
Product	*Cell 1*	w_1	w_4	w_7	*Cell 2*	w_2	w_3	w_5	W_6	w_8	Difference of cells
1	0.98	1	0.96	0.98	1.016	1.05	1	1.03	1	1	−0.036
2	1	1	1.02	0.98	1.012	1.07	1.07	1.03	0.91	0.98	−0.012
3	1.053	1.09	1.07	1	1.04	1	1.04	1.09	1.05	1.02	0.013
4	1.076	1.08	1.1	1.05	1.034	1.06	1.07	1.01	0.97	1.06	0.042
5	0.97	0.94	0.98	0.99	1.088	1.1	1.12	1.05	1.09	1.08	−0.118

w_i represents Worker i.

five product types. The cells' skill level for each product is calculated as the average skill level of workers in the cell. The smaller the value is, the better the skill level is.

From Table 11, we can observe the trend that the workers with similar skill levels for certain products should be assigned to the same cell, namely, for Products 1, 2, and 5, the workers' skill levels of Cell 1 are similar, for Products 3 and 4, the workers' skill level of Cell 2 are similar too. This coincides with the practical experience that the smaller the workers' skill level gaps, the better the cell balance and productivity are.

In addition, for Product 5, the skill level of Cell 1 is much better than that of Cell 2. Similarly, for Product 4, the skill level of Cell 2 is better than that of Cell 1. Therefore, allocating all batches of Products 5 and 4 to Cells 1 and 2 respectively is a considerable solution for the assembly cell loading of Experiment 22. We discuss this in Subsection 5.2.1.

Table 12. Assigned batches to Cell 1 of the $mTTPT$ in Experiment 22.

Batches	1	4	7	10	12	15	17	19
Product type	1	5	3	5	5	5	2	2
Lot size	27	33	35	33	31	27	21	31

5.1.2 *ACF for the minimum TLH*

For $mTLH$, Figure 12 shows that the numbers of cells are large, and Figure 13 shows that the ratios of the number of cells to the number of stations (workers) are almost larger than 0.5 and even close to 1. This means that we should create many cells to improve the TLH performance.

Property 2: Consider a situation where the numbers of batches and stations are smaller than the numbers of workers and η_i, respectively. To minimise TLH, we should create at least N (the number of product types) cells, and assign a product and workers who have the shortest process time (SPT) for this product to the same cell.

Explanation: Let $\{P_1, P_2, \ldots, P_N\}$ be a sequence of N product types, and $\{C_1, C_2, \ldots, C_N, \ldots\}$ be a sequence of cells. We get $TLH = \sum_{m=1}^{M} B_m TC_m W$ from Equations (4) and (7). Assume product type P_i, its batch m, and the worker(s) with the SPT for P_i are assigned to cell C_i, because TC_m of batch m is the minimum, TLH is the best.

Unfortunately, Property 2 cannot be obtained by using the FCFS principle. Figure 12 and Figure 13, however, still show the tendency that many cells should be created for improving the TLH performance. For example, Experiment 22's solution for the $mTLH$ is {{1}, {5}, {3}, {7}, {8}, {6}, {2}, {4}} (that is to say, eight cells are formed). Moreover, its TLH performance is much better than that of the assembly line, (8756.208 versus 11630.448).

5.2 *On the assembly cell loading*

ACL, a step after ACF, is to allocate batches to cells. Using Experiment 22, we investigate how to load cells for improving TTPT and TLH performances.

5.2.1 *ACL for the minimum TTPT*

Tables 12 and 13 show the assigned batches to Cells 1 and 2 of the $mTTPT$ in Experiment 22, respectively. The TTPT of Cells 1 and 2 are 1135.912 and 1117.037, respectively, so the TTPT of the $mTTPT$ is 1135.912, which is much better than that of the assembly line (1497.806).

From Tables 12 and 13, we can observe the trend that most batches of a product have been assigned to the cell staffed with the SPT workers for this product. For example, four batches of Product type 5 and three batches of Product type 4 are assigned to Cells 1 and 2, respectively.

Since ACL result from the FCFS principle is invariable, we restart ACL, but not using FCFS, to investigate the insights of ACL for improving the TTPT performance. Applying the rule that all batches of a product type should be assembled in the cell with the SPT workers for the product type (see Table 11), Cell 1 assembles four batches of Product type 1 and four batches of Product type 5, and Cell 2 assembles other batches. Then the TTPT of Cells 1 and 2 are 1148.824 and 1099.619 respectively, which is worse than before (1148.824 versus 1135.912). The reason is that the TTPT of Cell 1 is longer, but the TTPT of Cell 2 is shorter than before, so the imbalance of the cells deteriorates, from 18.875 = 1135.912–1117.037 to 49.205 = 1148.824–1099.619.

Therefore, to improve the TTPT performance of a cell system, we should consider TTPT balance among cells. For example, if we perform a new ACL to assign Batches 4, 8, 10, 11, 12, 15, 17, and 19 to Cell 1 (Product types 5, 1, 5, 1, 5, 5, 2, and 2 respectively), and other batches to Cell 2. Then the TTPT of Cells 1 and 2 are 1119.888 and 1122.383 respectively, at this time the TTPT imbalance among cells is as small as 2.495 = 1122.383–1119.888, much smaller than before (18.875), and the TTPT of the cell system is 1122.383, much better than before (1135.912).

Table 13. Assigned batches to Cell 2 of the *mTTPT* in Experiment 22.

Batches	2	3	5	6	8	9	11	13	14	16	18	20
Product type	4	3	3	2	1	4	1	2	3	3	4	1
Lot size	33	32	26	30	32	27	29	33	33	31	36	32

Table 14. ACF, ACL, and workers' skill levels of the *mTLH* in Experiment 22.

Cell	Worker	Batch	Product type	Skill level
1	1	1, 10, 19	1, 5, 2	1, 0.94, 1
2	5	2, 15	4, 5	1.01, 1.05
3	3	3, 14	3, 3	1.04, 1.04
4	7	4, 13	5, 2	0.99, 0.98
5	8	5, 9, 17	3, 4, 2	1.02, 1.06, 1
6	6	6, 11, 18	2, 1, 4	0.91, 1, 0.97
7	2	7, 16	3, 3	1, 1
8	4	8, 12, 20	1, 5, 1	0.96, 0.98, 0.96

Table 15. Assigned batches to cells for minimising TLH.

Cell	Worker	Batches	Product types	Skill level
1	1	4, 10, 12, 15	5, 5, 5, 5	0.94
2	5			
3	3			
4	7	3, 5, 7, 14, 16	3, 3, 3, 3, 3	1
5	8			
6	6	6, 13, 17, 19, 2, 9, 18	2, 2, 2, 2, 4, 4, 4	0.91, 0.97
7	2			
8	4	1, 8, 11, 20	1, 1, 1, 1	0.96

5.2.2 *ACL for the minimum TLH*

Table 14 shows Experiment 22's results of the ACF, ACL, and workers' skill levels for *mTLH*. For example, the first row represents that Batches 1, 10, and 19 (Product types 1, 5, and 2 respectively) are assigned to Cell 1 which is staffed with Worker 1 whose skill levels for Product 1, 5, and 2 are 1, 0.94 and 1, respectively. Other rows are similar.

From Table 14, we can also observe the trend that most batches of a product have been assigned to the cells staffed with the SPT workers for this product. For example, the batches of Product 3 are assigned to Cells 3, 5, and 7 (Workers 3, 8, and 2 respectively). These three workers have higher skill levels for Product 3 than other workers.

Again, the ACL result from the FCFS principle is invariable. We restart the assembly cell loading by the rule that a batch should be assembled in the cell with the SPT for it. The result is shown in Table 15.

According to Table 15, the TLH of the cell system is 8446.032, which is better than before (8756.208) and is the optimal TLH for Experiment 22. The ACL result coincides with Property 2. Therefore, we may get a proposition that we should assign a product to the cell staffed with the SPT workers for this product to improve the TLH performance.

Another important finding is that Cells 2, 3, 5, and 7 are empty, which means that four required workers (5, 3, 8, and 2) are freed up. This can explain why *seru* production can reduce required workforce largely (for example, 35,976 required workers, equal to 25% of Canon's previous total workforce, have been saved (Yin *et al.* 2012)). On the other hand, because of the reduction of the workforce, TTPT increases greatly, from 1325.208 to 2849.888, and the TTPT unbalance is as large as 2849.888 = 2849.888–0.

5.3. Discussion

Several insights on ACF and ACL for improving the TTPT and TLH performances during the line–cell conversion can be remarked as follows.

Remark 1: To improve the TTPT performance, during ACF, we should create fewer cells and assign workers with similar skill levels for product types to the same cell.

Remark 2: To improve TTPT performance, during ACL, not only should we assign a product to the cell staffed with the SPT workers for this product but also reduce the TTPT imbalance among cells.

Remark 3: To improve TLH performance, during ACF, we should create many cells.

Remark 4: To improve TLH performance, during ACL, we should assign a product to the cell staffed with the SPT workers for this product. However, this may cause a longer TTPT.

Remark 5: In summary, to improve TTPT and TLH performances simultaneously, we should assign the workers with similar skill levels to the same cell, and not only schedule a product to the cell staffed with the SPT workers for this product but also reduce the TTPT imbalance among cells.

6. Conclusions and future research

To analyse performance improvements of the line–cell conversion, we have performed a full factorial experiment and made the following two contributions to the literature. First, we performed a 64-array experiment and used three non-dominated solutions to investigate which operational factors or interactions between factors may influence performance improvements in the line–cell conversion. Second, we summarised several insights on how to form assembly cells and load cells based on the experimental results, for example (1) to improve TTPT alone, fewer cells should be created and the workers with similar skill levels should be assigned to the same cell, but to improve TLH alone, many cells should be created; (2) allocate a batch to the cell staffed with the SPT workers for this product; and (3) reduce the TTPT imbalance among cells.

Line–cell conversion has been carried out in Japan, the US (Williams 1994), Europe, Korea (Yin 2006), China (Cao 2008), and other countries (Yin *et al*. 2011). However, the research in this area is relatively lacking. A thorough research problem list can be found in Yin *et al*. (2012). We only consider the line–cell conversion problem with the FCFS rule, so an immediate future research is a comparative study on different scheduling rules. Other problems should consider various production factors, such as partially cross-trained workers (a worker cannot perform all assembly tasks), different products have different assembly tasks, the cost of *karakuri* (the duplication of equipment), human and psychology factors, and so on.

Acknowledgments

This research has been supported by the Post Doctoral Foundation of Akita Prefectural University, the National Natural Science Foundation of China (71021061, 70971019), the Fundamental Research Funds for the Central Universities (N110404021), the China Postdoctoral Science Foundation (2011M500827, 2012M510828), the Startup Foundation for Doctors of Liaoning Province (20101039), and the project of Sanqin Scholars of Shaanxi Province.

References

Bukchin, J., Darel, E., and Rubinovitz, J., 1997. Team-oriented assembly system design: A new approach. *International Journal of Production Economics*, 51 (1–2), 47–57.

Burbidge, J.L., 1989. *Production flow analysis*. Oxford: Clarendon Press.

Cao, S., 2008. *Production reform: Seru cases in Japan and China* (in Japanese). Unpublished thesis. Yamagata University, Japan.

Feare, T., 1995. Less automation means more productivity at Sun. *Modern Materials Handling*, 50 (13), 39–41.

Goicoechea, A., Hansen, D.R., and Duckstein, L., 1982. *Multiobjective decision analysis with engineering and business applications*. New York: Wiley.

Isa, K. and Tsuru, T., 1999. Cell production and workplace innovation in Japan: Toward a new model for Japanese manufacturing? *Industrial Relations*, 4 (1), 548–578.

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

Kaku, I., *et al*., 2008a. A mathematical model for converting conveyor assembly line to cell manufacturing. *International Journal of Industrial Engineering and Management Science*, 7 (2), 160–170.

Kaku, I., *et al*., 2009. Modeling and numerical analysis of line–cell conversion problems. *International Journal of Production Research*, 47 (8), 2055–2078.

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

Karp, R.M., 1972. Reducibility among combinatorial problems. *Complexity of Computer Computations*. New York: Plenum, 85–103.

Klazar, M., 2003. Bell numbers, their relatives, and algebraic differential equations. *Journal of Combinatorial Theory, Series A*, 102 (1), 63–87.

Kimura, T. and Yoshita, M., 2004. Konomama deha ayaui *seru* seisan [*Seru* systems run into trouble when nothing is done]. *Nikkei Monozukuri*, 7, 38–61.
Levin, D.P., 1994. Compaq storms the PC heights from its factory floor, *New York Times*, 13 November, section 3, p. 5.
Liu, C.G., *et al*., 2010. *Seru seisan* – An innovation of the production management mode in Japan. *Asian Journal of Technology Innovation*, 18 (2), 89–113.
Miyake, D.I., 2006. *The shift from belt conveyor line to work-cell based assembly system to cope with increasing demand variation and fluctuation in the Japanese electronics industries*. Report paper of F-397, Center for International Research on the Japanese Economy, Japan.
Sakazume, Y., 2005. Is Japanese cell manufacturing a new system? A comparative study between Japanese cell manufacturing and cell manufacturing. *Journal of Japan Industrial Management Association*, 55 (6), 341–349.
Sengupta, K. and Jacobs, F.R., 2004. Impact of work teams: A comparison study of assembly cells and assembly line for a variety of operating environments. *International Journal of Production Research*, 42 (19), 4173–4193.
Shinohara, T., 1995. Konbea tekkyo no syougeki hashiru: hitorikanketsu no seru seisan [Shocking news of the removal of conveyor systems: Single-worker seru production system]. *Nikkei Mechanical*, 24 (July), 20–38.
Stecke, K.E., *et al*., 2012. *Seru*: The organizational extension of JIT for a super-talent factory. *International Journal of Strategic Decision Sciences*, 3 (1), 105–118.
Takeuchi, N., 2006. *Seru Seisan [Seru Production System]*. Tokyo: JMA Management Center.
Tsuru, T., 1998. Cell manufacturing and innovation of production system. Report paper of September 1998, Economic Research Institute, Japan Society for the Promotion of Machine Industry, Japan (in Japanese).
Williams, M., 1994. Back to the past: some plants tear out long assembly lines, switch to craft work, *The Wall Street Journal*, October 24, A-1.
Yamada, H. and Kataoka, T., 2001. *Jyousiki Yaburi no Monozukuri [Unusual production revolution]*. Tokyo: NHK.
Yin, Y., 2006. The direction of Samsung style next generation production methods. A speech given at the *Samsung Production Methods Innovation Forum*, 17 October 2006 Samsung Electronics in Suwon City, Korea.
Yin, Y., *et al*., 2011. Improving productivity, agility, and efficiency using *seru*, a flexible manufacturing organization. Working paper (unpublished). Yamagata University.
Yin, Y., *et al*., 2012. Integrating lean and agile production paradigms in a highly volatile environment with *seru* production systems: Sony and Canon case studies. Working paper (unpublished). Yamagata University.
Yin, Y., Stecke, K.E., and Kaku, I., 2008. The evolution of *seru* production systems throughout Canon. *Operations Management Education Review*, 2, 27–40.
Yu, Y., *et al*., 2011. Several mathematical insights and solutions for multi-objective line–cell conversion problem. Working paper submitted to European Journal of Operational Research.

Appendix

Results of 64 experiments.

	Factors			*mTTPT*			*mTLH*			*aveNDSolution*	
No.	*A*	*B*	*C*	*P_TTPT*	*P_TLH*	*cells*	*P_TTPT*	*P_TLH*	*cells*	*P_TTPT*	*P_TLH*
1	4	1	10	0.06	0.06	1	−0.06	0.06	4	0.04	0.06
2	4	1	30	0.05	0.05	1	0.01	0.05	4	0.03	0.05
3	4	1	50	0.05	0.05	1	−0.05	0.05	4	0.01	0.05
4	4	1	70	0.05	0.05	1	−0.06	0.05	3	0.01	0.05
5	4	5	10	0.28	0.24	2	0.21	0.25	4	0.21	0.25
6	4	5	30	0.14	0.12	1	0.12	0.14	4	0.14	0.12
7	4	5	50	0.10	0.09	1	0.03	0.11	4	0.06	0.10
8	4	5	70	0.09	0.08	2	0.09	0.10	4	0.09	0.08
9	4	10	10	0.27	0.24	2	0.20	0.24	3	0.21	0.24
10	4	10	30	0.14	0.12	1	0.11	0.14	4	0.13	0.14
11	4	10	50	0.10	0.10	2	0.05	0.11	4	0.09	0.10
12	4	10	70	0.10	0.09	3	0.08	0.10	4	0.09	0.09
13	4	15	10	0.27	0.23	2	0.21	0.25	4	0.26	0.23
14	4	15	30	0.14	0.12	1	0.11	0.13	3	0.11	0.13
15	4	15	50	0.10	0.09	1	0.02	0.11	4	0.09	0.11
16	4	15	70	0.08	0.08	1	0.07	0.09	3	0.08	0.09
17	8	1	10	0.07	0.07	2	−0.22	0.08	6	0.00	0.08

(*continued*)

Continued.

No.	Factors			*mTTPT*			*mTLH*			*aveNDSolution*	
	A	*B*	*C*	*P_TTPT*	*P_TLH*	*cells*	*P_TTPT*	*P_TLH*	*cells*	*P_TTPT*	*P_TLH*
18	8	1	30	0.06	0.06	1	−0.16	0.06	6	0.00	0.06
19	8	1	50	0.05	0.05	1	−0.15	0.06	7	−0.04	0.05
20	8	1	70	0.05	0.05	1	−0.15	0.05	6	−0.04	0.05
21	8	5	10	0.43	0.41	4	0.34	0.42	7	0.43	0.41
22	**8**	**5**	**30**	**0.24**	**0.23**	**2**	**0.12**	**0.25**	**8**	**0.14**	**0.24**
23	8	5	50	0.18	0.18	4	0.04	0.20	7	0.16	0.18
24	8	5	70	0.14	0.14	4	−0.03	0.16	8	0.07	0.15
25	8	10	10	0.43	0.41	4	0.29	0.43	8	0.41	0.42
26	8	10	30	0.24	0.23	2	0.09	0.26	7	0.21	0.24
27	8	10	50	0.18	0.18	2	0.04	0.20	8	0.13	0.19
28	8	10	70	0.15	0.15	4	0.01	0.17	7	0.05	0.16
29	8	15	10	0.43	0.41	4	0.29	0.43	8	0.42	0.42
30	8	15	30	0.25	0.23	2	0.13	0.26	8	0.23	0.24
31	8	15	50	0.18	0.18	3	0.01	0.19	7	0.14	0.19
32	8	15	70	0.14	0.14	1	−0.02	0.17	7	0.10	0.16
33	12	1	10	0.05	0.05	2	−0.45	0.06	9	−0.04	0.05
34	12	1	30	0.02	0.02	2	−0.25	0.03	11	−0.06	0.03
35	12	1	50	0.02	0.02	2	−0.24	0.02	9	−0.05	0.02
36	12	1	70	0.01	0.01	2	−0.22	0.02	12	−0.08	0.02
37	12	5	10	0.51	0.50	3	0.24	0.51	8	0.43	0.51
38	12	5	30	0.29	0.28	3	0.16	0.30	7	0.27	0.29
39	12	5	50	0.21	0.20	3	0.05	0.23	10	0.16	0.21
40	12	5	70	0.16	0.16	4	−0.02	0.19	9	0.08	0.17
41	12	10	10	0.51	0.50	5	0.32	0.52	11	0.49	0.51
42	12	10	30	0.29	0.28	3	0.10	0.31	11	0.25	0.29
43	12	10	50	0.21	0.20	3	0.07	0.24	8	0.19	0.22
44	12	10	70	0.17	0.17	4	0.00	0.19	10	0.09	0.18
45	12	15	10	0.51	0.49	3	0.23	0.52	11	0.49	0.51
46	12	15	30	0.29	0.28	3	0.13	0.32	11	0.23	0.30
47	12	15	50	0.21	0.20	2	0.01	0.24	10	0.16	0.22
48	12	15	70	0.17	0.16	3	−0.06	0.19	8	0.10	0.18
49	16	1	10	0.04	0.04	3	−0.79	0.05	8	−0.05	0.04
50	16	1	30	0.00	0.00	2	−0.63	0.01	7	−0.10	0.00
51	16	1	50	−0.01	−0.01	2	−0.54	0.01	8	−0.13	0.00
52	16	1	70	−0.01	−0.01	3	−0.56	0.00	15	−0.14	−0.01
53	16	5	10	0.57	0.56	6	0.27	0.57	12	0.53	0.56
54	16	5	30	0.32	0.31	3	−0.03	0.34	12	0.31	0.33
55	16	5	50	0.23	0.22	3	−0.08	0.25	9	0.12	0.24
56	16	5	70	0.17	0.17	4	−0.25	0.20	13	0.05	0.19
57	16	10	10	0.57	0.56	7	0.33	0.58	11	0.51	0.57
58	16	10	30	0.33	0.32	5	−0.01	0.35	13	0.28	0.33
59	16	10	50	0.24	0.23	3	−0.15	0.26	12	0.14	0.24
60	16	10	70	0.18	0.17	4	−0.23	0.21	15	0.13	0.19
61	16	15	10	0.57	0.56	6	0.25	0.58	13	0.49	0.57
62	16	15	30	0.33	0.32	4	0.00	0.35	14	0.27	0.34
63	16	15	50	0.24	0.23	4	−0.16	0.26	13	0.11	0.24
64	16	15	70	0.18	0.18	4	−0.19	0.22	14	0.14	0.19

mTTPT, *mTLH*, and *aveNDSolution* are the non-dominated solutions as defined in Definition 1, Definition 2, and Definition 3, respectively