

Assembly Line Balancing Problem with Reduced Number of Workstations

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Abstract: This paper considers heuristics which can be helpful in reducing a workstations number in assembly line balancing problem. In the last sixty years a large variety of heuristics and exact solution procedures have been proposed to balance different structures of assembly lines. The author of this paper discussed some heuristics which almost lead to the reduction of the number of workstations (parallel single lines or u-line configuration) and productivity improvement. Special attention was given to the quality of final results. These are some measures of solution quality: line efficiency (LE), line time (LT) and smoothness index (SI) are calculated and compared. At the end final remarks are given.

Keywords: parallel assembly lines, u-line structure, assembly line balancing problem, quality measures

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. 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. 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). 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 and Birnie (Helgeson et al. 1961) were the first to propose the ALBP, and Salvendy (Salvendy 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). Salvendy (Salvendy 1955) provided the first mathematical attempt by solving the problem as a linear program. Gutjahr and Nemhauser (Gutjahr et al. 1964) showed that the ALBP problem falls into the class of NP-hard combinatorial optimization problems. Therefore, heuristic methods have

become the most popular techniques for solving the problem (Fonseca et al. 2005). The remainder of the paper is organized as follows: in Section 2 selected assembly line structure are presented, heuristic methods are discussed more precisely in Section 3. Section 4 includes popular in assembly line balancing problem quality measures of final results. Numerical example is reported in section 5. Finally, conclusions are given in section 6.

2. SELECTED ASSEMBLY LINE STRUCTURES

In practice we can find different structures of assembly lines (serial line, with parallel workstations line, two-sided line, u-line, etc.). All of them can be classified into two general types: type I with constant cycle time and minimization of workstations' number and type II with constant number of workstations and minimization of cycle time. All of them can be used in single or multi/mixed model production. A lot of methods and procedures were introduced for solving the assembly line balancing problem what can satisfy in the future production rates and utilization of tools in real companies. The first described assembly line structure was serial assembly line (Fig. 1). A traditional line organizes workstations and the tasks that comprise them sequentially along straight line. Nowadays, many products are produced not only from simple parts but very often from complex elements (earlier assembled) are used. It causes that even complex products need limited number of assembly operations. Therefore serial layout is still popular in assembly of final products.

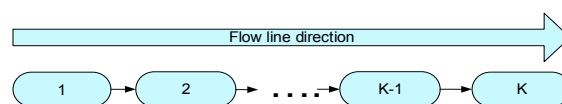


Fig. 1. Two-sided assembly line

The U-line structure was introduced first time in 1994. In a U-line layout, workstations are arranged around U-shaped line

(Fig. 2). Operators work inside the U-line. The U-shaped assembly line has become an alternative for assembly production system since operator may perform more than one task located to different places of assembly line. Moreover, U-line disposition allows for more possibilities on how to assign the tasks to the workstations and therefore the number of workstations needed for U-shaped line layout is never more than the number of workstations needed for the traditional straight assembly line. In the traditional assembly line balancing problem for a given cycle time, the set of possible assignable tasks is confirmed by those tasks whose predecessors have already been assigned to workstations, whereas in the U-line balancing problems, the sets of assignable tasks is determined by all those tasks whose predecessors and successors have already been assigned (Miltenburg 1998, 2001). One of the important characteristics that make U-shaped structures different from straight assembly lines is that the entrance and the exit of these lines are at the same position (Shwetank et al. 2013).

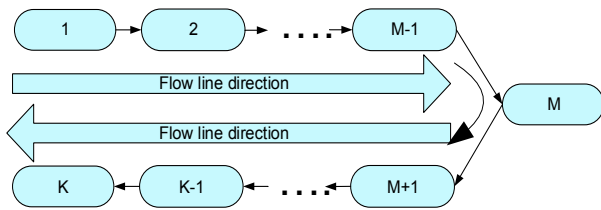


Fig. 2. U-shaped assembly line

Products enter the U-shaped assembly line at the front-side and exit from the back-side of the line. Studies on U-shaped assembly lines provide evidence for the potential to improve visibility and communications skills between operators, reduce operator requirements, increase quality, reduce work-in-process inventory, etc. (Nakade and Nishiwaki, 2008).

In the same year as U-line layout was introduced, the problem of balancing parallel assembly lines was presented (Fig. 3). In the article (Gökce et al. 2006, Ismail et al. 2011) authors studied alternative assembly line design for a single and mixed model products. The objective was to determine the number of assembly lines with minimum total manpower. In 2009 a description of parallel assembly line balancing problem (PALBP) which consists of two connected sub-problems: assigning of tasks to parallel lines and balancing parallel lines was given.

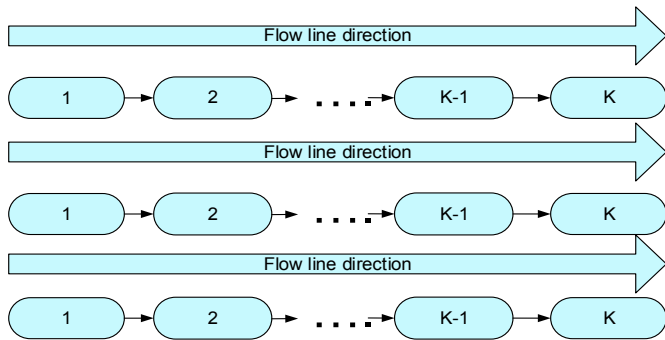


Fig. 3. Parallel assembly lines

Most companies consist of one or more assembly lines. When the market demand is high enough, it is not uncommon to duplicate the entire assembly line. This provides the advantage of realisation of production rate in given period of time. Another advantage of parallel assembly lines is seen during workstation breakdowns. If equipment problems occur at workstation, other lines can continue to run.

3. SELECTED HEURISTIC PROCEDURES

In this section heuristics which are useful in the balancing of the serial line, U-shaped line and parallel assembly lines are presented. In many papers it is possible to find different heuristic approaches (Scholl 1998). Most of the heuristics are based on genetic algorithms, tabu search and simulated annealing techniques. In each of these heuristics different strategies are used to represent assembly line balancing solutions and neighbour generation mechanism. The common assumptions of the heuristics are listed below:

1. only one product is produced on each assembly line,
2. precedence graphs for each product are known,
3. task performance times of each product are given,
4. Operators working on each workstation of the line are multi-skilled.

In 1961 was proposed the well known Ranked Positional Weight procedure which bases on precedence graph and task times (Halgeson et al. 1961). The steps involved in this method are as follows:

1. Determine the positional weight (PW) for each task (time of the longest path from the beginning of the operation through the remainder of the network),
2. Rank the work elements based on the PW. The work element with the highest PW is ranked first,
3. Proceed to assign work elements (tasks) to the workstations, where elements of the highest positional weight and rank are assigned first,
4. If at any workstation additional time remains after assignment of an operation, assign the next succeeding ranked operation to the workstation, as long as the operation does not violate the precedence relationships, and the station times do not exceed the cycle time,
5. Repeat steps 3 and 4 until all elements are assigned to the workstations.

Similar to straight line, U-shaped assembly line balancing problem can be solved using heuristic methods. Very often there are adopted from serial lines procedures. The difference between the original versions and the modified versions is that tasks are available for assignment to a workstation by having all successors or all predecessors previously assigned to a workstation, and when solving for the simple line balancing problem, tasks are available for assignment by having all successors previously assigned only. The Modified Ranked Positional Weight procedure was introduced by Miltenburg and Wijngaard (Miltenburg et al. 1994).

Parallel assembly lines are considered in literature rather seldom. Sürer and Dagli (Sürer et al. 1994) suggested heuristic procedures and algorithms to determine the number of lines and the line configuration dynamically. Gökçen (Gökçen et al. 2006) presented heuristic procedures and mathematical model for multiple or parallel assembly line balancing problem. They divided their study problem of parallel lines balancing in two cases: passive (same products are assembled with the same cycle time in two different assembly lines) and (the products assembled at each line should be different or similar models of a single product and their cycle times should also be the same. For passive case, the following steps should be carried out:

1. balance each assembly line using any single model assembly line balancing method,
2. compute the idle times for each workstation of each assembly line,
3. find the workstation k with an idle time that is equal to or greater than the half of the cycle time, and assign the task(s) in workstation k of another assembly line to the operator of the related workstation. Repeat this process for all workstations.

For an active case procedure, the product assembled at each line should be different or similar models of single product and their cycle times should be also same. In some practical, even though the product is same on both lines, the cycle times can be different.

4. MEASURES OF FINAL RESULTS

Some measures of solution quality have appeared in line balancing problem. Three of these are presented below (Scholl 1998).

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:

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

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:

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

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:

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

where:

c - cycle time,

K -total number of workstations.

5. NUMERICAL EXAMPLE

In this section a numerical example is calculated and discussed. Table 1 includes the processing times of 30 tasks. The graph of the single product is presented in Fig. 4.

Table 1. Processing times

Task	t_i	Task	t_i	Task	t_i	Task	t_i
1	4	9	3	17	4	25	1
2	2	10	7	18	9	26	2
3	7	11	9	19	4	27	3
4	6	12	2	20	3	28	5
5	1	13	7	21	6	29	4
6	5	14	10	22	5	30	1
7	9	15	1	23	4		
8	5	16	6	24	3		

Results of the numerical experiment are given below. First a single line was balanced with different values of cycle times (c changed from 10 units of the time to 20 units of the time every 2 units – 5 steps). As we know, the great benefit of assembly lines is a quick response on market demand. Assembly lines are very common in automotive plants, consumer electronics and many different final products which are assembled in production systems. The market demand is strongly connected with cycle time c which is defined as:

$$c = \frac{\text{production time/day}}{\text{output rate/hour}} \quad (2)$$

Next a u-line shaped assembly line was considered. Similar to serial line, value of cycle times changed from 10 units of the time to 20 units of the time every 2 units – 5 steps. As a last step of the experiment, parallel assembly lines (only 2 lines) were studied as a possible configuration of assembly system. Some results are shown in Fig 5 - 10. Detailed solutions in serial and u-shaped line are presented in Table 2. Additionally, the quality measures were calculated and also added to the final knowledge of balance process.

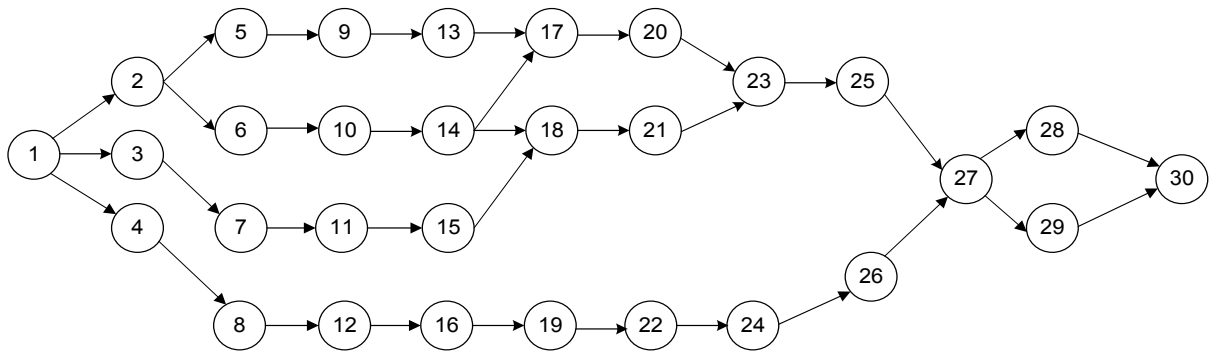


Fig. 4. Precedence graph of a numerical example

Table 2. Results of assembly balancing problem for a given numerical example

C	Serial line				U-shaped line			
	K	SI	LE	LT	K	SI	LE	LT
10	17	10,58	81,19	165	15	6,16	92	150
12	14	10,78	82,14	161	13	8,72	88,46	156
14	11	6,63	89,61	154	10	1,41	98,57	140
16	10	6,32	86,25	154	9	4,24	95,83	144
18	8	3,17	95,83	142	8	3,47	95,83	144
20	8	11,49	86,25	150	7	1,41	98,57	140

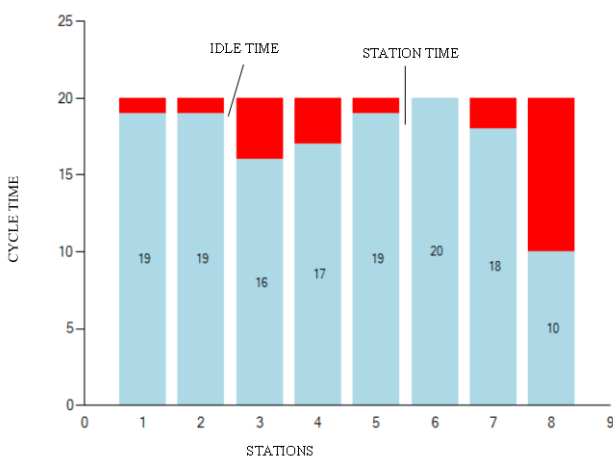


Fig. 5. Station times of serial assembly line for c=20

As we can notice this is only 1 workstation (k=6) with 100% utilization of processing time and some idle times occur on other workstations – Fig. 5. Balance for c=18 is

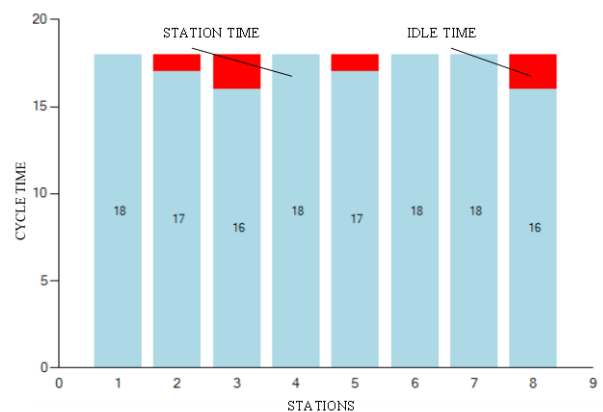


Fig. 6. Station times of serial assembly line for c=18

Shown in Fig. 6. We have still 8 stations line but the quality of the final balance is better. Now we have 4 workstations (k=1, k=4, k=6 and k= 7 with 100 % utilization of processing times and 4 workstations with idle times.

The highest speed of production line is when cycle time is equal 10 (because of the longest processing time of task 14). The balance of the line is shown in Fig. 7.

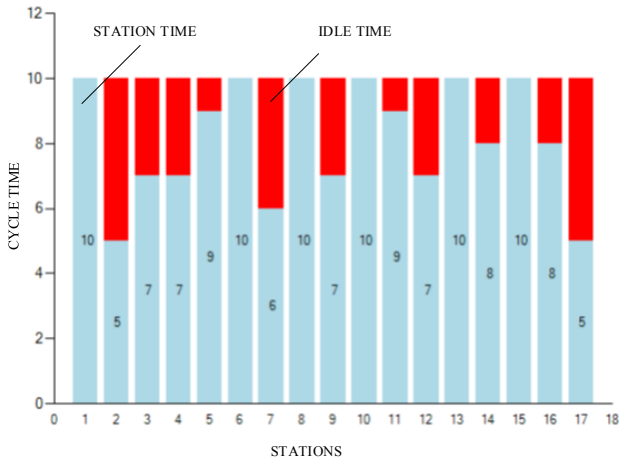


Fig. 7. Station times of serial assembly line for c=10

In this case we got the best rate (highest) of final product but the quality of balance is rather poor. Some workstations have idle times which are near 50 % of cycle time. Idle times are distributed very unequally in different workstations. Next some results for U-shaped assembly line balancing procedure are shown in Fig. 8.

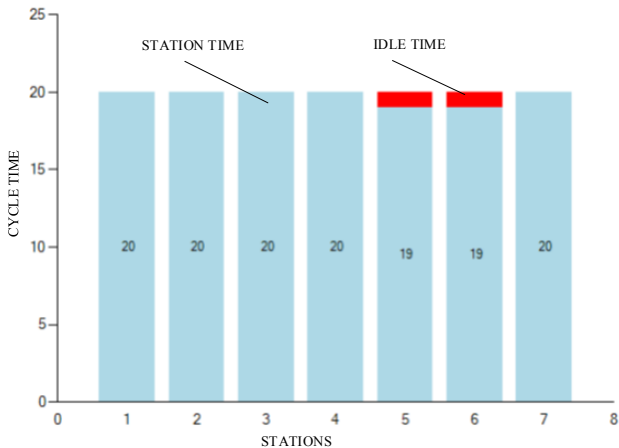


Fig. 8. Station times of U-shaped assembly line for c=20

Comparing this solution to serial line balance from Fig. 5 we can notice that the station times are almost perfect. In this case transforming serial line into U-shaped line gave a much better result. We obtained less 1 workstation (instead of 8 workstations we have only 7 now). The quality of balance is much better, too. But it is no rule in assembly line balancing problem. We can only be sure that the number of workstation can't exceed the number of workstations of existing serial assembly line balance solution. The quality of the final result of u-shaped line can be worse than for serial line. In Fig. 9 we can observe such case. Comparing to serial line solution for c=18 we have still 8 workstations but the smoothness index and line time are a bit higher than for the same conditions for serial line.

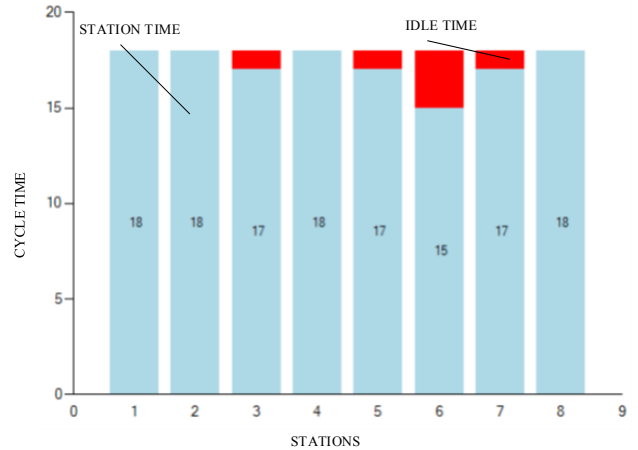


Fig. 9. Station times of U-shaped assembly line for c=18

The other way to reduce number of workstations is parallel assembly line balancing problem. As we can see in our case it is very difficult to cut some workstations. During our calculations we try to obtain feasible result with a good quality of smoothness index, line efficiency or line time. We reject solutions with unequal distribution of idle times and with bad utilization of workstation. But very often we get a solution with higher idle time only in the last station (Grzechca 2009). In this case if we need a higher rate of product, we can duplicate our serial line with the same balance but with changes in the station where idle time is bigger than 50 % of station's time. In our study we find two solutions where it is possible during parallelizing serial assembly lines to reduce the number of stations. If we consider the solution from Fig.7 we can find 2 workstations with idle times equal to 50% of station time and as final result we can create assembly system with two parallel assembly lines with 32 workstations instead of 34 (the cycle time is the same and the production rate of final product is twice higher). We can similar adopt assembly line from Fig. 5. Now we obtain 2 assembly parallel lines with 15 workstations for c=20 – Fig. 10.

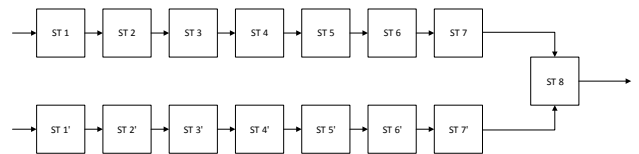


Fig. 10. Two parallel assembly lines with common last workstation

We can compare this solution with serial assembly line with c=10. As we can observe, this assembly line consists of 17 workstations. It is the same result as for U-shaped assembly line working with c=20 – Fig. 11. It is shown that even using only one heuristic method it is possible to reduce the number of workstations. The decision of building appropriate assembly line structure belongs to managers.

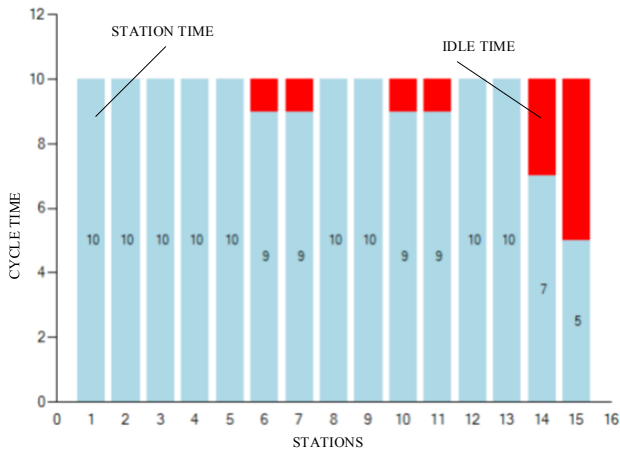


Fig. 11. Station times of U-shaped assembly line for $c=10$

6. CONCLUSIONS

The traditional assembly line is characterized by high efficiency or good value of smoothness index but due to its high specification and division of labor it has disadvantages in other areas. The assembly line has poor flexibility and can't adapt easily to either changes in product design or product demand changes. Almost any changes in product design, affects the entire system, requiring rebalance of the line and reallocation of resources. Problem of reducing number of workstations was discussed in this paper. Fluctuation of market demand cause changes in production systems. It was presented that even single product can lead to rebalance of assembly line in case of new market demands (new cycle time). The numerical example shown that in some cases it is worth to consider changes of assembly line structure (serial line, u-line or parallel lines). On the other hand we need to remember that any changes in real productions plants should take into account plant space, companies' finances or reallocation of workers. Assembly line balancing problem is connected with improvement of material and operations flow, better utilization of workstations (machines, robots, manual operators, etc.) and therefore we need to consider different possibilities. In some cases we can response for higher market demand not only with cycle time's changes (rebalance: changes of machines, workers, transport system) but we can try to find solution with known calculated balance in other assembly structure.

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