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Reducing worker(s) by converting assembly line into a pure cell system

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ABSTRACT

The line-cell conversion is established as a new production system towards converting traditional conveyor assembly line to a cell system, in which one (or multiple) worker carries out all of the operations of a job in a cell. Its performance improvement can be enhanced by reducing worker (s) without decreasing productivity. How to conduct this conversion by determining how many cells should be formatted and which workers are assigned in a cell, is a complicated decision problem. This paper presents a multi-objective line-cell conversion model with the two goals of reducing worker (s) and increasing productivity simultaneously, in a production environment that converts traditional conveyor assembly line into a pure cell system. We identify several mathematical insights on solution space of the multi-objective line-cell conversion model and prove that it is an NP-hard problem. Then we provide an improved exact algorithm to obtain Pareto-optimal solutions of the multi-objective model. Several numerical simulation experiments are performed to illustrate that the line-cell conversion can be used to reduce worker(s) and the total throughput time at the same time.
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1. Introduction

The line-cell (or line-*seru*) conversion, conceived at Sony, is an innovation of assembly systems used widely in the Japanese electronics industry. Also, it has been done in U.S. (Williams, 1994), Europe and Korea (Yin, 2006), China (Cao, 2008), and other countries (Yin et al., 2011). Its essence is that converting traditional conveyor assembly line to a cell system in which one (or multiple) worker carries out all of the operations of a job in a U-shaped station layout. A detailed introduction of cell 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 staffed within rotating *serus* or *yatais* are completely cross-trained. A rotating *seru* is often organized 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 organization. So a *yatai* owner does all operational and managerial tasks by her- or 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 2 h, or a luxury camera of 940 components in only 4 h (Kimura and Yoshita, 2004; Stecke et al., 2012). A NEC completely cross-trained worker can assemble a word processor of 120 components in 18 min (Yamada and Kataoka, 2001; Stecke et al., 2012). In this paper, we only analyze 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. It can reduce throughput time, setup time, required workers, WIP inventories, finished-product inventories, cost, and shop floor space. Therefore, the line-cell conversion can be used to increase the productivity and competitive advantages. However, how to complete this conversion is a very complicated decision making problem because when companies face a changing production environment (Duan and Liao, 2013) and want to convert their conveyor assembly line to a new production system, then they must decide that how many cells should be formatted and which workers should be assigned in each cell. Moreover, how to evaluate the performance improvement through the line-cell conversion is also an important decision issue. Such technical and decision making problems in the line-cell conversion had been defined as line-cell conversion problems (Kaku et al., 2008, 2009; Yu et al., 2012, 2013). Two objectives (the total throughput time and the total labor hours) were constructed in the model and

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numerical simulation based experiments were executed to analyze the influence on the line-cell conversion with several operating factors (Yu et al., 2012).

Reducing the workers or operators is another important function of the line-cell conversion. For example, assigning product to the cell which most appropriate worker(s); using fewer workers to complete the same jobs of assembly line and so on. We had investigated 24 cases of the line-cell conversion which reported in a Japanese technical journal (*Factory Management* 1995–2006) and found over one-third of them claimed that they can reduce workers from about 20% to 80% through the line-cell conversion. An amazing case related to reduce the workers is, 35,976 required workers, equal to 25% of Canon's previous total workforce, which have been saved (Yin et al., 2012).

However, workers reduction may lead worse total throughput time (TTPT). But when only consider reducing the TTPT, line-cell conversion has excellent performance. For example, Sony Kohda used line-cell conversion to reduce 53% TTPT (Yin et al., 2012). In fact, only the line-cell conversion where both workers and the TTPT are reduced can be adopted by the companies. Therefore, to investigate how to use line-cell conversion to reduce worker(s) and the TTPT simultaneously, we build the multi-objective line-cell conversion model with the two goals of minimizing the number of workers and minimizing the TTPT.

In this paper we have two contributions. First, we identify the mathematical insights on solution space of the multi-objective line-cell conversion model with the two goals of reducing worker(s) and minimizing the TTPT and prove it is an NP-hard problem. Second, we propose an improved exact algorithm for small-scale problems and use several numerical examples to illustrate that the line-cell conversion can be used to reduce worker(s) and the TTPT simultaneously.

The paper is organized as follows. The multi-objective line-cell conversion model with the two goals of minimizing the number of workers and minimizing the TTPT is presented in Section 2. The third section clarifies several mathematical insights on its solution space of the multi-objective line-cell conversion model and proves that it is an NP-hard problem. We propose an improved exact algorithm to solve the multi-objective model and some numerical examples are used to illustrate that the line-cell conversion can be used to reduce worker(s) and the TTPT simultaneously in the forth section. Finally, we end the paper with conclusions and with suggestions for future research.

2. Line-cell conversion model with the two goals of minimizing the number of workers and minimizing the TTPT

2.1. Problem description

Kaku et al. (2009) considered three types of assembly systems including a pure cell system, a pure assembly line, and a hybrid type of cells+assembly line. Here for simplicity and without loss of generality, we just consider a simple case in which traditional conveyor assembly line is converted to a pure cell system shown in Fig. 1. For evaluating the converted system performance two criteria are considered. They are total throughput time (TTPT) and total labor power (hours); the former represents the system productivity that is the time of all of product batches assembled, and the latter represents the work efficiency that is the cumulative working time of all of workers assigned in the system.

Reducing worker(s) is another important function of the line-cell conversion, and so this paper considers the two objectives of minimizing the number of workers and minimizing the TTPT. Therefore, our problem is to determine how many cells should be formatted, how to assign workers and product batches to appropriate cells to minimize the two objectives.

2.2. Problem features and assumption

The following assumptions are considered in this paper to construct the model of a pure cell system:

1. The types and batches of products to be processed are known in advance. There are N product types that are divided into M product batches. Each batch contains a single product type.
2. In the line-cell conversion process, the cost of duplicating equipment is ignored (Stecke et al., 2012; Yin et al., 2012). Since most assembly tasks within a *seru* are manual so need only simple and cheap equipment.
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 some product were unique, we assume the task time for these unique tasks was 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. In this paper, the number of tasks equals to W.
6. A worker only performs a single assembly task in the assembly line (i.e., 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, assembles an entire product from-start-to-finish (i.e., 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 in the charge of a single worker.
8. The number of workers within each cell may be different, but must be less than the total number of workers.
9. 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 in assembly line ($i=1,2,\ldots,W$).
  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: Fixed 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, i.e., 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
  $$X_{ij}=\begin{cases}1, & \text{if worker } i \text{ is assigned to cell } j\\ 0, & \text{otherwise}\end{cases}$$

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

In addition, if $k=0$, $Z_{mjk}=0$.

- Variables

SC_m: Variable setup time of product batch m in a cell.
TC_m: Variable assembly task time of product batch m per station in a cell, depending on the assigned worker.
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 problem in which there is an assembly product mix with M product batches and N product types. W workers are assigned to assembly cells during the line-cell conversion. The batches are assigned to cells with the FCFS principle. We define the TTPT 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 cost more time on tasks she or he is 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, i.e., $W>\eta_i$, then the worker will cost more average task time than her or his task time within the original assembly line. The details are given as follows:

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

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:

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

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.

$$SC_m=\begin{cases}SCP_nV_{mn}, & V_{mn}=V_{m'n}=1\\ 0, & V_{mn}=1,\ V_{m'n}=0\end{cases},\quad (m'|Z_{mjk}=1,\ Z_{m'j(k-1)}=1,\forall j,k) \tag{3}$$

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

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

Eq. (3) states the variable setup time of product batch, m. Variable setup time is considered when two different types of products are processed consecutively; otherwise the setup time is zero. For example, in Eq. (3), two adjacent assembled products in a cell are expressed as m and m'. If the product types of m and m' are identical, i.e., $V_{mn}=V_{m'n}=1$, and then the setup time of batch m is SCP_nV_{mn}. However, if the product type of m is different from that of m', i.e., $V_{mn}=1$, $V_{m'n}=0$, and then the setup time of batch m is 0. It is motivated by one of the authors, who visited three companies' (Omron, Yamaha, and Fujitsu) assembly cell factories recently. Eq. (4) states the flow time of product batch m within a cell. Eq. (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 variable setup time of the product batches processed prior to it in the same cell.

The comprehensive mathematical model of the multi-objective line-cell conversion with the two goals of minimizing the number of workers and minimizing the TTPT is given in Eqs. (6)–(12) as below.

Objective functions:

$$\text{Min}\left\{\sum_{j=1}^{J}\sum_{i=1}^{W}X_{ij}\right\} \tag{6}$$

$$\text{Min}\ \ TTPT=\text{Min}\left\{\text{Max}_{m}(FCB_m+FC_m+SC_m)\right\} \tag{7}$$

Subject to

$$\sum_{j=1}^{J}\sum_{i=1}^{W}X_{ij}<W \tag{8}$$

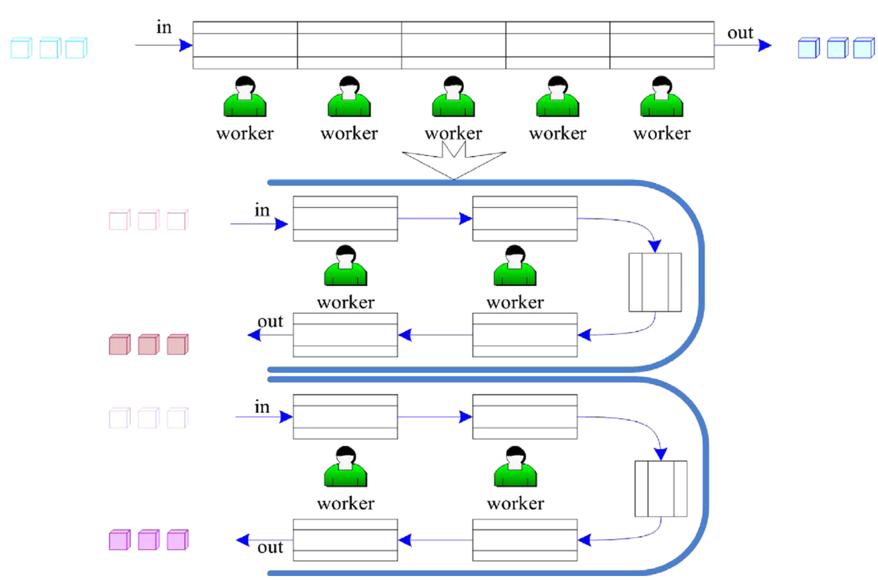

Fig. 1. An example of cell formation in line-cell conversion towards reducing worker(s).

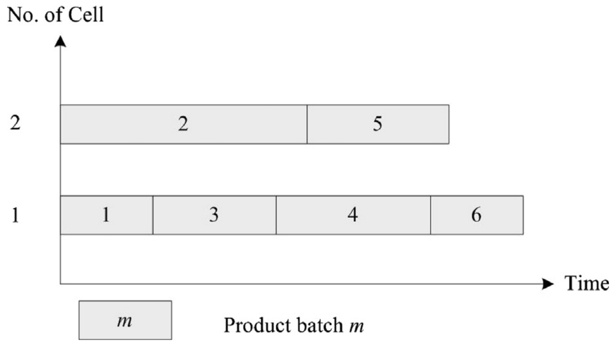

Fig. 2. An example of FCFS scheduling in a cell system (Yu et al., 2012).

$$1 \le \sum_{i=1}^{W} X_{ij}, \qquad \forall j \tag{9}$$

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

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

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

where, Eq. (6) states the objective to minimize the number of workers. Eq. (7) states the objective to minimize the TTPT of the total product batches. The TTPT is the due time of the last completed product batch. Eq. (8) is the reducing worker (s) constraint that the total number of workers in the cell system needs to be smaller than that of the assemble line. Eq. (9) is the rule of cell formation, which ensures that each formatted cell should contain at least one worker. Eq. (10) is the assignment rule by which a product batch is only assigned to a cell. Eq. (11) is the rule of assigning constraints; that means a product must be assigned to a cell in which a worker is assigned at least. That is to say, for any cell which has no worker, i.e., $\forall j | \sum_{i=1}^{W} X_{ij} = 0$, all batches cannot be assigned into the cell, i.e., $\sum_{m=1}^{M}\sum_{k=1}^{M} Z_{mjk} = 0$. Eq. (12) is the assignment rule by which product batches must be assigned sequentially.

Owing to the characteristic of the model, i.e., objective 1, objective 2 and the reducing worker(s) constraint, it is named as the multi-objective line-cell conversion towards reducing worker (s) in the paper.

3. Several mathematical insights of the model

It can be observed that the multi-objective line-cell conversion towards reducing worker(s) is not linear but bounded for a given number of workers. Hence, we must clarify its mathematical characteristics to find some hints for solving it.

3.1. Two steps of the line-cell conversion

The line-cell conversion is in effect with a two-stage decision process. The first step is the cell formation. Distinguishing the traditional manufacturing cell formation problems (Safaei and Tavakkoli-Moghaddam, 2009; Wu et al., 2009), the cell formation in line-cell conversion is to determine how many cells to form and how many workers to employ as well as to which cell a worker is assigned. To reduce workers (i.e., Eq. (8)), the total number of workers in the cell system should be smaller than that of line. An example of cell formation in line-cell conversion towards reducing worker(s) is shown in Fig. 1.

The second step is the cell loading. It decides which product batches are assigned to a cell and in which sequence (Che et al., 2012, 2013; Solimanpur and Elmi, 2013). Fig. 2 shows a cell loading example with six batches and two cells. The length of rectangle charts in Fig. 2 is the flow time of a product batch. We illustrate 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.

3.2. Solution space of cell formation

Theorem 1. *Cell formation of the multi-objective line-cell conversion towards reducing worker(s) is an NP-hard problem.*

Proof. Consider $\{1,2,\ldots,W\}$ as the worker set of a assembly line, and there are 2^W-2 non-empty proper subsets (expressed as $\{W_1,W_2,\ldots,W_R\}$, $R=2^W-2$, $W_r \subseteq \{1,2,\ldots,W\}$) of the worker set. Obviously, arbitrary non-empty proper subset W_r can represent a feasible option of reducing worker(s) by the line-cell conversion, in other words, W_r expresses the worker set of the converted cell system. Therefore, for the assembly line with W workers, there are 2^W-2 feasible options (expressed as $\{W_1,W_2,\ldots,W_R\}$, $R=2^W-2$) of reducing worker(s) by the line-cell conversion. For the subset W_r, its cell formation is to partition $|W_r|$ (the cardinality of W_r, i.e., the number of workers in the subset W_r) workers into pairwise disjoint non-empty cells; each cell may have one or several workers, and each worker is only assigned to be one cell. If the term 'worker' is generalized as element, cell formation is to partition $|W_r|$ elements of the set W_r into unordered pairwise disjoint non-empty sub-sets. Obviously, the cell formation of W_r is an instance of the unordered set partition problem. It is well-known that the set partitioning problem is NP-hard (Garey and Johnson, 1979). Therefore, the cell formation of the multi-objective line-cell conversion towards reducing worker(s) is an NP-hard problem. □

For example, an assembly line with 3 workers labeled as 1, 2 and 3, its non-empty proper subsets are {1},{2},{3},{1,2},{1,3}, {2,3}, and every subset expresses a feasible option of reducing worker(s) for the assembly line with workers 1, 2 and 3. For example, the subset {1, 2} represents that workers 1 and 2 are left in the cell system, and worker 3 is reduced. For the subset {1, 2}, its unordered set partitions are {1, 2} (this means 1 cell is constructed in which workers 1 and 2 are) and {{1}, {2}} (this means 2 cells are constructed in which worker 1 is in cell 1 and worker 2 is in cell 2). Therefore, for the assembly line with 3 workers, there are 6 feasible options of reducing worker(s) (i.e., {1},{2},{3},{1,2},{1,3},{2,3}) by the line-cell conversion, and there are 9 feasible cell formation (i.e., {1}, {2}, {3}, {1,2}, {{1},{2}}, {1,3}, {{1},{3}}, {2,3}, and {{2},{3}}) for reducing worker(s) by the line-cell conversion.

The number of unordered set partitions (Klazar, 2003; Knopfmacher and Mays, 2006; Williamson, 1985) can be expressed as following:

$$B(W) = \sum_{C=1}^{W} S(W, C) \tag{13}$$

where $S(W, C)$ is the number of the solutions of partitioning W workers in assembly line into C cells and equals to $S(n, k)$ in Stirling numbers of the second kind (Rennie and Dobson, 1969); $B(W)$ is the number of solutions of partitioning W workers into the cell system. The value of $B(0)$–$B(10)$ are 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21,147 and 115,975, respectively.

The number of feasible solutions ($F(W, r)$) of the cell formation for reducing r worker(s) from W workers can be expressed by unordered set partition, i.e., Eq. (13).

Property 1. *For the assembly line with W workers to reduce r worker(s),* $F(W,r)=\binom{W}{W-r}\sum_{C=1}^{W-r}S(W-r,C)$.

Explanation. For the assembly line with W workers to reduce r worker(s), there are $W-r$ workers left in the cell system. According to Eq. (13), $\sum_{C=1}^{W-r}S(W-r,C)$ represents the number of solutions of partitioning $W-r$ workers into the cell system. In addition, there are $\binom{W}{W-r}$ solutions for the left $W-r$ workers. □

Property 2. *For the assembly line with W workers towards reducing worker(s), the number of feasible solutions of the cell formation,* $F(W)=\sum_{r=1}^{W-1}\binom{W}{W-r}\sum_{C=1}^{W-r}S(W-r,C)$, *where r is the number of reduced workers.*

Explanation. For the multi-objective line-cell conversion towards reducing worker(s), it is to partition less than W workers of line into pair wise disjoint non-empty cells. That is to say, $F(W)=\sum_{r=1}^{W-1}F(W,r)$, and so according to Property 1,

$F(W)=\sum_{r=1}^{W-1}\binom{W}{W-r}\sum_{C=1}^{W-r}S(W-r,C)$. □

The value of $F(1)$–$F(10)$ are 0, 2, 9, 36, 150, 673, 3263, 17,006, 94,827 and 562,594, respectively.

3.3. Solution space of cell loading

Cell loading is the batches assignment to cells after the cell formation. Without a given scheduling rule, cell load is a scheduling problem and an NP-hard problem.

Theorem 2. *Cell loading of the multi-objective line-cell conversion towards reducing worker(s) is an NP-hard problem.*

Proof [Yin et al. (2011)]. have proven that even a simple cell loading of line-cell conversion (they use another term "just-in-time organization system") problem is NP-hard. □

Theorem 3. *The multi-objective line-cell conversion towards reducing worker(s) is an NP-hard problem.*

Proof. We can conclude that the multi-objective line-cell conversion towards reducing worker(s) is an NP-hard problem, because it includes cell formation and cell loading problems that are NP-hard problems proved by Theorems 1 and 2. □

Therefore, the multi-objective line-cell conversion towards reducing worker(s) is a more complex NP-hard problem which consists of two NP-hard problems. For simplicity and without loss of generality, we consider using the classical type of scheduling rule applied in many companies, i.e., FCFS. 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. Fig. 2 shows a FCFS cell loading example with six batches and two cells. However, the multi-objective line-cell conversion towards reducing worker(s) with the FCFS rule is still an NP-hard problem, according to Theorem 1.

In cell loading with the FCFS rule, the numbers of loading sequence (L) can be expressed by the number of cells (C) produced in cell formation.

Property 3. *In the cell loading with the FCFS rule and with C cells,* $L=C!$.

Explanation. In cell load with the FCFS rule, as shown in Fig. 2, the first C batches are assigned to cells according to the order of their coming and the sequence number of the C cells. So given the cell formation, the cell loading is a permutation problem. □

3.4. Solution space of the multi-objective line-cell conversion towards reducing worker(s)

Combining the solution spaces of the cell formation and the cell loading, we can clarify the solution space ($T(W)$) of the multi-objective line-cell conversion towards reducing worker(s).

Property 4. *With the FCFS rule,*

$T(W)=\sum_{r=1}^{W-1}\binom{W}{W-r}\sum_{C=1}^{W-r}S(W-r,C)C!$.

Explanation. Combining Property 2 with Property 3. □

The value of $T(1)$–$T(10)$ are 0, 2, 12, 74, 540, 4682, 47,292, 545,834, 7,087,260 and 102,247,562, respectively.

4. Improved exact algorithm and computational experiments

4.1. An improved exact algorithm

Since the multi-objective line-cell conversion towards reducing worker(s) with the FCFS rule is an NP-hard problem, the number of feasible solutions of the model increases exponentially with the number of workers. It is difficult to find the Pareto-optimal solutions for the large-scale problems within a reasonable computational time. For the small-scale problems, we propose an improved enumeration algorithm to obtain its Pareto-optimal solutions.

In the multi-objective line-cell conversion towards reducing worker(s), there are two objectives of minimizing the number of workers and minimizing the TTPT. If using the common enumeration algorithm for the multi-objective optimization, Deb et al. (2002) stated that the time complexity is $O(MN^2)$, where M is the number of objectives and N is the number of feasible solutions (i.e., Property 4).

To decrease the time complexity $O(MN^2)$, we propose an improved exact algorithm which converts the multi-objectives optimization into the single objective optimization. We firstly obtain 2^W-2 non-empty proper subsets of the set $\{1,2,\ldots,W\}$. For every non-empty proper subset, its unordered set partition is produced as the feasible solutions and search the solution with the minimum TTPT as its optimal solution. By comparing the numbers of workers and TTPT among the 2^W-2 solutions, at most $W-1$ non-dominated solutions can be obtained. The improved exact algorithm can be expressed as follows:

Input: W (the number of workers in line).

Output: The set of Pareto-optimal solutions of the multi-objective line-cell conversion towards reducing worker(s).

(1) Initialization. Set $P=\Phi$ (the set of non-empty proper subsets of the set $\{1,2,\ldots W\}$), $F=\Phi$ (the set of solution with the minimum TTPT in every non-empty proper subset). $N=\Phi$ (the set of solutions attending final non-dominated sorting).
(2) Generate 2^W-2 non-empty proper subsets (P_i) of the set $\{1,2,\ldots,W\}$ by recursive algorithm. The cardinality of P, $|P|=2^W-2$.
(3) For each $P_i \in P$ do
    Produce the set of ordered set partitions (S_i) of P_i as the set of feasible solutions.
    Initialize the minimum TTPT (mTS_i) of S_i. $mTS_i=\infty$ (infinity).
        For each $s_j \in S_i$ do
            If the TTPT of $s_j < mTS_i$ then
                $mTS_i=$ TTPT of s_j

Table 1
The parameters of the example of the multi-objective line-cell conversion towards reducing worker(s).

Factor	Value
Product Types	5
Batch Size	$N(50,5)$
ε_i	$N(0.2,0.05)$
SL_n	2.2
SC_n	1.0
T_n	1.8
η_i	10

$N(50,5)$: Normal distribution ($\mu=50$, $\sigma=5$).

Table 2
The coefficient of influencing level of skill to multiple stations for workers (ε_i) .

Worker	1	2	3	4	5	6	7	8	9	10
ε_i	0.18	0.19	0.2	0.21	0.2	0.2	0.2	0.22	0.19	0.19

Table 3
The data distribution of worker's level of skill (β_{ni}).

Product Type				
1	2	3	4	5
$N(1,0.1)$	$N(1.05,0.1)$	$N(1.1,0.1)$	$N(1.15,0.1)$	$N(1.2,0.1)$

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

Worker/Product	1	2	3	4	5
1	1.02	1.05	1.1	1.05	1.13
2	1.09	1.15	1.16	1.24	1.29
3	0.96	0.98	1.06	1.16	1.22
4	0.94	0.99	1.1	1.09	1.1
5	0.96	1.1	1.08	1.07	1.23
6	0.92	0.97	1.12	0.99	1.2
7	1.1	1.13	1.13	1.22	1.27
8	0.98	1.08	1.06	1.3	1.16
9	1.03	1.03	1.13	1.25	1.11
10	0.97	1.14	1.2	1.21	1.22

Else
$j=j+1$
Add mTS_i into F.
(4) According to the number of workers, partition F into $W-1$ subsets (F_s). In every subset, all elements have the same number of workers.
(5) For each $F_s \subseteq F$ do
Initialize the minimum TTPT (mTF_s) of F_s $mTF_s=\infty$ (infinity).
For each $f_j \in F_s$ do
If the TTPT of $f_j < mTF_s$ then
mTF_s=TTPT of f_j
Else
$j=j+1$
Add mTF_s into N.
(6) Output non-dominated solutions of N.

According to the steps (4) and (5), there are at most $W-1$ solutions attending the non-dominated sorting, so the time complexity is $O(M(W-1)^2)$.

Table 5
The data of batches.

Batch number	*Product type*	*Batch size* (B_m)
1	3	55
2	5	53
3	3	54
4	4	49
5	1	49
6	4	55
7	1	54
8	2	48
9	2	48
10	3	48
11	2	46
12	4	58
13	3	48
14	4	52
15	5	48
16	5	51
17	1	54
18	4	57
19	2	54
20	5	49
21	1	53
22	3	46
23	4	45
24	5	46
25	2	45
26	3	44
27	1	53
28	4	47
29	2	53
30	3	52

4.2. Test instances

The experimental data are described in Tables 1–5. They show the parameters of the experiment, the workers' coefficient of influencing level of doing multiple assembly tasks, the data distribution of worker's level of skill for each product type, the detailed data of each worker's skill level for each product type, and the data of 30 batches with 5 product types and lot sizes (50), respectively.

Table 1 shows the distribution of coefficient of influencing level of doing multiple assembly tasks for each worker (ε_i) is $N(0.2,0.05)$. The detailed data of ε_i are given in Table 2.

Table 3 shows that the mean of skill level of each worker for product type $n(\beta_{ni})$ has a range from 1 to 1.2. We fix the standard deviations as 0.1. For example, the first column represents the distribution of skill level of each worker for product type 1 (β_{1i}) is N (μ =1, σ =0.1). The detailed data of β_{ni} are given in Table 4.

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

In Table 5, 5 product types are divided into 30 batches. The mean of each batch's lot size is 50. For example, for the first batch, its product type is 3 and lot size is 55.

For the instance with W workers, we use the following data set from Tables 1–5: the entire Table 1, the first W rows of Table 2 and Table 4, and the entire Table 5.

4.3. Hardware and software specifications

The improved enumeration algorithm was coded in C# and executed on an Intel Core(TM) 2 processor at 2.66 GHz under Windows XP using 3.49 GB of RAM.

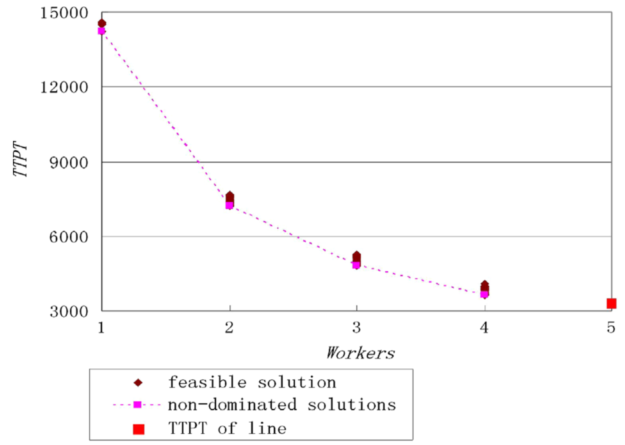

Fig. 3. The feasible and Pareto-optimal solutions of the instance with 5 workers.

4.4. Results of computational experiments

There are 540 feasible solutions for the instance with 5 workers. Using the improved enumeration algorithm, the 30 feasible solutions with the minimum TTPT in every non-empty proper subset and the final 4 Pareto-optimal solutions are shown in Fig. 3. There the solution {1, 3, 4, 5} has just one cell and four workers, and its TTPT is 3672. The value is near but over the TTPT of line (3525), however, by using fewer workers. In this case, there is not any solution whose number of workers is smaller and the TTPT is less than those of line simultaneously.

From Fig. 3, we can observe that reducing number of workers may increase TTPT, even so there are still two improvements can be performed. One is the discussion on how much workers can be reduced for a given TTPT of a fixed assembly line. For example, in Fig. 3, reducing one worker just leads to a 4% TTPT increase, which may be improved by other Kaizen actives like as lot split, cross training. Other is the discussion on reducing worker(s) and improving the TTPT performance simultaneously. That is using less number of workers to get better TTPT performance. We use several examples shown in Table 6 to explain it.

Table 6 shows all satisfying solutions produced by the improved enumeration algorithm and the optimal unsatisfying solutions for the lines with 6, 7, 8 and 9 workers. The TTPTs of these lines are 3581, 3649, 3748 and 3809, respectively. The TTPT of the solutions are shown in last row. Additionally, the solutions marked with ^{ou} and $*$ are the optimal unsatisfying solutions and the Pareto-optimal solutions, respectively. Other solutions are satisfying solutions.

4.5. Discussion

It can be observed from Table 6 that, firstly reducing worker(s) without decreasing productivity can be achieved through the line-cell conversion, in the Pareto-optimal solutions at least one worker (in the case of 9 workers is two workers) may be reduced and the TTPT are less than that of line. That is to say in our examples reducing about 10–20% of workers may also increase about 3–12% productivity.

Secondly the cell formations may have different types in which reducing worker(s) and increasing productivity are achieved simultaneously. For example in the case of 6 workers, two cells with two types ({4,5}, {2,3,6}) and ({3,4,}, {1,2,6}) and three cells with four type ({1},{2,4},{3,5}), ({5},{1},{2,3,6}), ({5},{1},{2,4,6}), ({5},{6},{1,3,4}) satisfied the objectives but with different TTPT. The more the number of workers, the more complicated the cell types. It gives us suggestions to select an appropriate cell formation and assign rationally the workers to the cells. Additionally, in any case

Table 6
All satisfying solutions and the optimal unsatisfying solution of reducing worker(s) for the instances with 6, 7, 8 and 9 workers.

Workers in line	Cell formation	Workers reduced	TTPT
6	{1,3,4,6}	2	4353^{ou}
6	{{4,5},{2,3,6}}	1	3571
6	{{3,4},{1,2,6}}	1	3564
6	{{1},{2,4},{3,5}}	1	3557
6	{{5},{1},{2,3,6}}	1	3553
6	{{5},{1},{2,4,6}}	1	3541
6	{{5},{6},{1,3,4}}	1	3469*
7	{{5},{6},{1,3,4}}	2	4044^{ou}
7	{{2,5},{1,3,4,7}}	1	3530
7	{{1,5,6,7},{2,3}}	1	3518
7	{{2,6,7},{1,4,5}}	1	3518
7	{{4,5,6,7},{2,3}}	1	3512
7	{{1,4,6,7},{2,3}}	1	3506
7	{{5},{1,4,6},{2,3}}	1	3447*
7	{{5},{1,4,6},{3,7}}	1	3447*
8	{{3},{4},{8},{1,5,6}}	2	3879^{ou}
8	{{2},{1,7,8},{3,4,5}}	1	3458
8	{{7},{5},{2},{1,3,8},{6}}	1	3438
8	{{8},{5},{2},{1,4,7},{6}}	1	3438
8	{{2},{6,7,8},{1,3,4}}	1	3431
8	{{2},{4,7,8},{3,5,6}}	1	3425
8	{{1,5,6},{3,4,7},{2}}	1	3409
8	{{1,5,6},{2,3,4},{8}}	1	3381
8	{{8},{3,4,7},{1,5,6}}	1	3368*
9	{{2,3,5,6},{1,4,9}}	2	3816^{ou}
9	{{1,5,6},{2,3,4},{8}}	2	3803
9	{{7},{1,5,6},{3,4,9}}	2	3797
9	{{8},{3,4,7},{1,5,6}}	2	3788
9	{{5,6},{1,3,4,8,9}}	2	3780*
9	{{8},{1,4,5,9},{2,3,7}}	1	3397
9	{{2,7},{1,5,9},{3},{6},{8}}	1	3366
9	{{2,9},{1,4,7},{3},{6},{8}}	1	3364
9	{{2,5},{4},{1,7,9},{6},{8}}	1	3364
9	{{2,7},{4,5,9},{3},{6},{8}}	1	3364
9	{{3,4,5},{2,7,9},{1,6}}	1	3350
9	{{1,3,8},{4,6},{2,5,7}}	1	3349
9	{{2,8,9},{3},{1,4,5,6}}	1	3336*

of cell formation, cutting the lowest skill worker may cause better balancing than any other one. For example, in the instances with 6, 7 and 8 workers, the optimal solutions always reduce the worker 2 whose skill is the lowest; and for the instance with 9 workers, the optimal solution reduces workers labeled as 2 and 7, because their skills are the lowest among 9 workers (see Table 4).

Thirdly there exists a possibility to reduce more workers by the line-cell conversion. Two results can explain it. The first result is the possibility of reducing worker(s) that is increasing with the number of workers, which can be observed by comparing the optimal unsatisfying solutions of reducing worker(s) in the cases 7, 8 and 9. For reducing two workers, the differences of TTPT with line are 395 (i.e., 4044–3649), 131 (i.e., 3879–3748) and 7 (i.e., 3816–3809). That means we have a larger possibility to reducing more workers in a larger number of workers. Second result is shown in the case of 9 workers. In the case of 8 workers, two workers reduction may lead to worse productivity (a larger TTPT (3879) than that of line (3748). However in the case of 9 workers, there are several cell formations which can achieve better TTPT by reducing two workers (there are 5 cases of reducing two workers but just one case has worse TTPT and other four cases have better TTPT). For clearly showing how much workers can be reduced by the line-cell conversion, we define *dTTPT* is the difference of TTPT and expressed as follows:

$$dTTPT = TTPT\ \text{of line} - \text{Min}TTPT\ \text{ofcell} \tag{14}$$

Clearly, if *dTTPT* is larger than zero, then the TTPT performance of the line-cell conversion is better than that of line. Fig. 4 shows

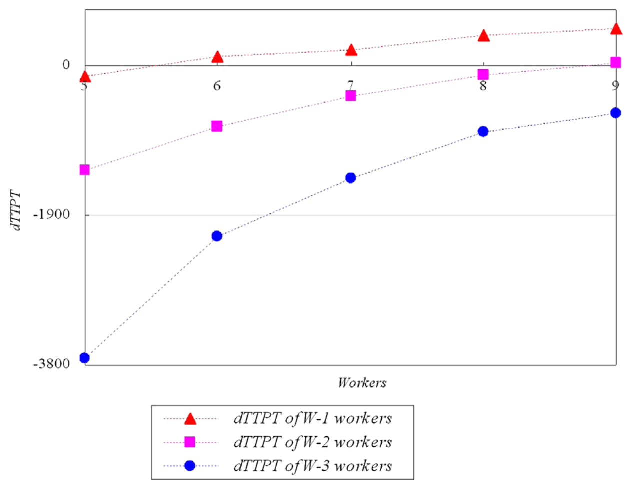

Fig. 4. The relationship between *dTTPT* and number of workers.

the influence of the number of workers on reducing worker(s). It can be observed from Fig. 4 that *dTTPTs* increase with the increasing of number of workers. When $W>5$, *dTTPT* of $W-1$ workers is always larger than zero. That means the line-cell conversion may reduce 1 worker and not decrease TTPT performance for the instances with 6, 7, 8 and 9 workers. However, almost *dTTPTs* of $W-2$ workers are smaller than zero except the case of 9 workers. That means the line-cell conversion may reduce 2 workers and not decrease TTPT performance for the instances with 9 workers but not in the other cases. In our experiment conditions, all *dTTPTs* of $W-3$ workers are larger than zero. That means reducing 3 workers in our situations is not possible to decrease TTPT performance.

Additionally, there may exist multiple optimal solutions in the line-cell conversion. For example in the case of 7 workers, two cell formations of ({5},{1,4,6},{2,3}) and ({5},{1,4,6},{3,7}) are optimal with the same TTPT. It seems true in practice because there may exist different workers but with the same level of skill. Moreover, the performance of reducing worker(s) is also possibly influenced by other operating factors, such as worker's level of skill, batches and lot sizes. However, which operating factor significantly influences the performance of reducing worker(s) is not clear in this research. Both clarifying such relationship and how to format cell and load cell are key issues in successful line-cell conversion towards reducing worker(s) and the TTPT. Therefore, they will be researched in the future.

5. Conclusions and future research

Our contributions in this paper are following. First of all, we present a multi-objective line-cell conversion with the two goals of minimizing the number of workers and minimizing the TTPT. Second, several theorems show that the defined multi-objective line-cell conversion model is an NP-hard problem, and several mathematical insights on solution space are clarified. Third, we propose an improved exact algorithm to obtain the Pareto-optimal solutions of the small-scale problem. By several numerical experiments and performance comparison between cell and line, we illustrate that the line-cell conversion can be used to reduce worker(s) and the TTPT simultaneously.

The research on the line-cell conversion is relatively lacking. A thorough research problem list can be found in Yin et al. (2012), such as partially cross-trained workers (i.e., a worker cannot perform all assembly tasks), different products have different assembly tasks, cost of *karakuri* (i.e., duplication of equipment), human and psychology factors, and so on.

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