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Assembly Line Balancing Problem Single and Two-Sided Structures

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1. Introduction

The manufacturing assembly line was first introduced by Henry Ford in the early 1900's. It was designed to be an efficient, highly productive way of manufacturing a particular product. The basic assembly line consists of a set of workstations arranged in a linear fashion, with each station connected by a material handling device. The basic movement of material through an assembly line begins with a part being fed into the first station at a predetermined feed rate. A station is considered any point on the assembly line in which a task is performed on the part. These tasks can be performed by machinery, robots, and/or human operators. Once the part enters a station, a task is then performed on the part, and the part is fed to the next operation. The time it takes to complete a task at each operation is known as the process time (Sury, 1971). The cycle time of an assembly line is predetermined by a desired production rate. This production rate is set so that the desired amount of end product is produced within a certain time period (Baybars, 1986). In order for the assembly line to maintain a certain production rate, the sum of the processing times at each station must not exceed the station's cycle time (Fonseca et al, 2005). If the sum of the processing times within a station is less than the cycle time, idle time is said to be present at that station (Erel et al,1998). One of the main issues concerning the development of an assembly line is how to arrange the tasks to be performed. This arrangement may be somewhat subjective, but has to be dictated by implied rules set forth by the production sequence (Kao, 1976). For the manufacturing of any item, there are some sequences of tasks that must be followed. The assembly line balancing problem (ALBP) originated with the invention of the assembly line. Helgeson et al (Helgeson et al, 1961) were the first to propose the ALBP, and Salveson (Salveson, 1955) was the first to publish the problem in its mathematical form. However, during the first forty years of the assembly line's existence, only trial-and-error methods were used to balance the lines (Erel et al,, 1998). Since then, there have been numerous methods developed to solve the different forms of the ALBP. Salveson (Salveson, 1955) provided the first mathematical attempt by solving the problem as a linear program. Gutjahr and Nemhauser (Gutjahr & Nemhauser, 1964) showed that the ALBP problem falls into the class of NP-hard combinatorial optimization problems. This means that an optimal solution is not guaranteed for problems of significant size. Therefore, heuristic methods have become the most popular techniques for solving the problem. Author of this book chapter

underlines the importance of the final results estimation and proposes for single and two-sided assembly line balancing problem modified measures.

2. Two-sided Assembly Lines

Two-sided assembly lines (Fig. 1.) are typically found in producing large-sized products, such as trucks and buses. Assembling these products is in some respects different from assembling small products. Some assembly operations prefer to be performed at one of the two sides (Bartholdi, 1993).

Station 1	Station 3		Station (n-3)	Station (n-1)

Conveyor

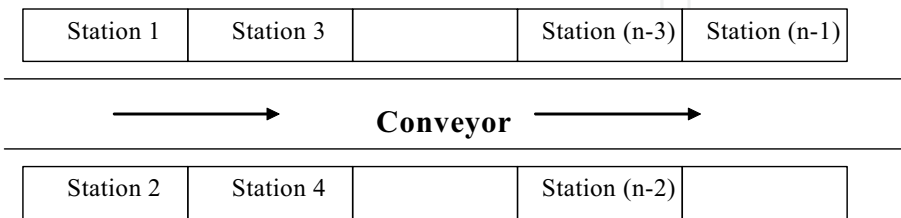| Station 2	Station 4		Station (n-2)	

Fig. 1. Two-sided assembly line structure

Let us consider, for example, a truck assembly line. Installing a gas tank, air filter, and toolbox can be more easily achieved at the left-hand side of the line, whereas mounting a battery, air tank, and muffler prefers the right-hand side. Assembling an axle, propeller shaft, and radiator does not have any preference in their operation directions so that they can be done at any side of the line. The consideration of the preferred operation directions is important since it can greatly influence the productivity of the line, in particular when assigning tasks, laying out facilities, and placing tools and fixtures in a two-sided assembly line (Kim et al, 2001). A two-sided assembly line in practice can provide several substantial advantages over a one-sided assembly line (Bartholdi, 1993). These include the following: (1) it can shorten the line length, which means that fewer workers are required, (2) it thus can reduce the amount of throughput time, (3) it can also benefit from lowered cost of tools and fixtures since they can be shared by both sides of a mated-station, and (4) it can reduce material handling, workers movement and set-up time, which otherwise may not be easily eliminated. These advantages give a good reason for utilizing two-sided lines for assembling large-sized products. A line balancing problem is usually represented by a precedence diagram as illustrated in Fig. 2.
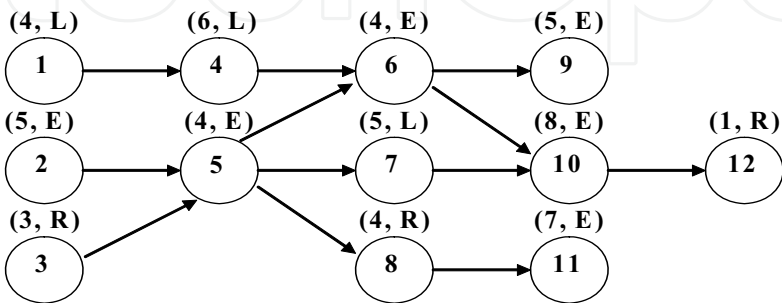

Fig. 2. Precedence graph

A circle indicates a task, and an arc linking two tasks represents the precedence relation between the tasks. Each task is associated with a label of (t_i, d), where t_i is the task processing time and d (=L, R or E) is the preferred operation direction. L and R, respectively, indicate that the task should be assigned to a left- and a right-side station. A task associated with E can be performed at either side of the line. While balancing assembly lines, it is generally needed to take account of the features specific to the lines. In a one-sided assembly line, if precedence relations are considered appropriately, all the tasks assigned to a station can be carried out continuously without any interruption. However, in a two-sided assembly line, some tasks assigned to a station can be delayed by the tasks assigned to its companion (Bartholdi, 1993). In other words, idle time is sometimes unavoidable even between tasks assigned to the same station. Consider, for example, task j and its immediate predecessor i. Suppose that j is assigned to a station and i to its companion station. Task j cannot be started until task i is completed. Therefore, balancing such a two-sided assembly line, unlike a one-sided assembly line, needs to consider the sequence-dependent finish time of tasks.

3. Heuristic Methods in Assembly Line Balancing Problem

The heuristic approach bases on logic and common sense rather than on mathematical proof. Heuristics do not guarantee an optimal solution, but results in good feasible solutions which approach the true optimum.

3.1 Single Assembly Line Balancing Heuristic Methods

Most of the described heuristic solutions in literature are the ones designed for solving single assembly line balancing problem. Moreover, most of them are based on simple priority rules (constructive methods) and generate one or a few feasible solutions. Task-oriented procedures choose the highest priority task from the list of available tasks and assign it to the earliest station which is assignable. Among task-oriented procedures we can distinguish immediate-update-first-fit (IUFF) and general-first-fit methods depending on whether the set of available tasks is updated immediately after assigning a task or after the assigning of all currently available tasks. Due to its greater flexibility immediate-update-first-fit method is used more frequently. The main idea behind this heuristic is assigning tasks to stations basing on the numerical score. There are several ways to determine (calculate) the score for each tasks. One could easily create his own way of determining the score, but it is not obvious if it yields good result. In the following section five different methods found in the literature are presented along with the solution they give for our simple example. The methods are implemented in the Line Balancing program as well. From the moment the appropriate score for each task is determined there is no difference in execution of methods and the required steps to obtain the solution are as follows:

STEP 1. Assign a numerical score $n(x)$ to each task x.

STEP 2. Update the set of available tasks (those whose immediate predecessors have been already assigned).

STEP 3. Among the available tasks, assign the task with the highest numerical score to the first station in which the capacity and precedence constraints will not be violated. Go to STEP 2.

The most popular heuristics which belongs to IUFF group are:

IUFF-RPW Immediate Update First Fit – Ranked Positional Weight,

IUFF-NOF Immediate Update First Fit – Number of Followers,
IUFF-NOIF Immediate Update First Fit – Number of Immediate Followers,
IUFF-NOP Immediate Update First Fit – Number of Predecessors,
IUFF-WET Immediate Update First Fit – Work Element Time.

3.2 Two-sided Assembly Line Balancing Heuristic Method

A task group consists of a considered task i and all of its predecessors. Such groups are generated for every un–assigned task. As mentioned earlier, balancing a two–sided assembly line needs to additionally consider operation directions and sequence dependency of tasks, while creating new groups (Lee et al, 2001). While forming initial groups IG(i), the operation direction is being checked all the time. It's disallowed for a group to contain tasks with preferred operation direction from opposite sides. But, if each task in initial group is E – task, the group can be allocated to any side. In order to determine the operation directions for such groups, the rules (direction rules DR) are applied:

DR 1. Set the operation direction to the side where tasks can be started earlier.

DR 2. The start time at both sides is the same, set the operation direction to the side where it's expected to carry out a less amount of tasks (total operation time of unassigned L or R tasks).

Generally, tasks resulting from "repeatability test" are treated as starting ones. But there is exception in form of first iteration, where procedure starts from searching tasks (initial tasks IT), which are the first ones in precedence relation. After the first step in the first iteration we get:

$$IG(1) = \{1\}, \; Time\{IG(1)\} = 2, \; Side\{IG(1)\} = 'L'$$
$$IG(2) = \{2\}, \; Time\{IG(2)\} = 5, \; Side\{IG(2)\} = 'E'$$
$$IG(3) = \{3\}, \; Time\{IG(3)\} = 3, \; Side\{IG(3)\} = 'R$$

where:

Time$\{IG(i)\}$ – total processing time of ith initial group,

Side$\{IG(i)\}$ – preference side of ith initial group.

To those who are considered to be the first, the next tasks will be added, (these ones which fulfil precedence constraints).

Whenever new tasks are inserted to the group i, the direction, cycle time and number of immediate predecessors are checked. If there are more predecessors than one, the creation of initial group j comes to the end.

First iteration – second step

$$IG(1) = \{1, 4, 6\}, \; Time\{IG(1)\} = 8, \; Side\{IG(1)\} = 'L'$$
$$IG(2) = \{2, 5\}, \; Time\{IG(2)\} = 9, \; Side\{IG(2)\} = 'E'$$
$$IG(3) = \{3, 5\}, \; Time\{IG(3)\} = 7, \; Side\{IG(3)\} = 'R'$$

When set of initial groups is created, the last elements from those groups are tested for repeatability. If last element in set of initial groups IG will occur more than once (groups pointed by arrows), the groups are intended to be joined – if total processing time (summary time of considered groups) is less or equal to cycle time. Otherwise, these elements are deleted.

In case of occurring only once, the last member is being checked if its predecessors are not contained in Final set FS. If not, it's removed as well. So far, FS is empty.

First iteration – third step

$$IG(1) = \{1, 4\}, \; Time\{IG(1)\} = 4, \; Side\{IG(1)\} = 'L'$$

$$IG\ (2) = \{2, 3, 5\},\ Time\{IG\ (2)\} = 12,\ Side\{IG\ (2)\} = \text{'R'}$$

Whenever two or more initial groups are joined together, or when initial group is connected with those one coming from Final set – the "double task" is added to initial tasks needed for the next iteration. In the end of each iteration, created initial groups are copied to FS.

First iteration – fourth step

$$FS = \{\ (1, 4);\ (2, 3, 5)\ \},$$
$$Side\{FS\ (1)\} = \text{'L'},\ Side\{FS\ (2)\} = \text{'R'}$$
$$Time\ \{FS(2)\} = 12,\ Time\ \{FS(1)\} = 14,$$
$$IT = \{5\}.$$

In the second iteration, second step, we may notice that predecessor of last task coming from IG(1) is included in Final Set, FS(2). The situation results in connecting both groups under holding additional conditions:

$$Side\{IG(1)\} = Side\{FS(2)\},$$
$$Time + time < cycle.$$

After all, there is no more IT tasks, hence, preliminary process of creating final set is terminated.

The presented method for finding task groups is to be summarized in simplified algorithm form. Let U denote to be the set of un – assigned tasks yet and IG_i be a task group consisting of task i and all its predecessors (excluded from U set).

STEP 1. If U = empty, go to step 5, otherwise, assign starting task from U.

STEP 2. Identify IG_i . Check if it contains tasks with both left and right preference operation direction, then remove task i.

STEP 3. Assign operation direction Side{ IG_i } of group IG_i . If IG_i has R-task (L-task), set the operation direction to right (left). Otherwise, apply so called direction rules DR.

STEP 4. If the last task i in IG_i is completed within cycle time, the IG_i is added to Final set of candidates FS(i). Otherwise, exclude task i from IG_i and go to step 1.

STEP 5. For every task group in FS(i), remove it from FS if it is contained within another task group of FS.

The resulting task groups become candidates for the mated-station

$$FS = \{(1,4),\ (2,3,5,8)\}.$$

The candidates are produced by procedures presented in the previous section, which claim to not violate precedence, operation direction restrictions, and what's more it exerts on groups to be completed within preliminary determined cycle time. Though, all of candidates may be assigned equally, the only one group may be chosen. Which group it will be – for this purpose the rules helpful in making decision, will be defined and explained below:

AR 1. Choose the task group FS(i) that may start at the earliest time.

AR 2. Choose the task group FS(i) that involves the minimum delay.

AR 3. Choose the task group FS(i) that has the maximum processing time.

In theory, for better understanding, we will consider a left and right side of mated – station, with some tasks already allocated to both sides. In order to achieve well balanced station, the AR 1 is applied, cause the unbalanced station is stated as the one which would probably involve more delay in future assignment. This is the reason, why minimization number of stations is not the only goal, there are also indirect ones, such as reduction of unavoidable delay. This rule gives higher priority to the station, where less tasks are allocated. If ties occurs, the AR 2 is executed, which chooses the group with the least amount of delay among the considered ones. This rule may also result in tie. The last one, points at relating work

within individual station group by choosing group of task with highest processing time. For the third rule the tie situation is impossible to obtain, because of random selection of tasks. The implementation of above rules is strict and easy except the second one. Shortly speaking, second rule is based on the test, which checks each task consecutively, coming from candidates group FS(i) – in order to see if one of its predecessors have already been allocated to station. If it has, the difference between starting time of considered task and finished time of its predecessor allocated to companion station is calculated. The result should be positive, otherwise time delay occurs.

Having rules for initial grouping and assigning tasks described in previous sections, we may proceed to formulate formal procedure of solving two – sided assembly line balancing problem (Kim et. al, 2005).

Let us denote companion stations as *j* and *j'*,

D(i) – the amount of delay,

Time(i) – total processing time (Time{FS(i)}),

S(j) – start time at station j,

STEP 1. Set up j = 1, j' = j + 1, S(j) = S(j') = 0, U – the set of tasks to be assigned.

STEP 2. Start procedure of group creating (3.2), which identifies

FS = {FS(1), FS(2), …, FS(n)}. If FS = $\varnothing$, go to step 6.

STEP 3. For every FS(i), i = 1,2, … , n – compute D(i) and Time(i).

STEP 4. Identify one task group FS(i), using AR rules in Section 3.3

STEP 5. Assign FS(i) to a station j (j') according to its operation direction, and update S(j) = S(j) + Time(i) + D(i). U = U – {FS(i)}, and go to STEP 2.

STEP 6. If U $\neq$ $\varnothing$, set j = j' + 1, j' = j + 1, S(j) = S(j') = 0, and go to STEP 2, otherwise, stop the procedure.

4. Measures of Final Results of Assembly Line Balancing Problem

Some measures of solution quality have appeared in line balancing problem. Below are presented three of them (Scholl, 1999).

Line efficiency (LE) shows the percentage utilization of the line. It is expressed as ratio of total station time to the cycle time multiplied by the number of workstations:

$$LE = \frac{\sum_{i=1}^{K} ST_i}{c \cdot K} \cdot 100\% \tag{1}$$

where: K - total number of workstations,

c - cycle time.

Smoothness index (SI) describes relative smoothness for a given assembly line balance. Perfect balance is indicated by smoothness index 0. This index is calculated in the following manner:

$$SI = \sqrt{\sum_{i=1}^{K} \left(ST_{max} - ST_i \right)^2} \tag{2}$$

where:

ST_{max} - maximum station time (in most cases cycle time),

ST_i - station time of station i.

Time of the line (LT) describes the period of time which is need for the product to be completed on an assembly line:

$$LT = c \cdot (K - 1) + T_K \qquad (3)$$

where:

c - cycle time,

K -total number of workstations,

T_K – processing time of last station.

The final result estimation of two-sided assembly line balance needs some modification of existing measures (Grzechca, 2008).

Time of line for TALBP

$$LT = c \cdot (Km - 1) + Max\{t(S_K), t(S_{K-1})\} \qquad (4)$$

where:

Km – number of mated-stations

K – number of assigned single stations

$t(S_K)$ – processing time of the last single station

As far as smoothness index and line efficiency are concerned, its estimation, on contrary to LT, is performed without any change to original version. These criterions simply refer to each individual station, despite of parallel character of the method.

But for more detailed information about the balance of right or left side of the assembly line additional measures will be proposed:

Smoothness index of the left side

$$SI_L = \sqrt{\sum_{i=1}^{K}(ST_{maxL} - ST_{iL})^2} \qquad (5)$$

where:

SI_L- smoothness index of the left side of two-sided line

ST_{maxL}- maximum of duration time of left allocated stations

ST_{iL}- duration time of i-th left allocated station

Smoothness index of the right side

$$SI_R = \sqrt{\sum_{i=1}^{K}(ST_{maxR} - ST_{iR})^2} \qquad (6)$$

where:

SI_R- smoothness index of the right side of two-sided line,

ST_{maxR}- maximum of duration time of right allocated stations,

ST_{iR}- duration time of i-th right allocated station.

5. Numerical examples

An numerical example from Fig. 3. will be considered. The number of tasks, precedence graph and processing times are known and there are given in Table 1.The cycle time is 10.
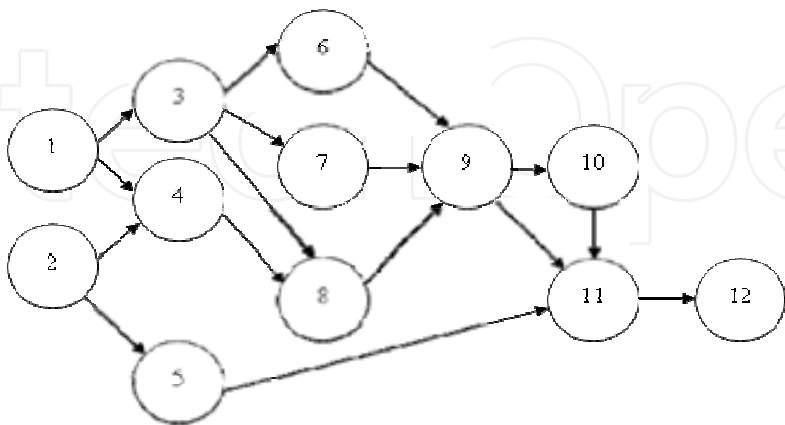

Fig. 3. Precedence graph for single line

Number of task	Processing Time	Weight	Positional Rank
1	1	29	2
2	5	27	1
3	4	28	3
4	3	22	4
5	2	11	5
6	6	24	7
7	3	21	6
8	1	19	8
9	7	18	11
10	6	11	9
11	3	5	10
12	2	2	12

Table 1. Input data of numerical example – IUFF Ranked Positional Weight
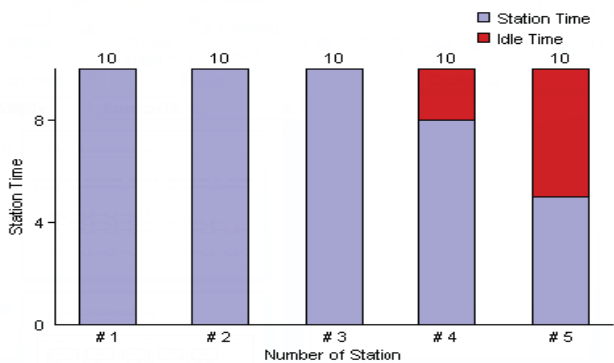
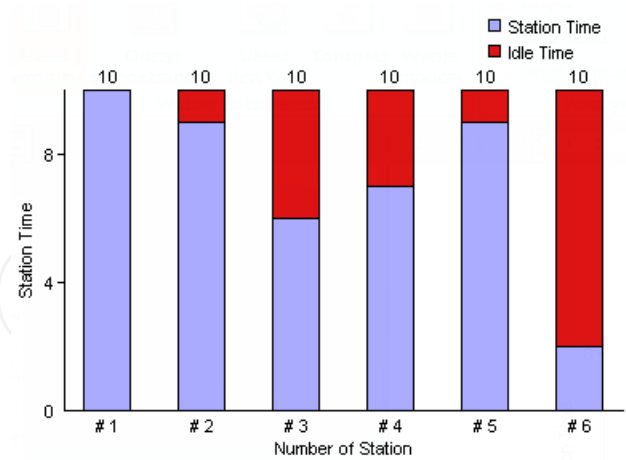Fig. 4. Assembly line balance for IUFF-RPW and IUFF-NOF methods

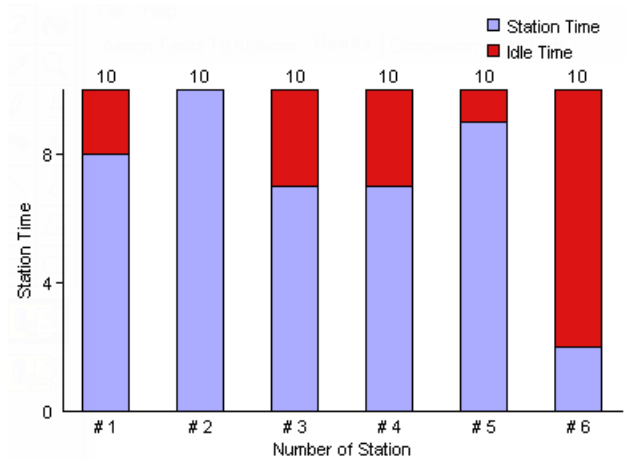Fig. 5. Assembly line balance for IUFF-NOP and IUFF-NOIF methods

Fig. 6. Assembly line balance for IUFF-WET method

Method	K	Balance	LE	SI	LT
IUFF-RPW	5	S1 – 1, 3, 2 S2 – 6, 4, 8 S3 – 7, 9 S4 – 10, 5 S5 – 11, 12	86%	5,39	45
IUFF-NOF	5	S1 – 1, 3, 2 S2 – 6, 4, 8 S3 – 7, 9 S4 – 10, 5 S5 – 11, 12	86%	5,39	45
IUFF-NOIF	6	S1 – 1, 2, 3 S2 – 5, 4, 7, 8 S3 – 6 S4 – 9 S5 – 10, 11 S6 – 12	71,67%	9,53	52

IUFF-NOP	6	S1 – 1, 2, 3 S2 – 5, 4, 7, 8 S3 – 6 S4 – 9 S5 – 10, 11 S6 – 12	71,67%	9,53	52
IUFF-WET	6	S1 – 2, 5, 1 S2 – 3, 6 S3 – 4, 7, 8 S4 – 9 S5 – 10, 11 S6 – 12	71,67%	9,33	52

Table 2. Results of balance for IUFF methods

Number of task	Processing Time	Position (Constraints)
1	4	L
2	5	E
3	3	R
4	6	L
5	4	E
6	4	E
7	5	L
8	4	R
9	5	E
10	8	E
11	7	E
12	1	R

Table 3. Input data of numeraical example – two-sided line from Fig. 2.

The results of heuristic procedure for the example from Fig. 2 and cycle time c=16 are given in a Gantt chart – Fig. 7.
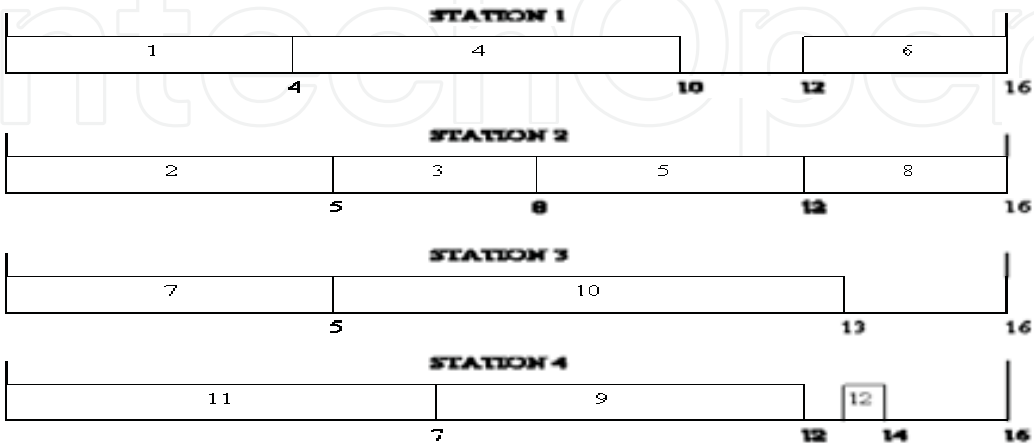

Fig. 7. Gantt chart of assembly line balance of two-sided structure (Fig. 2.)

Before presenting performance measures for current example, it would be like to stress difference in estimation of line time form, resulting from restrictions of parallel stations. In two – sided line method within one mated-station, tasks are intended to perform its operations at the same time, as it is shown in example in Fig. 7., where tasks 7, 11 respectively are processed simultaneously on single station 3 and 4, in contrary to one – sided heuristic methods. Hence, modification has to be introduced to that particular parameter which is the consequence of parallelism. Having two mated-stations from Fig. 7, the line time LT is not 3*16 + 13, as it was in original expression. We must treat those stations as two double ones (mated-stations), rather than individual ones S_k (4). As far as smoothness index and line efficiency are concerned, its estimation, on contrary to LT, is performed without any change to original version. These criterions simply refer to each individual station, despite of parallel character of the method. But for more detailed information about the balance of right or left side of the assembly line additional measures (5) and (6) was proposed (Grzechca, 2008).

Name	Value
LE	84,38%
LT	30
SI	4,69
SI_R	2
SI_L	3

Table 4. Numerical results of balance of two-sided assembly line structure

6. Conclusion

Single and two-sided assembly lines become more popular in last time. Therefore it is obvious to consider these structures using different methods. In this chapter a heuristic approach was discussed. Single assembly line balancing problem has very often difficulties with the last station. Even optimal solution (100 % efficiency of workstations except the last one is impossible to accept by production engineers in the companies. Different heuristic methods allow to obtain different feasible solutions and then to choose the most appropriate result. Two-sided assembly line structure is very sensitive to changes of cycle time values. It is possible very often to get incomplete structure of the two-sided assembly line (some stations are missing) in final result. We can use different measures for comparing the solutions (line time, line efficiency, smoothness index). Author proposes additionally two measures: smoothness index of the left side (SI_L) and smoothness index of the right side (SI_R) of the two-sided assembly line structure. These measurements allow to get more knowledge about allocation of the tasks and about the balance on both sides.

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Automation Control - Theory and Practice

Edited by A D Rodi

The present edited book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of automation and control. The volume is organized in four parts according to the main subjects, regarding the recent advances in this field of engineering. The first thematic part of the book is devoted to automation. This includes solving of assembly line balancing problem and design of software architecture for cognitive assembling in production systems. The second part of the book concerns different aspects of modelling and control. This includes a study on modelling pollutant emission of diesel engine, development of a PLC program obtained from DEVS model, control networks for digital home, automatic control of temperature and flow in heat exchanger, and non-linear analysis and design of phase locked loops. The third part addresses issues of parameter estimation and filter design, including methods for parameters estimation, control and design of the wave digital filters. The fourth part presents new results in the intelligent control. This includes building a neural PDF strategy for hydroelectric satation simulator, intelligent network system for process control, neural generalized predictive control for industrial processes, intelligent system for forecasting, diagnosis and decision making based on neural networks and self-organizing maps, development of a smart semantic middleware for the Internet , development of appropriate AI methods in fault-tollerant control, building expert system in rotary railcar dumpers, expert system for plant asset management, and building of a image retrieval system in heterogeneous database. The content of this thematic book admirably reflects the complementary aspects of theory and practice which have taken place in the last years. Certainly, the content of this book will serve as a valuable overview of theoretical and practical methods in control and automation to those who deal with engineering and research in this field of activities.

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