A Review: Practice and Theory in Line-Cell Conversion

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1. Introduction

Since the 1990s, Japanese manufacturers had been faced with a dynamic production environment of decreased market demands and increased product variations. To survive in such an extremely tough business environment, the traditional high-volume conveyor assembly lines were no longer fulfilled. Speedy adjustments were needed to handle transitions in product models and demands. A company's competitiveness was becoming dependent on whether or not it can respond to these transitions. Instead traditional conveyer assembly line, several flexible manufacturing methods were developed to handle the outside changing factors like as varying product types, smaller batch sizes, varying task sizes, and inside changing factors like as flexible layout and planning, cross-training of workers. These challenges and innovations of manufacturing methods have resulted a remarkable improvement in productivity, reduction on capital investment, shortened lead times, saving of manufacturing work space, improvement in product quality, decreasing work in process and parts storage, and so on.

Traditionally, such innovations have been called totally *Seru Seisan* (cellular manufacturing or shorten it by CM) in Japan, because the system was adopted usually a U-shaped layout in which one (or multiple) worker carries out all of the operations of a job. However, even it is not a problem in Japan because the special characteristic of Japanese, the naming may confuse the understanding of the innovations against traditional cellular manufacturing. In fact, we refer the new innovations now in Japan include the traditional cellular manufacturing. For example, Tanaka (2005) reported that there are seven manufacturing methods have been used to correspond the new manufacturing in RICOH UNITECHNO Inc., which is a middle scale Japanese company to manufacture facsimiles/copy machines/printers. Those methods are as follows: (1) One worker-One machine method (the product will be assembled by only one worker, he should do all of the assembly operations); (2) Two workers-One machine method (there are too operational works to assemble for a larger machine that can not complete by one worker, in such case two workers should be assigned to do this assembly operation); (3) Cart pulling method (instead conveyor line a cart is used as transport tool, which is pulled among several workers to complete the

assembly operations); (4) Relay method (the form of assembly line is existed but the workers assigned in the line do not only those operations for themselves but also the operations not assigned for them, by their operation ability); (5) Conveyor assembly line (traditional assembly method is also remained for those large lot size products); (6) One worker cell (only one worker does all of the assembly operations of products usually in a U-shaped layout. The difference with method (1) is that the worker in the cell can do all of assembly operations of several products, that means he has a higher operation ability.); (7) Division cell (several workers are assigned in a cell, who may do the assembly operations using the methods of (3), (4) or (6)). Those methods and their combinations are used to correspond flexibly different kinds (over 400 kinds of products) and different quantities (70% of products are under 100 units/month) of products, and successful performances were gained. Therefore, to distinguish the circumstance of converting traditional conveyor assembly line (shorten by CAL) to new production system (including CM) in Japanese manufacturer's real life from previous situation of changing traditional function layout to CM, the circumstance of converting CAL to CM is called line-cell conversion in this chapter. It should be pointed that line-cell conversion is based on the reflection of mass conveyor manufacturing and is for searching more effective production systems, so that converting old conveyor assembly line to new production systems is a considerable strategy in order to increase the productivity of companies. However, how to complete this conversion is a very complicate decision making problem for those companies who wanted to do such conversion. That means when a company faces a changing production environment and wants to convert their conveyor assembly line to a new production system, then the company must decide that how many cells should be formatted, how many workers should be assigned in each cell and how many workers should be rested in the shortened conveyor line. Moreover, how to evaluate the performance improvement through the line-cell conversion is also an important decision making factor. We define such technical and decision making problems in the line-cell conversion as line-cell conversion problems.
In this chapter, a review of line-cell conversion based on a serial research developed by Kaku, et al. (2008a,2008b,2009b,2009c) is proposed. Firstly a content analysis is examined by reviewing a technical journal (*Factory Management 1995-2006)* published in Japan, in which total 24 cases of line-cell conversion were reported. It can be understood why the line-cell conversion is porpular in Japan and what are the insights of such innovation through the content analysis. Secondly a mathematical model has been built to analyze quantitatively the system performances of line-cell conversion problems. By using the model it can be clarified that how are the system performances influenced by which operating factor of inside and outside. Also a linear weighted method is used to solve the multi objective optimization problem, in which two objectives of total throughput time and total labor power are optimized together. Thirdly the influences of operating factors are analyzed by a L27 arrays experiments. Here four factors are designed to represent the complex production environment, which are multiple types of product, different batches and batch sizes, number of stations, and be very important in the decisions of line-cell conversion.
The remainder of this chapter is organized in the following way. An overview of line-cell conversion is presented in the second section. Then the mathematical model is proposed in third section. A linear weighted method is illustrated by using a simple numerical example in fourth section. A L27 arrays is designed and executed in fifth section, also the result analysis are presented. Finally conclusions are given in the sixth section.

2. Overview of line-cell conversion in Japanese industry

An early document of line-cell conversion was reported by Tsuru (1998), which is based on a questionnaire of 13 factories and one consulting company. These anonymous factories converged in electronic and automobile industries. The main standpoint of the document claimed that line-cell conversion can be recognized as a form of the knowledge of Toyota Production System which has been historically transferred to other industries. At the same period, other large-scale investigation on Japanese manufacturing firms (Economic Research Institute 1997) was reported that 48.2% of the respondents had adopted or were planning to implement line-cell conversion. A tremendous achievement of line-cell conversion was brought from CANON Inc., a famous Japanese electronic company. Takahashi, Tamiya and Tahoku (2003) reported that by introducing line-cell conversion into their factories in CANON, since 1995 there were over 20,000 meters of belt conveyor had been withdrawn and 720,000 square meters of working space from 54 related factories were emptied. The total cost rate was decreased from 62% to 50% during past eight years. Since then the line-cell conversion was coming into fashion in Japanese manufacturers.

2.1 Limitations of conveyor line

It is no necessary to describe the greatness of Fordist paradigm afresh. Its economies of scale attained by mass production and shorter throughput time brought material civilization and modern industrial innovation, and lead the production revolution in past 20th century. In fact, further developments and adaptations brought by variant systems such as automated transfer-lines, mixed-model production lines, and robotized flexible assembly lines which were better suited to new business and competition circumstances, were based on the recognition and consideration of the reflection of conveyer production line. Even the famous Toyota Production System is also not exceptional.

However in recent years, after many companies shifted their production organizations to out of Japan, those manufacturers left behind in Japan have been changing their production systems remarkably. Several manufacturing methods have been developed for strengthening their competitive power. In addition, instead conveyor mass production, only the products what suited the needs of customers (the kinds of products are changing dynamically) should be manufactured flexibly when they were needed (the production quantities are also variable). This changing of production system is constructed with the limitations of classical conveyer line, which have been discussed by a series of Japanese field studies (see Shinohara 1997, Tsuru 1998, Isa and Tsuru 1999, Sakazume 2005, Miyake 2006). Briefly two inefficiencies of conveyer line have been investigated. One is that conveyor line presents a series of detrimental aspects for productivity which may be epitomized by the following seven categories of waste: (1) underutilization of workforce due to the face that line cycle time is bounded by slowest worker; (2) waste of time in reaching work-piece on conveyor and returning it onto conveyor after task completion; (3) waste of inventory due to the holding of work-in-process (WIP) between successive stations; (4) waste due to defective parts and rework; (5) waste of resource capacity during product model changeover; (6) waste due to difficulty in promoting mutual support; (7) waste of waiting time by workers operating partially automated short cycle process that does not allow handling of multiple machines. The other is that conveyer line lacks manufacturing flexibilities in product model changes; introduction of new products; changeover of jigs and devices costly and time-consuming, and layout reconfiguration extremely difficult.

2.2 Motivations for the development of line-cell conversion

Japanese manufacturers have been under strong pressure to devise a more effective and agile production system in face of the limitations of their former systems. The line-cell conversion problems had arisen under this challenging context as a promising and competitive production system alternative. Yagyu (2003) speculated that large manufacturers in Japanese electronics industries were the pioneers to embark on the experimentation of line-cell conversion by the first half of 1990s. Shinohara (1997) contributed to increase the awareness on this matter surveying the initiatives taken by samples of manufacturers that had implemented production systems based on this emerging organization pattern.

Different goals and motivations are driving Japanese manufacturers to embrace line-cell conversion. Among the primary motivations, Yagyu (2003) proposed that (1) the flexibility constraints of production systems organized around conveyor lines and dedicated automated machines to cope with high-mix small-lot production and its fluctuating nature became increasingly evident; (2) the wastes and deficiencies that are intrinsic of conveyor lines have become critical restrictions in the increasingly complex market environment; and (3) an opportunity has been perceived in this shift to reinvigorate the workers' morale and motivation by refreshing production organization practices and establishing more autonomous settings.

The above viewpoints indicate that Japanese manufacturers have identified striking potentials in the line-cell conversion as an alternative that may make up for the incapacity of the conveyor line system to coping with the new issues imposed by the current market and labor environments. Thus, the line-cell conversion can be admitted as an outcome that emerged from the amalgamation of the efforts towards the development of an alternative production system which were driven by these motivations.

2.3 Case studies of line-cell conversion

In this chapter we invested 24 cases of line-cell conversion reported in *Factory Management (1995-2006)* (Appendix 1), which is a common Japanese technical journal facing to factory managers. The cases covered mostly electric appliances and information equipment such as digital camera, printer, CD&DVD player and facsimile machines (92% of the cases). Several manufacturers in the cases like Canon and Fujifilm are playing the leading role in their manufacturing field. These cases represented that line-cell conversion can be adapted to various types of processes, including assembly, finishing, testing, packing, forming, casting, heat treating and so on.

Two kinds of implemental changes in line-cell conversion were classified. One is division method of labor power by setting up U-shaped layout or multiple cells (40% of the cases) and by improving the worker's level of skill to do all of the operations in an assembly process (44% of cases). The other is changing of production layout and equipment by removing of conveyors and expensive automated equipment (44% of the cases) and by composing a line with simple equipment (20% of the cases).The first change shows a change in the division of labor in the line system. This is a series of changes that reorganizes the line so that one or a few workers can do all of the operations, by reducing the number of workers who are involved in the division of labor per line, and expanding the extent of operations per worker. The second change indicates a change of production equipment in the related lines. This is part of a series of changes to the conventional production line carried out by removing the automated equipment such as conveyors and robots, implementing simpler equipments and jigs and tools, and formulating a line with a simple workbench and part boxes.

The system performance improvements achieved by line-cell conversion are popularity with those measures related to productivity, parts storage, work-space, lead time, operators, work-in-process and so on. For example in our cases, by introducing line-cell conversion into their factories, SANYO TOKYO manufacturing, IKEDA Electric, YAMADA Metal, CANON can easily adapt multi-item small-sized products and production volume changes. SONY Mexico also can manufacture 15 models of television and increased their productivity 29%. CANON declared that there are 400 Kaizen activities arranged by workers in 9 months and ULVAN COATING declared that the work defectiveness decreased 50%. TOKIN decreased lead time from one month to a week. SHOWAD DENKI shortened the cycle time from 2 minutes 26 seconds to 1 minute 56 seconds. However, it should be considered that line-cell conversion is a very complex and difficult operation. Sengupta and Jacobs (1998) found environments where the conventional assembly line outperformed assembly cells in a plant that assembles television sets. These environments occurred when conversion also results in an increase in task time or other loss of efficiency in the assembly cells. Shmizu (1997) reported that the performance of the assembly cells used in Volvo was inferior to the more traditional assembly line. There are also several researches reported the advantages and disadvantages of line-cell conversion (see Tsuru 1998, Isa and Tsuru 1999, Sakazume 2005). Combining those researches and the content analysis, we simply illustrate the advantages and disadvantages of line-cell conversion in table 1.

<Advantages>

- Increased adaptability to the market demand fluctuations

(1) Easily adaptable to product volume changes
(2) Easily adaptable to frequent model changes
(3) Easily adaptable to multi-item small-sized products

- Improvement in Q.C.D. competitiveness

(1) improvement in product quality and productivity (13 cases)
(2) decrease the parts storage (5 cases)
(3) decrease the work-space (9 cases)
(4) decrease the lead-time (7 cases)
(5) decrease the operators (8 cases)
(6) decrease the work-in-process inventory (3 cases)

<Disadvantages>

(1) Operators are required to have higher skills
(2) It takes time to acquire the required skills
(3) Operators are required to have a stronger sense of responsibility
(4) Increase the input of machines

Table 1. The advantages and disadvantages of line-cell conversion

As shown in Table 1, the interrelations among 9 advantages were classified that three items concerned the adaptability to the market demand fluctuations, while six items concerned the improvement of Q.C.D (quality, cost, delivery). These advantages suggest that line-cell conversion can lead an effective production system for companies pursuing flexibility in

production with a stable Q.C.D competitiveness, especially under market conditions in which 1) there are drastic fluctuations in demand; 2) frequent model changes are necessary; 3) the company has been obliged to adopt small-lot multi-kind production. Several disadvantages of line-cell conversion were also classified. The first three of disadvantages were related with cross-training of workers and the last is related with possible increasing capital investment.
Based on these findings, the product and process conditions of successful line-cell conversion can be summarized as follows. First, there are three product conditions: 1) low total assembly man-hours while production volume is high; 2) small number of assembly components; 3) small products and components. Secondly, there are five process conditions: 1) high possibility of securing multi-skilled workers because of the low production volume; 2) few difficult operations requiring a high level of proficiency; 3) no need for expensive equipment; 4) high possibility of sharing equipment; and 5) small equipment.
As mentioned above, line-cell conversion is often used to increase manufacturer's competitive ability and may has different multiple objectives. In order to increase the productivity manufacturer may for example either shorten their assembly time per product (per lot) or reduce operators or take both decision polices. It makes the line-cell conversion problems become difficult to analyze and evaluate. That is how could an operating factor influence what objective still be not clear through the content analysis and clarifying such relationship is a very key issue in successful line-cell conversion.

3. Modelling of line-cell conversion problem

3.1 Problem description and modeling

Following mathematical model of line-cell conversion is built by Kaku, et al. (2009) and cited below. We consider a real problem of not only assembly but also assembly manufacturing: there exists a traditional belt conveyor assembly line with multiple assembly stations. Workers were assigned at each station according to a traditional job design method but they have had abilities to do more tasks than that were assigned to them. We assume that the worker's abilities are different with stations and products. Multiple products will be assembled in the conveyor line, each product is able to have different batch sizes but with a known distribution of demand. Products should be assembled by a given scheduling rule like as First Come First Service (FCFS) but with a full batch (i.e., we do not consider batch splitting). When the products are assembled in the conveyor line, the stations and workers used to complete the assembly jobs are active. Because workers have different abilities to do those jobs (which belong to stations and products) how long the batch will be finished is dependent on the worker who has the slowest speed to do the jobs. That means the abilities of the other workers were not useful sufficiently, which may lead to decreasing the motivation of workers. On the other hand, all of the products should be assembled at the same conveyor line with a fixed order; there may be some waiting times in the assembly processing so that we can not response flexibly to the customer's variant demand. Assume that the workers will do all of jobs that they can do even that are not assigned for them, there are several KAIZEN methods be able to implement the assembly conveyor line. For example, workers who have higher abilities could help other workers in the conveyor line; or converting the conveyor line to some assembly cells; or converting part of assembly line to cells in which the frequent flexibilities exist and assigning workers who have higher abilities, and remain the part of conveyor line for workers who have lower abilities otherwise.

Here we consider three types of assembly systems including a pure cell system, a pure assembly line and a hybrid type of cells + assembly line. Because it does not influence the system performance either the cells are set to front or behind of assembly line (Van der Zee and Gaalman 2006). For simplicity and without lose of generality, we assume assembly line is formatted behind assembly cells in the hybrid assembly system as shown in Fig. 1. We propose a two step approach to design the assembly system from Fig. 1. First step is a cell formation approach: if there were only cells formatted in the system (pure cells), we assign all of workers to cells according to their abilities which are different with products and stations (jobs); if there were part of assembly line should be converted to cells, we assign the workers who have higher abilities to cells and remain the workers who have lower abilities into assembly line. As a special example, the case of workers can help each other in the assembly conveyor line just should be considered like as a pure cell in which all workers are assigned in a cell. Finally, pure assembly line is the traditional belt conveyor line.

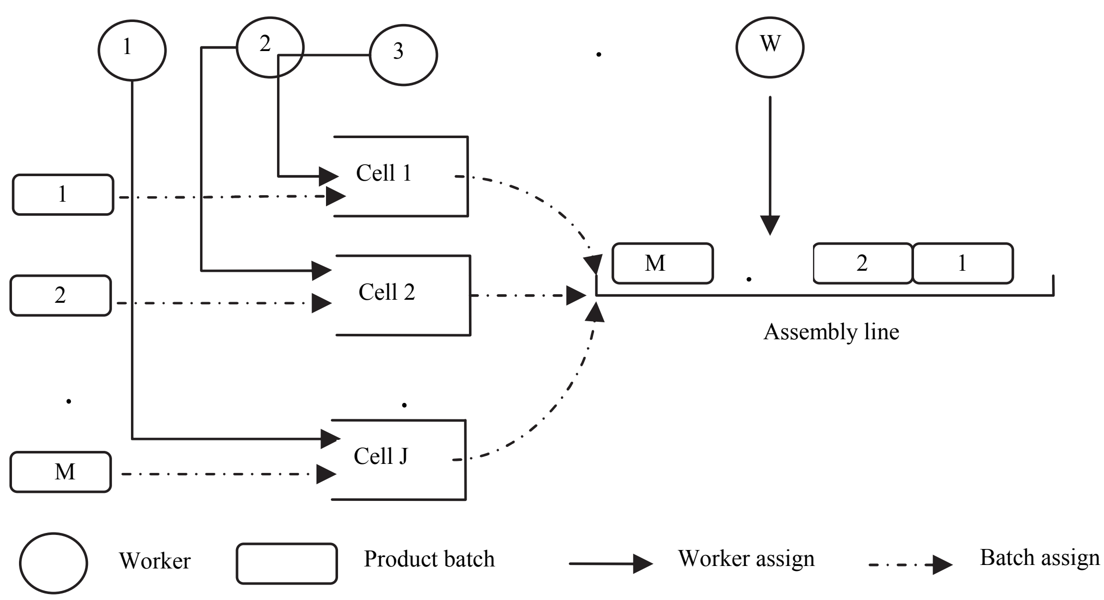


Fig. 1. A hybrid assembly system

The second step is a scheduling approach: We use the FCFS rule to assign assembly product batches to cells or line. In the case of pure assembly line the product batches are just scheduled according to the order of their coming; in the case of pure cells the product batches are scheduled according to not only the order of their coming but also the ability of workers (that means that product should be assigned prior to the worker (cell) who has higher ability to assembly the product). In the case of hybrid system, the product batches are firstly assigned to cells with the FCFS rule, then assigned to assembly line with the order calculated by the earliest finish time rule. Fig. 2 shows an example of the hybrid system with four batches and three cells, where the length of rectangle chart in Fig. 2 states the flow time of that assembly product batch.

For evaluating the system performance two criteria are considered. Firstly we define total throughput time to represent the system productivity that is the time of all of product batches had been assembled. That is to say, for given assembly product mix instead assembly line the new production system should have a shorter total throughput time. Secondly we define total labor power (hours) to represent the work efficiency that is the cumulative working time of all of workers assigned in the system. Therefore, our problem is to determine the number of cells and number of workers in each cell to minimize the total throughput time and total labor power.

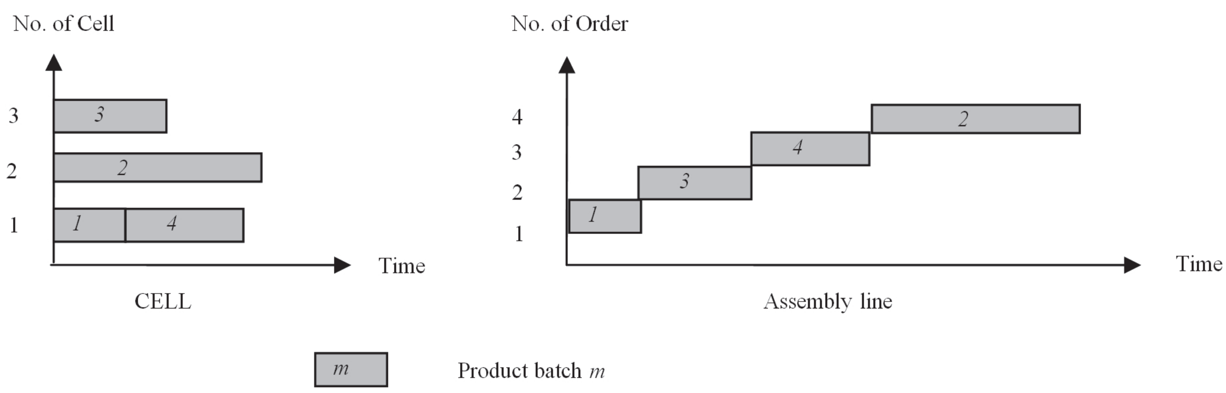


Fig. 2. An example of scheduling in the joint cells + assembly line system

3.2 Problem features and assumption

Following assumptions are considered in this chapter to construct the model:

1. Multiple products are planned to assembly with a product mix.
2. The products are assembled with different batches and different batch sizes.
3. The types and batches of products are known and constant.
4. The number of assembly tasks is the same to all of product types (if the tasks of products were different then assume the task time to do the different tasks was zero so that we can treat the products with different assembly tasks).
5. If the assembly system is a conveyor line, just one conveyor line is considered.
6. The number of workers is same with the number of tasks on assembly line.
7. A worker only does one assembly task in assembly line.
8. The number of workers in each cell may be different but limited.
9. The number of tasks assigned to each cell is the same.
10. The number of tasks assigned to each cell is at least greater than a constant (that means the workers assigned in the cell should do more tasks than in assembly line).
11. A worker assigned in a cell can operate all the tasks assigned in a cell.
12. An assembly product batch is just processed in a cell.
13. Setup time is considered when two different types of product have been assigned into a cell, but the setup time between two batches with the same product type is zero.

3.3 Notations

We define the following terms:

- Indices

i : Index set of workers $(i = 1,2,...,W)$.
j : Index set of cells $(j = 1,2,...,J)$.
n : Index set of product types $(n = 1,2,...,N)$.
m : Index set of product batches $(m = 1,2,...,M)$.

k : Index set of sequences of product batches in a cell $(k = 1,2,...,M)$.
r : Index set of orders of product batches in the assembly line $(r = 1,2,...,M)$.

- Parameters

$W_{\max}$: Maximum number of workers in one cell.
$S_{\min}$: Minimum number of stations in one cell.
V_{mn} : A 0-1 binary variable where $V_{mn} = 1$, if product type of product batch m is as same as product type n ; otherwise 0.
B_m : Size of product batch m .
T_n : Balanced cycle time of product type n in the assembly line.
SL_n : Setup time of product type n in the assembly line.
SC_n : Setup time of product type n in a cell.
ε_i : Coefficient of influencing level of skill to multiple stations for worker i .
η_i: Upper bound on the number of tasks for worker i in a cell, if a number of tasks assigned to a worker is over than it, the task time will become longer than ever.
β_{ni} : Level of skill of worker i for one task of product type n .

- Decision variables

X_{ij} = 1, if worker i is assigned to cell j , otherwise 0.
Y_i =1, if worker i is assigned to line, otherwise 0.
Z_{mjk} =1, if product batch m is assigned to cell j in sequence k , otherwise 0.if $k = 0$, $Z_{mjk} = 0$.
O_{mr} =1, if product batch m is assembled by order r in the assembly line, otherwise 0. Moreover, if $r = 0$, then $O_{mr} = 0$.

- Variables

C_i : Coefficient of variation of assembly task time of worker i in each cell accounting for the effect of multiple stations.
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.
SL_m : Setup time of product batch m in the assembly line.
TL_m : Assembly task time of product batch m per station in the assembly line.
FL_m : Flow time of product batch m in the assembly line.
FLB_m : Begin time of product batch m in the assembly line.
P = 1, if the assembly line exists in the hybrid assembly system, otherwise 0.

3.4 Problem formulation

Here we consider the assembly planning problem which is based on a fixed assembly product mix with M product batches and N product types. W workers are assigned to the system which may be pure assembly cells or pure assembly line or a joint type system. Given the upper bound $W_{\max}$ on the number of workers and the lower bound $S_{\min}$ on the number of stations in a cell, the objective is to determine the number of cells and workers in each cell to minimize the total throughput time and the total labor hours.

3.4.1 Scheduling of assembly batches in cells

For defining the total throughput time of the assembly batch assignments in cells, the assembly plan will be scheduled with a given scheduling rule under the worker assignments to cells. Firstly, a worker's level of skill is able to vary with the number of tasks. If the number of tasks is over an upper bound η_i, the task time will become longer. This can be represented as below:

$$C_i = 1 + \varepsilon_i \max((W - \sum_{i'=1}^{W} Y_{i'} - \eta_i), 0) \quad \forall i \tag{1}$$

Secondly, the task time of a product is also able to vary with workers. Consequently, the task time of a product is calculated by mean task time of all workers in the same cell. Actually, the task time of product batch m per station in a cell is represented via following equation:

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

Then, using the FCFS rule, the setup time SC_m, the flow time FC_m and the begin time FCB_m of product batch m are represented as below.

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

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

$$FCB_m = \sum_{s=1}^{M}\sum_{j=1}^{J}\sum_{k=1}^{M}\sum_{k'=0}^{k-1} (FC_s + SC_s) Z_{mjk} Z_{sjk'} \tag{5}$$

Where, equation (3) states the setup time of product batch m. If there are more than two batches assigned in a cell and the type of those batches is same then the setup time will be set to be zero. Equation (4) states the flow time of product batch m. 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 one product batch is the aggregation of flow time and setup time of all the prior product batches which are in the same cell.

3.4.2 Scheduling of batches production in the assembly line

For defining the total throughput time of the assembly batch assignments in the assembly line, the assembly plan will be scheduled with a given scheduling rule under the worker assignments. Therefore, if all workers are assigned to the assembly line, then that is a traditional assembly line system; otherwise, that is a hybrid assembly system. Here, the task time is calculated by the longest task time among the workers in the assembly line. Actually, the task time of product batch m is represented via the following equation:

$$TL_m = \sum_{n=1}^{N} \max(V_{mn} T_n \beta_{ni} Y_i) \qquad \forall i \tag{6}$$

Then, using the FCFS rule, the setup time SL_m, the flow time FL_m and begin time FLB_m of product batch m are presented as below.

$$SL_m = \sum_{n=1}^{N} SL_n V_{mn} (1 - \sum_{m'=1}^{M} V_{m'n} O_{m'(k-1)}) \quad O_{mk} = 1, \forall k \tag{7}$$

$$FL_m = \sum_{n=1}^{N} \sum_{i=1}^{W} V_{mn} T_n \beta_{ni} Y_i + TL_m (B_m - 1) \tag{8}$$

$$FLB_m = \begin{cases} \max(FCB_m + FC_m + SC_m, FLB_{m'} + FL_{m'} + SL_{m'}) \\ \qquad \left\{ m' \middle| O_{mk} = 1, O_{m'(k-1)} = 1 \quad k = 2,3,\ldots,M \right\} \\ FCB_m + FC_m + SC_m \qquad O_{m1} = 1 \end{cases} \tag{9}$$

Where, equation (7) states the setup time of product batch m. If the product type of coming product batch is as same as the preceded product batch, the setup time of this product batch will be set to be zero. Equation (8) states the flow time of product batch. Equation (9) states the begin time of each product batch. If the production system is the hybrid one, the waiting time between two product batches will be considered, otherwise no consideration for waiting time. In the hybrid model, the begin time of product batch m is the maximum value between the end time of the prior product batch in assembly line and the end time of product batch m in cells. In the assembly line model, the begin time of product m is the end time of the prior product batch which is assigned by the FCFS rule.

3.4.3 The comprehensive mathematical model

The comprehensive mathematical model is given in equation (10)-(23) as below.
Objective functions:

$$TTPT = Min\left\{ \underset{m}{Max}\left[(1-P)(FCB_m + FC_m + SC_m) + P(FLB_m + FL_m + SL_m) \right] \right\} \tag{10}$$

$$TLH = Min \sum_{m=1}^{M} \sum_{i=1}^{W} \left(\sum_{j=1}^{J} \sum_{k=1}^{M} FC_m X_{ij} Z_{mjk} + FL_m Y_i \right) \tag{11}$$

Subject to

$$\sum_{i=1}^{W} X_{ij} \le W_{\max} \qquad \forall j \tag{12}$$

$$\sum_{i=1}^{W} X_{ij} \le \sum_{i=1}^{W} X_{ij'} \qquad \forall j > j', (j = 1,2,..J) \tag{13}$$

$$\sum_{i=1}^{W} Y_i \leq W - S_{\min} \tag{14}$$

$$\sum_{j=1}^{J} X_{ij} + Y_i \leq 1 \qquad \forall i \tag{15}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{M} Z_{mjk} = 1 \qquad \forall m \tag{16}$$

$$Z_{mjk} \leq Z_{m'j(k-1)} \qquad \forall m, m' = 1,2,...,M, m' \neq m, k = 2,3...,M \tag{17}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{M} Z_{mjk} = 0 \qquad \{j \left| \sum_{i=1}^{W} X_{ij} = 0, \forall j \right.\} \tag{18}$$

$$FCB_m \leq FCB_{m+1} \qquad \forall m \tag{19}$$

$$\sum_{m=1}^{M} O_{mr} = 1 \qquad \forall r \tag{20}$$

$$\sum_{r=1}^{M} O_{mr} = 1 \qquad \forall m \tag{21}$$

$$\begin{gathered} O_{mr} FLB_m \geq O_{m'(r-1)} (FLB_{m'} + TL_{m'} + SL_{m'}) \\ \forall m, m' = 1,2,...,M \end{gathered} \tag{22}$$

$$P = \begin{cases} 1 & \sum_{i=1}^{W} Y_i \geq 1 \\ 0 & \sum_{i=1}^{W} Y_i = 0 \end{cases} \tag{23}$$

Where, equation (10) states the objective to minimize the total throughput time (TTPT) of the total product batches assignments. The total throughput time is the due time of the last completed product batch. The first part is the throughput time in cells. The second part is the throughput time in the assembly line. Equation (11) states the objective to minimize the total labor hours (TLH) of the product batches assignments. The total labor hours is the time of all workers assembly the total product batches. The first part is the labor hours in cells. The second part is the labor hours in the assembly line. Equation (12) is a cell size constraint because the space of a cell is limited. The value of the maximum number of workers in one cell will be a function of plant size, design and process technology. Equation (13) is the rule of cell formation ensures that the number of workers in prior cell is greater than that in next cell. Equation (14) is a minimum number of tasks in each cell which means if there were no tasks assigned to cells the production system will become traditional assembly line. Equation (15) is the rule of worker assignment ensures that each worker should be at most assigned to one cell or the line. The sign of inequality means that the worker who has the worse ability is discarded possibly. Equation (16) is the assignment rule in which a product batch is only assigned to a cell. Equation (17) is the assignment rule in which product batches must be assigned sequentially. Equation (18) are the rules of assigning constraints, that means a product must be assigned to a cell in which a worker is assigned at least. Equation (19) is the FCFS rule which means the prior product batch must be assembled before the next product batch. Equation (20) ensures that a product batch must be assigned by a fixed scheduling order. Equation (21) ensures that an order also must be assigned to fix the product batches. Equation (22) ensures that the begin time of a product batch must be late the end time of the prior product batch. Equation (23) is a flag variable shown whether the assembly line exists in the system. This rule can lead a smaller search space of feasible solutions but guarantee the optimality of solutions.

4. A linear weighted method to solve the multi-objective model

4.1 The consideration

By using formula (10)-(23), the line-cell conversion can be described completely that whether the conveyer assembly line should be converted to cell(s) and how to do such conversion. In the above model there are two objective functions of total throughput time and total labor hours, which are most important evaluation factors in line-cell conversion. Usually, increasing manufacturer's productivity can be executed by shortening total through put time or decreasing number of workers or some other efforts. However, shorten total throughput time may lead to increasing demand of workers which offend against the other objective function of total labor hours, and vice versa. So that the objective functions should be solved simultaneously. In this chapter, we just use a linear weighted method to construct the total throughput time and total labor hours into a new utility function in which objective functions are related with a linear weight (usually the linear weighted method should be used in a convex space of solutions, later we show the convex property of solution space with an example but not theoretical proof).

Based on the consideration, the two objectives of total throughput time (*TTPT*) and total labor hours (*TLH*) can be construted together with the linear factors α_1 , α_2 as below.

$$U(X) = \alpha_1 \cdot TTPT + \alpha_2 \cdot TLH$$

where $U(X)$ is the utility function when the solution of the model is X, and α_1 , α_2 are the linear weights. For determining the α_1 , α_2 , we consider following simultaneous equations:

$$\alpha_1 \cdot TTPT^*(X_{TTPT}) + \alpha_2 \cdot TLH^0(X_{TTPT}) = c$$
$$\alpha_1 \cdot TTPT^0(X_{TLH}) + \alpha_2 \cdot TLH^*(X_{TLH}) = c$$

Where, c is a constant (c≠0) and

$$TTPT^*(X_{TTPT}) = \min_X TTPT(X)$$
$$TLH^*(X_{TLH}) = \min_X TLH(X)$$
$$TTPT^0(X_{TLH}) = TTPT(X_{TLH})$$
$$TLH^0(X_{TTPT)}) = TLH(X_{TTPT})$$

Solving the simultaneous equations and set $\alpha_1 + \alpha_2 = 1$, then α_1, α_2 can be shown as bellows.

$$\alpha_1 = \frac{TLH^0(X_{TTPT}) - TLH^*(X_{TLH})}{TLH^0(X_{TTPT}) - TLH^*(X_{TLH}) + TTPT^0(X_{TLH}) - TTPT^*(X_{TTPT})}$$

$$\alpha_2 = \frac{TTPT^0(X_{TLH}) - TTPT^*(X_{TTPT})}{TLH^0(X_{TTPT}) - TLH^*(X_{TLH}) + TTPT^0(X_{TLH}) - TTPT^*(X_{TTPT})}$$

Hence, linear weights α_1, α_2 show the percentages of the objectives. Following we give a simple numerical example to illustrate how to calculate α_1, α_2.

4.2 A simple example

In the hybrid line-cell conversion model, workers assigned in the conveyer line can be considered not only re-assign into a cell but also may remain in the shortened line because they have not enough ability to do those operations in cell. For a given number of workers ($X + Y$), the objective functions are not linear but bounded. Hence, we must conduct an exhaustive search over $X + Y$. For simplifying the calculation but not lose generality, following example only considers the case where all of workers in line be reassigned to cells. Table 1, Table 2 and Table 3 show the parameters, level of skill of workers and coefficient of influencing level of skill to multiple stations for workers, respectively.

Factor	Number	Parameter
Stations	5	$W = 5$
Workers	5	$W = 5$
Lot sizes	10	$B_m = 10$
Batches	5	$M = 5$
Product Types	3	$N = 3$

Table 1. The parameters of line-cell conversion example

Product/Worker	1	2	3	4	5
1 (A)	0.97	0.93	1.19	1.17	1.11
2 (B)	0.96	0.9	1.28	1.26	1.17
3 (C)	0.94	0.87	1.38	1.34	1.23

Table 2. level of skill of workers (β_{nw})

Worker	1	2	3	4	5
ε_i	0.18	0.16	0.29	0.28	0.25

Table 3. Coefficient of influencing level of skill to multiple stations for workers （ε_i）

From Table1, Table 2 and Table3, it can be observed that the conveyer line has five stations in which 3 types of product are manufactured with 5 batches and the lot size of each batch is

10. Five workers are assigned into the line and have different skill level to do those operations of products. The ability of workers is also different with stations. When we are going to convert the line to a cellular manufacturing system, consider that cell may be constructed into several form like one worker cells or multi workers cells, there are total 52 feasible solutions in above case (see Appendix 2). By using the model we can calculate TTPT and TLH for each solution. Therefore,

$$TTPT^*(X_{TTPT}) = \min_X TTPT(X) = 166.13$$
$$TLH^*(X_{TLH}) = \min_X TLH(X) = 766.65$$
$$TTPT^0(X_{TLH}) = TTPT(X_{TLH}) = 201.84$$
$$TLH^0(X_{TTPT)}) = TLH(X_{TTPT}) = 811.14$$

Then the linear weights can be calculated as bellows.

$$\alpha_1 = \frac{TLH^0(X_{TTPT}) - TLH^*(X_{TLH})}{TLH^0(X_{TTPT}) - TLH^*(X_{TLH}) + TTPT^0(X_{TLH}) - TTPT^*(X_{TTPT})} = \frac{811.14 - 766.65}{811.14 - 766.65 + 201.84 - 166.13} = 0.55$$
$$\alpha_2 = \frac{TTPT^0(X_{TLH}) - TTPT^*(X_{TTPT})}{TLH^0(X_{TTPT}) - TLH^*(X_{TLH}) + TTPT^0(X_{TLH}) - TTPT^*(X_{TTPT})} = \frac{201.84 - 166.13}{811.14 - 766.65 + 201.84 - 166.13} = 0.45$$

Finally, the utility function is as bellow.

$$U(X) = 0.55 \cdot TTPT + 0.45 \cdot TLH$$

By using this utility function, the values of *U(X)* can be calculated, which are also shown in Appendix 2. According to the calculating results, optimal solution is two cells {(12), (345)} (() represents one cell and {}represents a solution). if we only consider TTPT, whereas is four cells {(45), (1), (2), (3)} if we only consider TLH. However the total optimal solution is 2 cells {(34), (125)} when the multi objectives should be considered.

Moreover as shown in Figure 3, all of the feasible solutions of the defined line-cell conversion problem are plotted in a two demention space, in which vertical axle is TLH and horizontal axle is TTPT. Then *U(X)* is a straight line contacted the solution of {(12), (345)} and {(45), (1), (2), (3)} and the sloop of dotted line is parallel to α_1/α_2. Moving the line parallely the total optimal solution {(34), (125)} is obtained at the point which contacted with the line and solution space. However, it does not mean that the space of solutions is convex so in general case the linear weighted method may is not appropreate. Here a very theoretical work to make a proof of convexity should be done in future.

Because the linear weights are very important for solving the multi objective line-cell conversion problem, its sensitivity is calculated in Table 4.

As shown in Table 4, there are three intervals in the solution space. In interval of $\alpha_1 \le 0.4$ the optimal solution is {(45),(1),(2),(3)} which means TLH (hours productivity) is considered preferentially; in interval of $0.4 \le \alpha_1 \le 0.8$ the optimal solution is {(34),(125)} which means TTPT and TLH are considered simultaneously; in interval of $\alpha_1 \ge 0.9$ the optimal solution is {(3),(12),(45)} which means TTPT (product productivity) is considered preferentially. Consider that how to increase labor productivity is a main theme of line-cell conversion, it is noticeable that cellular form has an advantage over almost interval of α_1 in above example.

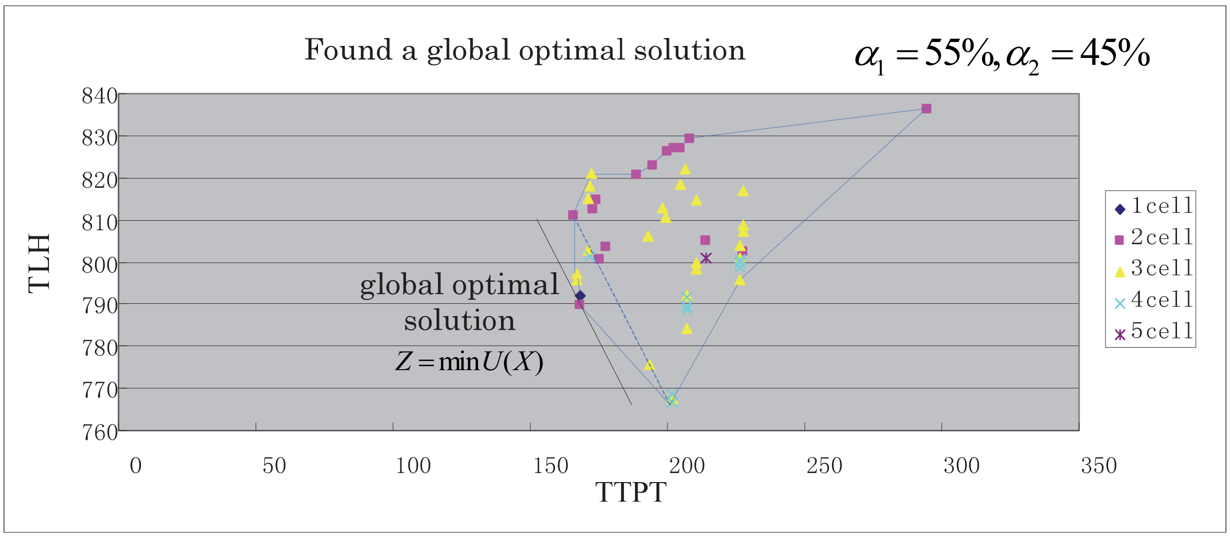


Fig. 3. Geometrical illustration of optimal solution

No	α_1	U(X)	Optimal solution
1	0.1	710.17	(45) (1) (2) (3)
2	0.2	653.69	(45) (1) (2) (3)
3	0.3	624.82	(45) (1) (2) (3)
4	0.4	540.73	(45) (1) (2) (3)
5	0.5	478.86	(34) (125)
6	0.6	416.71	(34) (125)
7	0.7	354.56	(34) (125)
8	0.8	292.41	(34) (125)
9	0.9	229.86	(3) (12) (45)

Table 4. Sensitivity analysis of linear weights

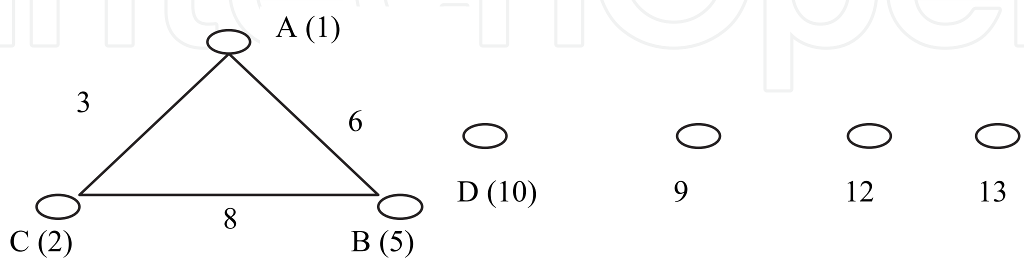
5. Stochastic analysis for operating factors with L27 array

5.1 The L27 experiment design

Therefore, the line-cell conversion problem in a special production environment can be solved completely where how to convert the line to cell and how to assign workers to each cell are optimally determined. However, line-cell conversion in real world is usually considered with changing production environment and the decision-making is depended on those factors influence their production environment. Hence, which factor is how to influence the environment should be defined. In this chapter, we design a L27 experiment to determine which factors most affect the system performance improvement of line-cell conversion with a minimum amount of experimentation thus saving time and resources. The system performance of line-cell conversion is represented by using a multi objective function constructed with total throughput time and total labor hours. Table 5 shows that there are four factors are organized to represent the complex production environment, which are multiple types of product, different batches and batch sizes, number of stations (workers). The first three factors are representing outside influence and the last factor is representing the inside influence. Each factor has three varied levels.

Factors	Level 1	Level 2	Level 3
Station A	4	8	12
Product type B	1	10	20
Lot size C	10	30	50
Batch number D	5	10	15
Worker (A)	4	8	12

Table 5. Experiment factors design



Also three specific 2-factors interactions are investigated through the experiment. Above graph shows the factors (A, B, C and D) and their specific 2-factors (A×B, A×C and B × C) interactions and which column they will be in Appendix 3.

5.2 Analysis and discussion

According to the above design, we do numerical experiments to simulate the effects of factors influenced on the performance improvement of line-cell conversion and show the computational results of the L27 experiment in Appendix 3. Generally, we define an index P which represents the ascendancy of line-cell conversion. i.e., the positive value of P shows an ascendancy of cellular form over line form, and the negative value of P shows the reverse. Figure 4 shows all 27 results in where 10 cases show cellular form is at an advantage over line form, and 17 cases show line form is at an advantage over cellular form. That means cellular form can be used to improve the system performance well when the system (operations) is comparatively smaller. Against, line form is appropriate when there are many stations (operations) needed to assembly a product. However, it does not mean that line form should be used but effort of shortening the line into several cellular forms should be done to improve their manufacturing performance. This is the key strategy for successful line-cell conversion which has been executed by Japanese industries.

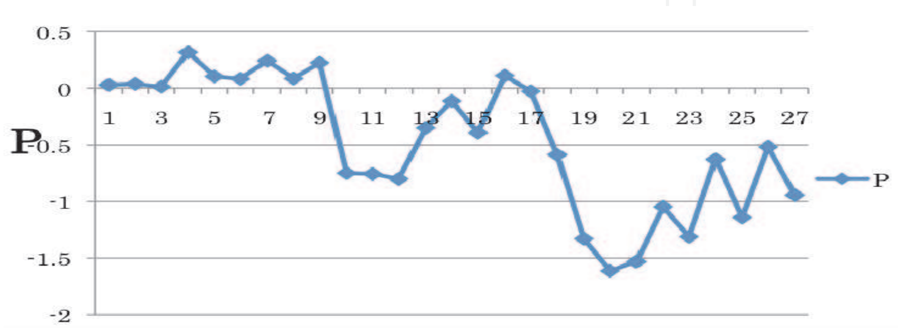


Fig. 4. The index P in 27 cases

For analyzing the effects of each factor and the specific 2-facotrs interactions which may influence the performance of line-cell conversion, detail calculations were made as below. Table 6 shows the calculation results. In Table 6, each column shows the factors, S1, S2, S3 mean the sum of data in all level, m1, m2, m3 show the average value of the data in all level, R1 shows the error and Rank shows the ranking of the factors. From Table 6 it can be observed that workstations (workers), product types, and their interaction are strong, however lot size (which has been considered as a barrier of line-cell conversion) is not almost influencing the performance improvement of line-cell conversion. It can be understood that workstation may give a negative influence on line-cell conversion because the longer of the line, the worse the performance improvement of line-cell conversion, and the product type may give a positive influence vice versa. However, it seems that either line or cell can treat the problem of large lot size their own production form. It is a fact that even by using cell form large lot size production can be executed with same or small throughput time of line with several like lot splitting techniques. Moreover, batches of product show more completed behaviors. For clarifying the tendency of influenced factors, Figure 5 shows the calculated results of each factor in different level respectively.

	A	B	A×B	C	A×C	B×C	D
S1	1.126	-6.705	-3.415	-3.922	-4.636	-3.453	-5.486
S2	-3.669	-3.343	-4.411	-4.116	-3.872	-4.723	-2.704
S3	-10.064	-2.559	-4.781	-4.569	-4.099	-4.431	-4.417
m1	0.125111	-0.745	-0.37944	-0.43578	-0.51511	-0.38367	-0.60956
m2	-0.40767	-0.37144	-0.49011	-0.45733	-0.43022	-0.52478	-0.30044
m3	-1.11822	-0.28433	-0.53122	-0.50767	-0.45544	-0.49233	-0.49078
R1	1.243333	0.460667	0.151778	0.071889	0.084889	0.141111	0.309111
Rank	1	2	4	7	6	5	3

Table 6. The computational results of L27

From Figure5, it can be clearly observed that the system performance improvement was increasing with product types (B) and decreasing with workstations (A) and lot sizes (C). That means varying product types is promoting companies to convert their line to cell, and how to reduce the negative effect of stations and lot sizes is a key issue for a successful conversion. In fact, flexible layout and lot splitting technologies are useful in such KAIZEN activities. However, the system performance improvement is increasing when product batch is changing in a smaller interval but decreasing when product batches become larger.

Also the effects of factors and specific 2-factors interactions are estimated by using the analysis of variance (ANOVA). Table 7 shows the source of variation, degree of freedom, sum of squares, variance and the F-value, respectively. Because the critical value of F-test at 5% significance is $F_{2,6}(0.05) = 5.14$ and $F_{4,6}(0.05) = 4.53$, it can be recognized that three factors (product types, batches and stations), and two specific 2-factors interactions (A×B, A×C) are significant at 5% level. However, the F value of the 2-factors interactions is near the critical value. It can be considered that the interactions are strongly influenced by A because the F value of A is too big. For illustrating those 2-factors interactions under the designed conditions, Figure 6 shows the specific 2-factors interactions（A×B, A×C, B×C）. It can be observed from Figure 6 that the curves are not on a parallel with each other so that they will cross at some other point. That means the specific 2-factors interactions should not be ignored in some special production environment.

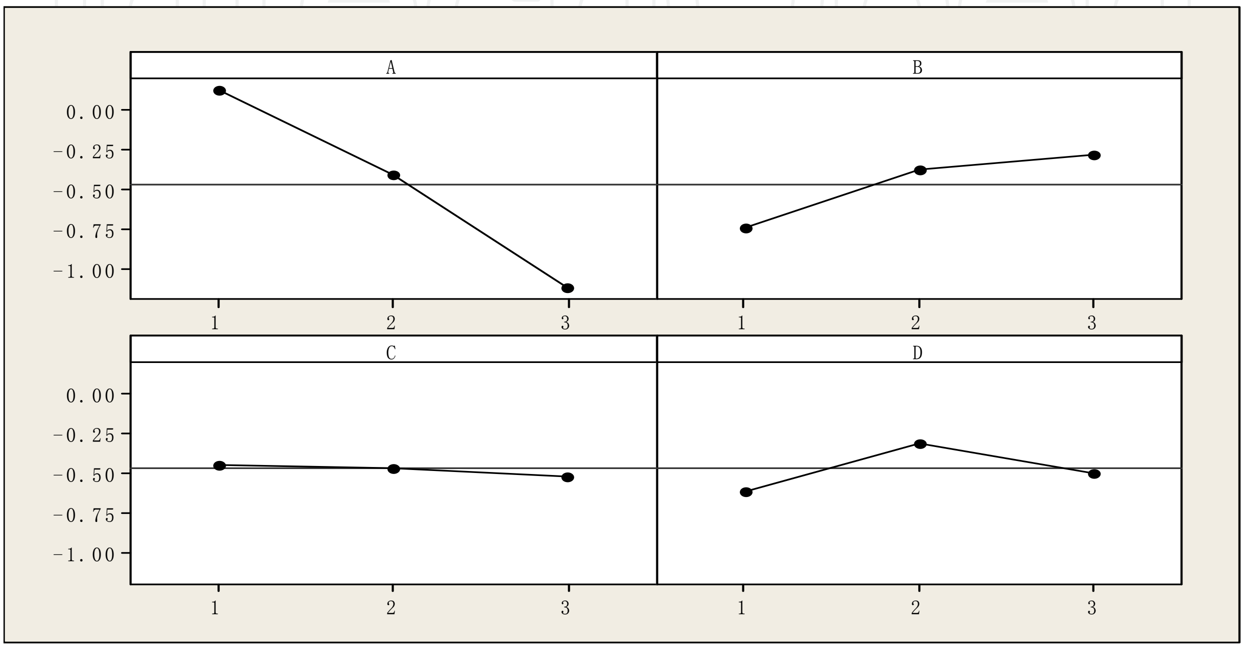


Fig. 5. The influence tendency of factors

Source of Variation	Df	SS	V	F
A	2	7.01532	3.50766	339.79
B	2	1.07815	0.53908	52.22
C	2	0.02457	0.01229	1.19
D	2	0.43788	0.21894	21.21
A×B	4	0.22636	0.05659	5.48
A×C	4	0.18888	0.04722	4.57
B×C	4	0.13871	0.03468	3.36
Error	6	0.06194	0.01032	
Total	26	9.17181		

Table 7. ANOVA results

General speaking, the numbers of station in a belt conveyer assembly line is the largest barrier in line-cell conversion indisputably. For example, a worker could not assembly an automobile only by himself. How many operations (stations) should be assigned to a worker is appropriate depends on many other factors include not only the outside and inside discussed above but also like cross training of workers, complexity of products, learning effect and so on. However, it may start up partially for converting an assembly line to cell not needs complete cross trained worker ability.

6. Conclusions

In this chapter we totally studied line-cell conversion problem. Several contributions are proposed. Firstly an overview of line-cell conversion was proposed by investigating 24 Japanese manufacturing cases. Content and mechanisms analysis on the cases generated the insights of line-cell conversion problems. Secondly we constructed a mathematical model of line-cell conversion with multi objective functions. Thirdly we applied a linear weight method to solve the multi objective problem. Fourthly we investigated some operating factors stochastically by using a L27 array. Through the simulation experiments several operating factors of line-cell conversion were clarified their contributions.

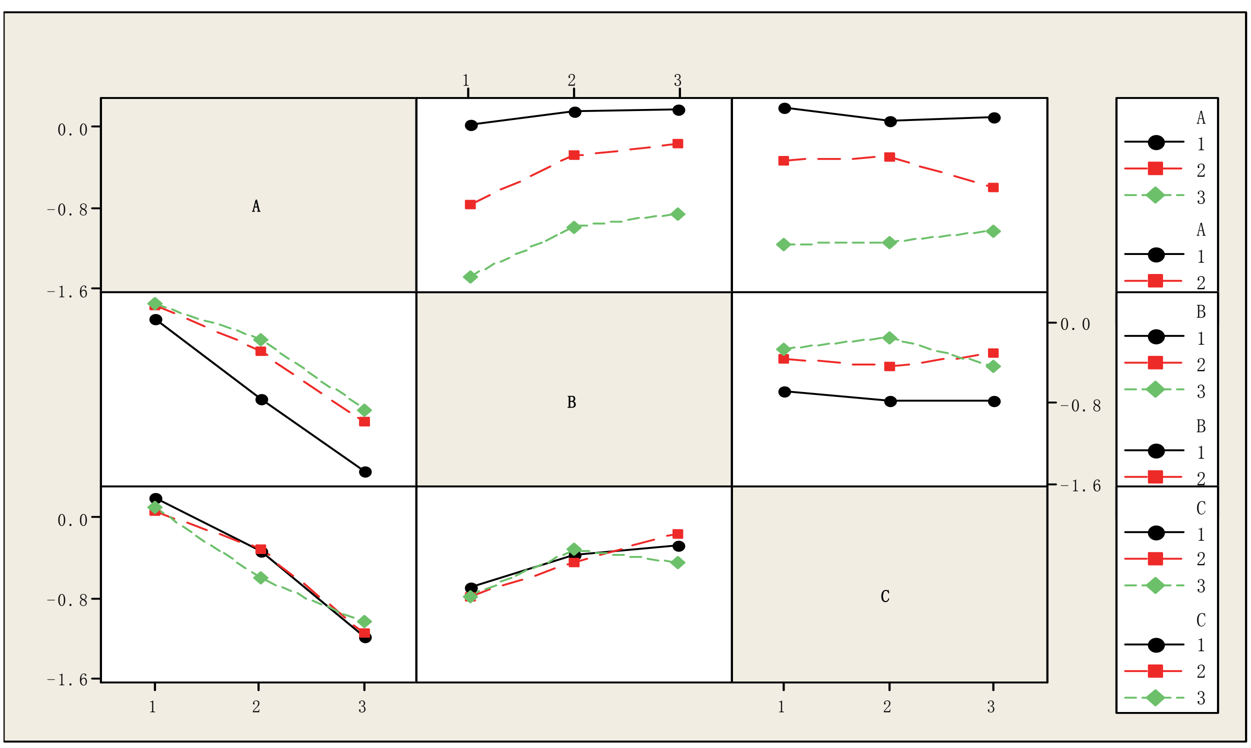


Fig. 6. The 2-factors interactions

7. Acknowledgements

This work is the result of our cooperating research group. I appreciate Dr. Jun Gong, Prof. Jiafu Tang and Prof. Yong Yin for their contributions. I also thank Ms. Lei Yu and Mr. Yang Liu (who were my graduate students) for their helps.

8. Appendix

Firm or factory name	Location	Introduction period	Product
Fuji film Corporation, Yoshida-Minami	Yoshida-Minami Mie		Printer
Fuji film Corporation, Yoshida-Minami	Yoshida-Minami Mie		Digital camera
FUKUTOME Meat Packers LTD	Hiroshima	2004,3	Ham, sausage
SANYO Tokyo Manufacturing Co.,LTD	Tokyo	2002	Cryogenic power generation
SANYO Electric Co.,LTD	Saitama	2002,1	Absorption chiller
Sony Mexico Factory	Mexico	2001	Camcorder
Chinontec Industries Co.,LTD	Nagano	2001,4	Optical equipment
Ikeda Electric Co.,LTd	Osaka		Electric equipment
YAMADA Metal Co.,LTD	Sendai		Automobile installation
ULVAC COATING CORPORATION	Saitama		ULCOAT
SHOWAD DENKI Co.,LTD	Osaka	2000	Electric wires
KANOU SHOU JUAN Co.,LTD	Nagahama, shiga		Japanese-style confection
Unitilka Group Film Division	Osaka		Plastic, resin
Sony EMCS Corp. Minokamo TEC	Gifu		Digital camera
Canon	AmiPlant, Ibaraki	1999	Digital copier
NEC TOCIN Corporation	Sendai	2002	Electron element
Harmonic Drive Systems Inc.	Saitama		Smart theater
Pioneer Corporation	Kawagoe	2000	CD player
Itoki Crebio Corporation	Osaka		Comnet table
STANLEY ELECTRIC Co., LTD	Yamagata	1997	Automobile accessories
Tokin Corporation	Tokyo	2001	Battery cell
Pioneer Corporation, MEC	Kawagoe	2002	CD,VCD player
Pioneer Corporation	Shizuoka		Laser, Display
Nagahama Canon	Nagahama, Shiga	1998	Laser beam printer

Sources: adapted from following materials.
Factory management, 1999, 45 (7), 63-74; 2000, 46(8), 40-42, 57; 2001, 47(14), 5-6, 36; 2003, 49(1), 23-24; 49(2), 4-5, 19, 111-112; 2004, 50(1), 14-19, 28-29; 50(10), 19, 20-27, 31, 39, 51-52, 53-60; 2005, 51(3), 21-22, 45, 65; 51(10), 66-73.

Appendix 1. Reported cases of Japanese firms and factories

	Combinations	TTPT	TLH	U(x)	
1	(12345)	168.39	791.93	448.98	
2	(1)(2345)	227.38	802.34	486.11	
3	(2)(1345)	214.28	805	480.10	
4	(3)(1245)	172.73	812.43	460.60	
5	(4)(1235)	174.26	814.79	462.50	
6	(5)(1234)	294.5	836.34	538.33	
7	(12)(345)	166.13	811.14	456.38	TTPT*
8	(13)(245)	208.22	829.13	487.63	
9	(14)(235)	204.72	826.85	484.68	
10	(15)(234)	194.77	822.89	477.42	
11	(23)(145)	202.43	826.8	483.40	
12	(24)(135)	199.85	826.32	481.76	
13	(25)(134)	188.98	820.55	473.19	
14	(34)(125)	168.11	789.61	447.79	Z=minU(X)
15	(35)(145)	175.41	800.49	456.70	
16	(45)(123)	177.69	803.6	459.35	
17	(123)(4)(5)	172.61	820.86	464.32	
18	(124)(3)(5)	171.4	815.05	461.04	
19	(125)(3)(4)	171.52	818.08	462.47	
20	(134)(2)(5)	207.32	784.14	466.89	
21	(135)(2)(4)	193.29	775.46	455.27	
22	(145)(2)(3)	207.32	792.18	470.51	
23	(234)(1)(5)	226.2	795.67	482.46	
24	(235)(1)(4)	226.2	801.08	484.90	
25	(245)(1)(3)	226.2	803.77	486.11	
26	(345)(1)(2)	201.84	767.37	456.33	
27	(1)(23)(45)	227.38	807.24	488.32	
28	(1)(24)(35)	227.38	808.6	488.93	
29	(1)(25)(34)	227.38	816.93	492.68	
30	(2)(13)(45)	210.8	798.38	475.21	
31	(2)(14)(35)	210.8	799.75	475.83	
32	(2)(15)(34)	210.8	814.72	482.56	
33	(3)(12)(45)	166.97	795.84	449.96	
34	(3)(14)(25)	192.998	806.065	468.88	
35	(3)(24)(15)	199.64	810.47	474.51	
36	(4)(12)(35)	166.97	797.26	450.60	
37	(4)(13)(25)	192.998	806.16	468.92	
38	(4)(15)(23)	198.35	812.68	474.80	
39	(5)(12)(34)	170.99	802.67	455.25	
40	(5)(13)(24)	204.63	818.41	480.83	
41	(5)(23)(14)	206.47	822.18	483.54	
42	(12)(3)(4)(5)	171.52	801.32	454.93	
43	(13)(2)(4)(5)	207.32	788.77	468.97	
44	(14)(2)(3)(5)	207.32	791.48	470.19	
45	(15)(2)(3)(4)	207.32	789.48	469.29	

46	(23)(1)(4)(5)	226.2	799.93	484.38	
47	(24)(1)(3)(5)	226.2	798.61	483.78	
48	(25)(1)(3)(4)	226.2	800.62	484.69	
49	(34)(1)(2)(5)	201.84	768.71	456.93	
50	(35)(1)(2)(4)	201.84	766.7	456.03	
51	(45)(1)(2)(3)	201.84	766.65	456.00	TLH*
52	(1)(2)(3)(4)(5)	214.28	800.77	478.20	

Here combinations of workers show possible form of cells. For example, (12345) shows one cell in which five workers are assigned and (1) (2) (3) (4) (5) show five cells in each of them only one worker is assigned.

Appendix 2. computational results of the simple example

	Contents							Multi objective function			Only conveyer line			Index
Factors	A	B	A×B	C	A×C	B×C	D	Linear weights		Utility function	Objectives		Utility function	P=
No.	1	2	3	5	6	8	10	α_1	α_1	$U_c(X)$	TTPT	TLH	$U_l(X)$	$\frac{U_l(X)-U}{U_l(X}$
1	1	1	1	1	1	1	1	0.203	0.797	323.080	134.59	383.00	332.475	0.028
2	1	1	1	2	2	2	2	0.481	0.519	1470.63	695.38	2300.00	1527.094	0.036
3	1	1	1	3	3	3	3	0.154	0.846	5062.35	1684.57	5751.00	5124.431	0.012
4	1	2	2	1	1	2	2	0.911	0.089	275.66	356.76	878.00	403.658	0.317
5	1	2	2	2	2	3	3	0.354	0.646	2662.08	1347.86	3858.00	2968.470	0.103
6	1	2	2	3	3	1	1	0.339	0.661	1441.91	655.58	2040.00	1570.246	0.081
7	1	3	3	1	1	3	3	(0,1)	(0,1)	(313,1205)	593.79	1410.00	(593,1410)	0.242
8	1	3	3	2	2	1	1	0.346	0.654	861.28	407.18	1224.00	941.034	0.084
9	1	3	3	3	3	2	2	0.873	0.127	1467.61	1524.60	4390.00	1890.215	0.223
10	2	1	2	1	2	1	3	0.222	0.778	3246.29	507.37	2241.0	1854.577	-0.750
11	2	1	2	2	3	2	1	0.511	0.489	3747.81	598.99	3735.0	2132.730	-0.757
12	2	1	2	3	1	3	2	0.084	0.916	12505.45	1195.78	7470.0	6940.255	-0.801
13	2	2	3	1	2	2	1	0.822	0.178	403.09	194.78	777.0	298.323	-0.351
14	2	2	3	2	3	3	2	0.992	0.008	1160.45	1012.68	4888.0	1042.309	-0.113
15	2	2	3	3	1	1	3	0.847	0.153	5260.41	2288.18	12032.0	3775.413	-0.393
16	2	3	1	1	2	3	2	0.992	0.008	389.71	428.76	1629.0	437.997	0.110
17	2	3	1	2	3	1	3	0.932	0.068	2169.64	1707.99	7670.0	2110.883	-0.027
18	2	3	1	3	1	2	1	0.818	0.182	2021.88	691.58	3885.0	1273.556	-0.587
19	3	1	3	1	3	1	2	0.591	0.409	2705.42	410.98	2245.0	1161.523	-1.329
20	3	1	3	2	1	2	3	0.229	0.771	21095.82	1257.97	10101.0	8071.205	-1.613
21	3	1	3	3	2	3	1	0.432	0.568	8759.90	634.99	5612.0	3460.054	-1.531
22	3	2	1	1	3	2	3	0.653	0.347	3551.30	731.54	3624.0	1734.084	-1.047
23	3	2	1	2	1	3	1	0.625	0.375	3730.45	479.18	3507.0	1613.588	-1.311
24	3	2	1	3	2	1	2	0.984	0.016	2995.85	1668.60	12274.0	1838.504	-0.629
25	3	3	2	1	3	3	1	0.628	0.372	1241.22	230.78	1169.0	579.413	-1.142
26	3	3	2	2	1	1	2	0.984	0.016	1800.23	1084.68	7365.0	1185.327	-0.518
27	3	3	2	3	2	2	3	0.774	0.226	12723.23	2822.19	19289.0	6542.556	-0.944

For each experiment we first calculated α_1 and α_1 to found the optimal solution $U_c(X)$ by repeating the calculations presented at section 3. Using the same parameters the utility function of line is also calculated for comparison. Then the index P is calculated.

Appendix 3. Results of L27 experiments

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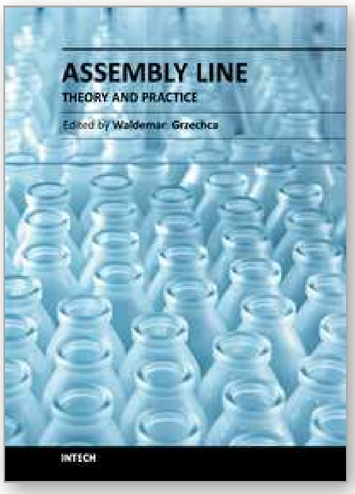

Assembly Line - Theory and Practice

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An assembly line is a manufacturing process in which parts are added to a product in a sequential manner using optimally planned logistics to create a finished product in the fastest possible way. It is a flow-oriented production system where the productive units performing the operations, referred to as stations, are aligned in a serial manner. The present edited book is a collection of 12 chapters written by experts and well-known professionals of the field. The volume is organized in three parts according to the last research works in assembly line subject. The first part of the book is devoted to the assembly line balancing problem. It includes chapters dealing with different problems of ALBP. In the second part of the book some optimization problems in assembly line structure are considered. In many situations there are several contradictory goals that have to be satisfied simultaneously. The third part of the book deals with testing problems in assembly line. This section gives an overview on new trends, techniques and methodologies for testing the quality of a product at the end of the assembling line.

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