Systematic Applications of IE Methods with Microcomputer* (An Assembly Line Balancing Method Considering the Performance Rate of Each Work Station)

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Assembly line balancing aims to assign work elements to serial work stations so as to make the work content at each station as close as possible to one limiting cycle time.

Until now, it is usually assumed that the performance rates of work stations are constant. But in practice, they are varied by their own working conditions. Then the actual station times are different from standard times, and consequently the line balance may diminish.

In this paper, we propose an improved balancing method, in which work elements are assigned to the work station varying the upper time limit according to its performance rate or ability. Further, to use the method effectively, we propose an assembly time observing system with microcomputer.

In an application of our method to the practical problems, it is shown that the actual efficiency of the production line attained can be as high as that planned.

Key Words : Production System, Assembly line, Line balancing, Industrial Engineering, Time Study, Microcomputer

1. Introduction

In previous assembly line balancing methods, it is assumed that the performance rates of every work station are constant and identical. Therefore the standard times for work elements were used in the assignment procedure. In the procedure, work elements were assigned to work stations so that the sum of the standard times of assigned elements could be as close as possible to one limiting cycle time.^(1,2,3)

But in practice the performance abilities of work stations are varied by their own working conditions. Then the actual station times turn out different from their standard times, and consequently the line balance may diminish in many cases.⁽⁴⁾ The variations are especially large at a stage where the production has just started.

By the way, in mass production type, the production periods are generally long. So we can revise the line balance after the working conditions become stable. But in small production for various product

models, we should try to raise the efficiency at the beginning period for the new product model.^(5,6) For that reason, we should monitor the real working conditions of each station incessantly, and revise the line balance according to their changes.

In this paper, we propose an assembly time observing system using a microcomputer, by which the station times are measured automatically and their performance rates are calculated immediately. Further we propose an improved balancing method, in which work elements are assigned to the work station varying the upper time limit according to its performance rate or ability.

The learning effects of each work station and the statistical control chart are considered and used in the real time control procedure of the assembly line.

The applications of our method are illustrated in solving an example problem.

2. Assembly Line Managing System

The proposed system is used to measure the station times and manage them immediately. Figure 1 shows an outline of the system. It is composed of two parts, i.e., some switches and a microcomputer. They are connected by about ten meters long electric wires through the interface.

2.1 Switches

The switch detects a division of work sequence. Now we can use 16 switches in parallel at the most.⁽⁷⁾ According to the types of time observing, various types of switches can be used as follows.

(1) Keyboard of the microcomputer

In this case, the system does not

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need any interfaces and external switches. When a division of work arises, the observer pushes the key corresponding to the worker.

(2) Toggle or push button switch

A pair of switches are installed at each work station. Each worker switches on when he gets the parts or subassemblies on the conveyor belt. He switches off when he finishes his work cycle and puts the assembly on the conveyor. Instead of workers, the observer may deal with some switches.

The switches with different color lights or LEDs can be used to prevent the mistakes in pushing them.

(3) Photosensor switch

Switches of this type are used to eliminate the additional work to push the button. If the light of the photosensor is shielded by a part or the worker, the switch is set off. If the light is not shielded, the switch is left on. The working states are measured automatically by the photosensor switches.

Fig. 1. Assembly line managing system with microcomputer

2.2 Software of the microcomputer

By using the microcomputer, the various IE methods, that is, time study, idle time analysis, statistical control, learning effect analysis, assembly line balancing methods and so on, are performed systematically with real time processing.

In the time study software, the on-off states of switches are detected through the input port of the microcomputer. Then the time of pushing the switch, that is, a division of work cycle, is recorded by the time function of the microcomputer. The time duration between two successive divisions is calculated immediately, and it means one work cycle time. The CRT (Cathode Ray Tube) display shows the number of work cycles, time durations, and so on.

Further using the obtained work time data, the means and variations of work or idle times of each stations are calculated statistically. The $\bar{x}$ -R control charts⁽⁸⁾ are used to control the working conditions of the line. The learning curves⁽⁹⁾ are predicted by the least square approximation.

In the line balancing software, the work elements are assigned to the work stations considering the result of work time measurements. The assigning procedure is illustrated in the next section.

3. The Assembly Line Balancing Method Proposed

3.1 Multiple product line

To meet the various demands, the assembly process generally uses the multiple product lines, which produces several models of a particular product type on a single line. It is classified into the following two types.⁽¹⁰⁾

3.1.1 Line changeover

In this case, the assembly line serves several product models by changing over from one to the other, but at any one period only one product model flows through the line. The line balancing of each models can be made separately.

As the line are changed over frequently, it is needed that the assigning procedure is very simple, the next product line are quickly set, and the line is well controlled at the beginning of each product model.

3.1.2 Mixed model line

In the mixed model line, several models of a particular product type, e.g. vehicles and refrigerators are progressively assembled on a single line.

When there are many products, it is difficult to make them on the same line. Some conditions, that is, work elements, time durations, tools, fixtures, the number of work stations and so on, must be similar among models.

There are two major problems discussed in model mix balancing: (1) determining the sequence of the units flowing down the line⁽¹¹⁾ and (2) assigning all the elements of all models to specific stations for a single model line balancing.⁽¹²⁾

3.2 Assigning procedure using the performance rates

3.2.1 Notations

We use the following notations for the assembly line terminology.

h : number of models

Q_f : production volumes of model f

$f=1, \dots, h$: serial number of models

Production schedule for model f ;

Cu_f : limiting cycle time, reciprocal of production rate

No : desirable number of work stations

Ebv : operating value for efficiency of line balancing

d : small decrement of Ebv

Work elements data for model f ;

n_f : number of work elements

w_{kf} : k th work element in the element list

t_{kf} : work element time of w_{kf} (standard time)

P_{kf} : set of work elements preceding w_{kf}

M_{kf} : performance restrictions of w_{kf}

$k=1, \dots, n_f$: work element serial number

$T_f = \sum_{k=1}^{n_f} t_{kf}$: total work content per unit product

$tmax_f = \max\{t_{kf}, k=1, \dots, n_f\}$: maximum work element time

Work stations data for model f ;

N_f : number of work stations

R_{if} : performance rate of i th station (coefficient multiplied)

D_{if} : setup time for i th station (constant reduced or added)

Cu_{if} : limiting station time of i th station
 Assignment results;
 T''_{if} : estimated station time at i th station
 T_{if} : station time of i th station by standard
 n_{if} : number of work elements in i th station
 w_{ijf} : j th work element in i th station
 t_{ijf} : work element time of w_{ijf} (standard time)
 $j=1, \dots, n_{if}$: work element serial number in i th station
 $i=1, \dots, N_f$: station serial number
 C_f : cycle time of the line
 Ebf : efficiency of line balancing

3.2.2 Relations and restrictions

We consider two kinds of values for the performance ability of each work station or worker in our proposed method.

The first one is a coefficient multiplied by the station standard time. In i th station for model f , it is denoted by R_{if} . R_{if} is defined as the ratio of the normal time to the worker's actual one. We simply assume that R_{if} is the rating value of the worker manning i th station and a particular worker's rate value is the same for every work element or any assembly of work elements.

The second one is a constant reduced from or added to the standard time. It is denoted by D_{if} . D_{if} is used for considering the setup time of i th station. For example, if the work-in-process handling time from the conveyor belt is much different among stations, we can use D_{if} profitably. And the balance loss times in the other models are compensated by using as D_{if} in model f .

Then there are some relations and restrictions among symbols.

$$Cu_{if} = (C_f - D_{if}) \times R_{if}, \quad (1)$$

$$Cu_{if} = \sum_{j=1}^{n_{if}} t_{ijf} / R_{if} + D_{if}, \quad (1')$$

$$T_{if} = \sum_{j=1}^{n_{if}} t_{ijf}, \quad (2)$$

$$\text{where } Cu_{if} > T_{if}, \quad (3)$$

$$T''_{if} = T_{if} / R_{if} + D_{if}, \quad (4)$$

$$\text{when } Cu_{if} > T''_{if}, \quad (5)$$

$$C_f = \max\{T''_{if}, i=1, \dots, N_f\}, \quad (6)$$

$$Ebf = \sum_{i=1}^{N_f} T''_{if} / (N_f \times C_f). \quad (7)$$

3.2.3 Loss times for line changeover or mixed line

Total loss time for changing over the line from model $f-1$ to f is calculated as follow;

$$LT = \sum_{i=1}^{N_f} D_{if} + |C_{f-1} - C_f| \times N_f(N_f - 1)/2. \quad (8)$$

And the loss time for the mixed line in model f is calculated as follow;

$$LT = (C_{max} - C_f) \times N_f \times Q_f, \quad (9)$$

where $C_{max} = \max\{C_f, f=1, \dots, h\}$.

Therefore the loss times in the multiple product line can be decreased by diminishing the setup times D_{if} and making the cycle times of each models equal.

3.2.4 The objective function of the method proposed

One goal of assembly line balancing is to minimize the balance loss or to maximize the efficiency of line balancing as follows;

$$\min\{N_f \times C_f - \sum_{i=1}^{N_f} T''_{if}\}, \text{ or} \quad (10)$$

$$\max\{Ebf\} = \max\{\sum_{i=1}^{N_f} T''_{if} / (N_f \times C_f)\}. \quad (11)$$

Here equations (10)(11) include the

cycle time C_f , which is calculated from the assignment solution. Then in assigning procedures to get the result, we use Cu_{if} instead of C_f ;

$$\min\{N_f \times Cu_{if} - \sum_{i=1}^{N_f} T''_{if}\} \quad (12)$$

In the heuristic method⁽¹³⁾ to get the solution quickly and easily, work elements are assigned to the first or last work station and the assignment is continued to next stations till all the elements are assigned. Then the objective function at i th station is as follows;

$$\min\{Cu_{if} - T''_{if}\} \quad (13)$$

Equation (13) leads to the next one when substituting equations (1)', (4) and multiplying R_{if} .

$$\min\{Cu_{if} - T''_{if}\} = \min\{Cu_{if} - \sum_{j=1}^{n_{if}} t_{ijf}\} \quad (14)$$

Therefore we obtain the sub set of work elements $\{w_{ijf}, j=1, \dots, n_{if}\}$ under the conditions (3) and (14) at every station, $i=1, \dots, N_f$.

3.2.5 Solution procedure

The proposed procedure of assigning work elements to work stations under their own performance rates is as follows.

Step 1. Input the work elements data

$\{n_f, w_{kf}, t_{kf}, P_{kf}, M_{kf}, k=1, \dots, n_f\}$ and the small decrement d .

Step 2. Input the work stations data

$\{N_o, R_{if}, D_{if}, i=1, \dots, N_o\}$.

Step 3. Select one of the Branching Decision(B&D) rules⁽¹⁴⁾ among the following.

$\left. \begin{array}{l} \text{*forward} \\ \text{or} \\ \text{*backward} \end{array} \right\} \times \left(\begin{array}{l} \text{*largest task time rule} \\ \text{*smallest task time rule} \\ \text{*highest ranked} \\ \text{positional weight rule} \\ \text{*random selecting rule} \end{array} \right)$

And set the ideal on the operational value for efficiency of line balancing, that is, put $Ebv = 1.0$.

Step 4. Put $Ebv = Ebv - d$, and calculate the upper time limit over the line, that is, $Cu_f = T_f / (N_o \times Ebv)$.

Step 5. Put $R = \{w_{kf}, k=1, \dots, n_f\}$, where R is the set of still unassigned work elements, and $i=0$.

Step 6. Proceed to next station, that is, $i=i+1$, and set the initial data in i th station, that is,

$n_{if}=0, T_{if}=0, j=0$.

Step 7. Put $j=j+1$. Using the B&D rule, select w_{ijf} under the following four conditions.

(1) $w_{ijf} \in R$, (unassigned work elements)

(2) $w_{ijf} \in P_{ijf} \cap R = \phi$
(workable work elements with preceding relations)

(3) $w_{ijf} \mid t_{ijf} < Cu_{if} - T_{if}$
(assignable work elements with the bound of slack times)

(4) $w_{ijf} \mid (M_{ijf} = M_{ikf}, k=1, \dots, j-1) \cup (M_{ijf} = \phi)$
(assignable work elements with the performance restrictions)

If no elements are selected here, return to step 6.

Step 8. Assign w_{ijf} to i th station, that is, $T_{if} = T_{if} + t_{ijf}$, $n_{if} = j$, $R = R - \{w_{ijf}\}$. If $R = \phi$, return to step 7. If $R \neq \phi$, all work elements are assigned. Then proceed to next step.

Step 9. Put $N_f = i$. Now we get the following result; N_f, T_{if}, w_{ijf} , $j=1, \dots, n_{if}, i=1, \dots, N_f$. If $N_f > N_o$, then proceed to next step and if

$N_f \leq N_0$, we get the possible result. Calculate the values by the following equations and remember the assignment result.

$$T_{if}'' = T_{if}/R_{if} + D_{if}$$

$$C_f = \max\{T_{if}'', i=1, \dots, N_f\}$$

$$Eb_f = \sum_{i=1}^{N_f} T_{if}'' / (N_f \times C_f)$$

To search for better result, put $Cu_f = C_f$ and return to step 5.

Step 10. If we cannot still get the possible result of N_0 , return to step 4. If we already got a result, we could not have better result by reducing the cycle time C_f . If we want to improve the result by the other B&D rules, change the rule and return to step 5. If we want to get the other result, return to step 3. If we do not want, we stop the procedure.

4. An Assembly Line Control Procedure Based on the Learning Effects

Learning effects have been observed to exist in the assembly line since the workers replicate the same operations. Therefore performance rates of each workers may vary and change with time.

The learning effect of each worker will be predicted from the time observing results with the proposed system. Using the performance rates predicted, the line balancing will be revised at every moment that the change arises. The $\bar{x}$ -R control charts will be used to detect the changes. The cycle time of the line may be revised according to the learning effects of the bottleneck station.

The following notations are used;

T_{if} : standard time of i th station
 $T_{if}'(x)$: x th actual station time of i th station
 $\hat{T}_{if}'(x)$: x th estimated station time of i th station by the learning curve
 r_{if} : the rate of learning of i th station
 $R_{if}(x)$: estimated performance rate of i th station in x th unit
 $x=1, 2, \dots$: the unit number

The model of learning curve is as follows;

$$\hat{T}_{if}'(x) = \hat{T}_{if}'(1)x^{r_{if}} \quad (15)$$

$R_{if}(x)$ is calculated as follows;

$$R_{if}(x) = T_{if}' / \hat{T}_{if}'(x) \quad (16)$$

A procedure for the assembly line control is as follows;

(1) Assembly line balancing is done with the method proposed in chapter 3. The performance rates of each work stations can be given by the performance rating method or the results of aptitude tests. If they are not obtained, the standards are used in the assignment method.

When the production starts, the station cycle times are measured till x_1 th unit by the time observing system. The following data are obtained;

$T_{if}'(x), x=1, \dots, x_1, i=1, \dots, N_f$.
 (2) The models of the learning effects are set by the least square method;

$\hat{T}_{if}'(x) = \hat{T}_{if}'(1)x^{r_{if}}, i=1, \dots, N_f$.
 And $R_{if}(x_2)$ can be predicted as follows;
 $R_{if}(x_2) = T_{if}' / \hat{T}_{if}'(x_2), i=1, \dots, N_f$.

(3) The assembly line is redesigned by using the $R_{if}(x_2), i=1, \dots, N_f$.

(4) The production is continued with the revised line. At the same time, the time measuring is done and the $\bar{x}$ -R control charts are displayed in CRT.

(5) The cycle time may be revised according to the change of working conditions. In the bottleneck station I , the x th performance rate $R_{If}(x)$ is predicted. Then the x th cycle time of the line is;

$$C_f(x) = T_{If} / R_{If}(x) \times (1+\alpha),$$

where α is the adjustment rate for operations.

5. Application Example

To explain the proposed procedure, we apply it to solve the problem for assembly works of table tap concentrators, which have three different models, that is, 2 plugs, 3 plugs, 4 plugs type. The precedence diagram of the 4 plugs model is shown in Fig. 2. Time values in the diagram are standard assembly times calculated by Method Time Measurement¹⁵⁾. The work element denoted by "A" is driving the bind screw to the metal plate, "B" is inserting the metal plate to the plastic case, "C" is inserting the spring, "D" is setting the cover, and "E" is fastening the cover and case with the small screw. The number of work element "C" differs in each model. The other elements are performed similarly among the models.

We intend to obtain the desirable line balance of these assembly works with three arbitrary workers.

Fig. 2. The precedence diagram of assembly work for table tap concentrator (4 plugs model).

5.1 Result under no consideration of worker's ability

We used the proposed procedure with forward and largest task time B&D rule. At first, we set the station data as follows;

$$R_{if}=1, D_{if}=0, i=1, 2, 3, f=1, 2, 3,$$

because each worker's ability or performance rate was unknown and every job could be done in the normal work area along the conveyor belt.

Then the assignment results under no consideration of worker's ability is shown in Table 1. The operations of each work stations were similar among the models and there were no setup times from one model

Table 1. The work assignment results.

i	T_{i1} w_{ij1}	T_{i2} w_{ij2}	T_{i3} w_{ij3}
1	18.8 A1 A2	22.7 A1 A2 B1	22.7 A1 A2 B1
2	20.2 B1 B2 C11,C21 C12,C22	22.5 B2 C11,C21 C12,C22 C13,C23	25.6 B2 C11,C21 C12,C22 C13,C23 C14
3	21.2 D E	21.2 D E	24.3 C24 D E
C_f	21.2 sec.	22.7 sec.	25.6 sec.
Eb_f	94.7%	97.5%	94.5%

to the other.

The loss times of changing over the line from 2 plugs model to 3 plugs one were calculated by Eq.(8), that is, $|21.2-22.7| \times 3 \times 2/2 = 4.5$ sec. The maximum value of cycle times was 25.6 sec., which was the cycle time of the mixed model line.

For the applications of the proposed method, we took the 3 plugs model which was expected the demand of the highest volumes. It has 97.5% balance and its pitch time is 22.7 seconds. The planned line has a productivity of 159 units per hour.

A production line manned by three arbitrary workers was designed on basis of the assignment result and then the production started under unpaced working condition. At the same time, the station cycle times were measured by the proposed computer system. The average cycle time for 5 cycles is shown in Fig. 3 compared with the standard in the form of a pitch diagram. $T'_{i2}(1-5)$ is the average time from 1st to 5th cycle at i th station.

As the result, the practical cycle time was 29.8 sec. and Eb_2 was 78.7%. The practical line had a productivity of 121 units per hour. Therefore the line balance diminished to 18.8% and the productivity dropped to 38 units per hour in comparison with the plan.

Then we would revise the line balance to improve the productivity. We would assign the work elements to three work stations considering the average time for each station in next section.

5.2 Result considering the performance rate of each work station

The performance rate of each worker was calculated from the result of Fig. 3, that is, the ratio of the station standard time to the average time was measured.

Then we revised the station data as follows;

$$R_{i2} = T_{i2} / T'_{i2}(1-5), \quad i=1,2,3,$$

and assigned work elements to three work stations considering their performance rates. The obtained result is shown in Fig. 4. Some work elements were exchanged between first and second station. C_2 was 23.04 sec. and Eb_2 was 97.2% in the planned line.

Fig. 3. The assignment result using the standards and the pitch diagram of first 5 cycles

Fig. 4. The assignment result considering the performance rates and the pitch diagram of next 10 cycles.

The assembly works continued under a redesigned line. The average cycle time for next 5 cycles is shown in Fig. 4. As the result, C_2 was 23.6 sec. and Eb_2 was 92.1%. The assembly works from 6th to 10th cycle nearly proceeded as scheduled.

The production was continued with the same line design. The average cycle times of another next 5 cycles, that is, from 11th to 15th cycle were shown in Fig. 4. The cycle time decreased in the 1st station, and increased in the 2nd and 3rd station. As the result, the line balance diminished to 86.8%.

5.3 Assembly line control considering the learning effects

The learning curves of each work station were calculated by using the 10 serial time data in Fig. 4, from 6th to 15th cycle. The 100th cycle times and the performance rates $R_{i2}(100)$ were predicted and calculated. The results were shown in Table 2.

Table 2. The learning effects predicted.

i	T_{i2} (sec.)	$\hat{T}_{i2}(1)$ (sec.)	r_{i2}	$\hat{T}_{i2}(100)$ (sec.)	$R_{i2}(100)$
1	16.4	26.7	-0.1378	12.2	1.34
2	28.8	22.0	0.0493	29.0	0.993
3	21.2	20.5	0.0314	24.5	0.865

Fig. 5. The assignment result considering learning effects and the pitch diagram of 101-105 cycles

The redesigned line with $R_{i2}(100)$ was shown in Fig.5. C_2 was 22.05 sec. and Eb_2 was 94.8%. Then the production was continued till 100 cycles with the revised line. The cycle time was set including 20% adjustments.

The average times from 101th to 105th cycle were shown in Fig.5. As the result, Eb_2 was 89.3%, and the line production proceeded steadily.

6. Conclusions

To achieve the balance and the productivity of the line as scheduled, we propose an improved balancing method, in which work elements are assigned to the work stations varying the upper time limit according to the performance rate.

And further, to use the method effectively, we propose an assembly time observing system using a microcomputer, by

which the station times can be measured automatically and the performance rates can be calculated immediately. From an application of the proposed method and system to practical assembly works of table tap concentrers, the following results have been obtained.

- (1) The algorithm for the balancing method proposed here is an extension from the previous ones. In the case of using the standard values as the station data, this method is identical to the previous ones.
- (2) By using the time observing system, the working conditions of workers are monitored and their performance rates are calculated immediately by the microcomputer.
- (3) By considering the workers performance rates in this method, the assembly line can achieve the balance and productivity scheduled.

References

- (1) AKAGI, F., et al., *Mem. School of Eng., Okayama Univ.*, Vol.13, No.1(1979), p.83.
- (2) AKAGI, F., et al., *Mem. School of Eng., Okayama Univ.*, Vol.15, No.2(1981-3), p.21.
- (3) AKAGI, F., et al., *Int. J. Prod. Res.*, Vol.21, No.5(1983), p.755.
- (4) Kottas, J.F. and Lau, H.S., *Int. J. Prod. Res.*, Vol.19, No.2(1981), p.177.
- (5) Dar-el, E.M. and Nadivi, A., *Int. J. Prod. Res.*, Vol.19, No.1(1981), p.69.
- (6) Arcus, A.L., *Int. J. Prod. Res.*, Vol.4, No.4(1966), p.259.
- (7) Maynard, H.B., *Industrial Engineering Handbook*, (1971), p.12-38, McGraw-Hill.
- (8) Fabrycky, W.J. and Torgersen, P.E., *Operations Economy*, (1966), p.198, Prentice-Hall.
- (9) Fabrycky, W.J. and Torgersen, P.E., *Operations Economy*, (1966), p.95, Prentice-Hall.
- (10) Maynard, H.B., *Industrial Engineering Handbook*, (1971), p.11-111, McGraw-Hill.
- (11) Thomopoulos, N.T., *Manage. Sci.*, Vol.14, No.2(1967), p.B-59.
- (12) Salvendy, G., *Handbook of Industrial Engineering*, (1982), p.3.4.8, John Wiley & Sons.
- (13) Tonge, F.M., *Manage. Sci.*, Vol.7, No.1(1960), p.21.
- (14) Pinto, P., et al., *Int. J. Prod. Res.*, Vol.13, No.2(1975), p.183.
- (15) Maynard, H.B., et al., *METHODS-TIME MEASUREMENT* (in Japanese), (1986), GIHOUDOU.