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Multi Objective Simultaneous Assembly Line Balancing and Buffer Sizing

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***Abstract*—**Assembly line balancing problem is aimed to divide the tasks among the stations in assembly lines and optimize some objectives. In assembly lines the workload on stations is different from each other due to different tasks times and the difference in workloads between stations can cause blockage or starvation in some stations in assembly lines. Buffers are used to store the semi-finished parts between the stations and can help to smooth the assembly production. The assembly line balancing and buffer sizing problem can affect the throughput of the assembly lines. Assembly line balancing and buffer sizing problems have been studied separately in literature and due to their collective contribution in throughput rate of assembly lines, balancing and buffer sizing problem are desired to study simultaneously and therefore they are considered concurrently in current research. Current research is aimed to maximize throughput, minimize total size of buffers in assembly line and minimize workload variations in assembly line simultaneously. A multi objective optimization objective is designed which can give better Pareto solutions from the Pareto front and a simple example problem is solved for assembly line balancing and buffer sizing simultaneously. Current research is significant for assembly line balancing research and it can be significant to introduce optimization approaches which can optimize current multi objective problem in future.

***Keywords*—**Assembly line balancing, Buffer sizing, Pareto solutions.

I. INTRODUCTION

ASSEMBLY lines are production systems in which some resources are used to perform production operations on the work pieces. They are designed when large quantity of products is desired to produce. The concept of assembly line is introduced by Ford manufacturing company. It is a significant system for cost efficient and mass production of products [1]. In assembly line system certain production stations are located at a specified distance from each other, called buffers, on a material handling system. The parts to be produced are moved down the assembly line from one station to another for processing after passing through the intermediate buffers between the stations. In assembly lines, each station may have different operational time and each station needs independence, so that its efficiency and effectiveness are not affected by the production variations in the precedent station. The lack of independence between the stations may cause blocking or sometimes cause starvation in the assembly line [2]. Buffers are significant to defend stations from starvation due to machine failures in the upstream, tasks processing time variations in the upstream or in the downstream, and stations blocking due to machines failure in downstream in the assembly lines. Buffers help to smooth and balance the flow of material between stations and therefore they are mostly introduced between stations in the assembly lines. However, larger buffer storage spaces incurs larger holding costs and therefore, appropriate buffer size design is significant to reduce manufacturing cost with required production rate in the assembly lines. Due to these facts, buffer allocation is an imperative optimization problem for the assembly line system designers. The problem of distributing workload among different stations and assigning storage spaces to different buffers with respect to certain objectives is called an assembly line balancing [3] and buffer sizing problem [4] respectively.

The most studied problem in assembly line is simple assembly line balancing problem (SALB). It includes lot of simplified assumptions to make the balancing problem easily solvable. These assumptions may consider that the task time is deterministic variable and there is no uncertainty in the assembly line environment etc. However, these assumptions make the problem much easier to solve and may not be practical for real cases. Therefore, some of the assumptions are tried to reduce in these problems to make them practical. These problems which can eliminate some of the assumptions are termed as general assembly line balancing problem (GALBP). Assembly line balancing is significant to reduce the overall cost of production and relies on different parameters such as, line balancing, buffer sizing and buffer allocation etc. In literature, line balancing problem separately has been widely addressed by researchers and different objectives, for example, minimization of cycle time [5], [6], minimization of number of workstations [5], [7], maximization of line efficiency [8] and maximization of system utilization [9] has been used for assembly line balancing. Similarly, buffer sizing problem in assembly line also contributes in the effective performance of an assembly line system and is studied

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separately by some researchers [10]-[12]. Buffer sizing problem has two types. The objective of first type is aimed to minimize total size of buffers of the assembly line while trying to achieve a known throughput rate. The second type of buffer sizing problem is focused to maximize throughput rate of the line with known value of maximum size of buffers in the assembly line [4].

Most of the research on assembly line balancing and buffer sizing problems used single objective for optimization. In real environment of assembly lines, two or more objectives are significantly desired to achieve simultaneously. Moreover, multi objective problems are more likely towards real situation and therefore, multi objective optimization of assembly line balancing has been discussed by several researchers in recent years. For example, [7], [13]-[25] projected different solution approaches for multi objective optimization of assembly line balancing problems. Furthermore, a little work has addressed multi objective optimization of buffer sizing problems [26]-[28].

Nevertheless, both single objective and multi objective assembly line balancing problems and buffer sizing problems has been investigated separately in literature, but suffers from the lack of simultaneous considerations. In real assembly line systems, buffers are present in between different stations and companies judge them as production constraint. Therefore, it is an important issue and is highly needed to reduce buffer size and improve production rate. Furthermore, size of buffers between different stations and assembly line balancing both can affect the throughput of the lines and therefore, it is desirable to balance the assembly line along with the optimization of buffer sizing objectives. Buffer sizing and balancing problems are preferred to be investigated simultaneously in order to effectively balance the line in considering the buffer spaces between stations. To the best of author’s knowledge, a little work on simultaneous line balancing and buffer sizing problems are studied in literature and is therefore presented here.

Rest of the paper is organized as follows; Section II presents problem description, Section III indicates interdependencies between the balancing and buffer sizing problems with a short example. Section IV presents a multi objective assembly line balancing with buffer sizing and illustrates an example problem. Section V describes the conclusion and future direction of research.

II. Problem Description

Single model assembly line which produces single type of product is considered for study here. Further, some of the assumptions used in simple assembly line problem are tried to be eliminated to introduce some of the real aspects in the assembly line. The assumptions and notations used are illustrated below:

Assumptions

- Single model assembly line balancing and buffer sizing problem is considered in which n number of tasks are assumed to process on m number of work stations.
- The machines on these stations are unreliable and each station is separated by an intermediate finite buffer.
- The size of these buffers is defined by its lower LB_q and upper bound UB_q values.
- It is assumed that all stations have similar failure rate and repair rate denoted by λ and μ respectively.
- Buffers in the assembly line do not fail and work pieces moves through them with zero transit time.
- Stations are only considered to fail when they are operating and do not fail when blocked or starved.
- The operating time between failure and repair time between failures are exponentially distributed.
- It is assumed that the first station is never starved and the last station is never blocked.
- The processing time of tasks t_i is a random variable of normal distribution with mean t_i^{μ} and variance of t_i^{σ}
- The setup time is included in the task times
- All tasks are processed according to their predecessor constraints
- Each task i is assigned to only one workstation j, processed once, and a single task is processed on a single workstation at a time.

Objectives

In current assembly line each station transfers the completed parts to the buffer and therefore cycle time of the assembly line may not be defined. Suppose average workload is denoted by AWL, throughput is denoted by TP, S_j indicates set of tasks assigned to a station j and b_{pq} defines the size p of buffer q. Then the current assembly line problem is aimed to divide all n tasks among all m workstations while optimizing the following objectives indicated in (1)-(3)

$$Max(Z_1) = TP \tag{1}$$

$$Min(Z_2) = \sqrt{\sum_{j=1}^{m}[AWL - t(S_j)]^2} \tag{2}$$

$$Min(Z_3) = \sum_{q=1}^{m-1}\sum_{p=1}^{B} X_{pq} b_{pq} \tag{3}$$

where,

$$AWL = \frac{1}{m}\sum_{j=1}^{m} t(S_j) \tag{4}$$

Subject to:

$$LB_q \le B_{pq} \le UB_q \tag{5}$$

$$\forall \ p = 1,2,.....,B;\ q = 1,2,.....,m-1$$

$$\sum_{q=1}^{m-1}\sum_{p=1}^{B} X_{pq} b_{pq} \le B_{Max} \tag{6}$$

$$X_{pq} \in \{0,1\} \tag{7}$$

$$\forall \ p = 1,2,.....,B\,;\ q = 1,2,.....,m-1$$

Equations (1) (2) and (3) indicate the objectives of the problem. The first objective shown in (1) indicates maximization of the throughput rate in assembly line. Second objective shown in (2) illustrates the minimization of variation of workload of a station from the average workload of all stations in the assembly line and third objective shown in (3) minimizes overall size of the buffer in the assembly line. Constrain (4) indicates that the average workload of a stations in the assembly line. Constrain indicated in (5) shows that the size of each buffer in assembly line is bound between lower and upper values. Constraint (6) shows that the total space allocated to all buffers should not exceed the maximum available space for the buffers in assembly line. Constraint (7) defines the binary decision variable. Where, $t(S_j)$ is the station load on any workstation j. The value of station load is illustrated in (8).

$$t(S_j) = \sum_{k=1}^{n_j} t_k^j \qquad (8)$$

The throughput objective in most of the research is obtained from simulation models due to its complexity. A little research in literature compute throughput from mathematical relations for the assembly line with buffers between their stations. Alden [29] proposed throughput equation for an assembly line of two stations. They considered random failure of the stations in their relation which can be considered as a building block for estimating throughput for assembly lines containing more than two stations. Dennis E. Blumenfeld and Jingshan Li [30] extended Alden's [29] relation to estimate throughput for the general case of assembly line with m number of work stations. Their proposed relation with the above mentioned assumptions is described in (9):

$$TP \cong \frac{X}{1 + \frac{\lambda}{\mu} + \frac{\{(m-1)\lambda/\mu\}}{\{1 + (m/4)(1+2\lambda/\mu)(B\mu/X\}}} \qquad (9)$$

where, X represents the production rate in the assembly line. Their proposed relation gives comparable results with the simulation approach for estimating throughput in the assembly lines and is therefore used here. However, in the relation, [30] considered same buffer sizes in the assembly line. But in the current case buffers have different sizes. In the proposed problem suppose, WL_j indicates the workload of any station j. Then in any two consecutive stations j and $j+1$ the difference between their workload may decide if there would be blockage or starvation in the assembly line in these two stations.

If, $WL_j < WL_{j+1}$ then after time $(WL_{j+1} - WL_j)$ the parts which have completed tasks on station j will move to the buffer B_{pq} between station j and $j+1$. However, it depends on the storage capacity or the buffer size of the buffer between these two stations that whether there would be blockage or starvation. The station j may not block until following condition remains true,

$$x_j(WL_{j+1} - WL_j) \le B_{pq}$$

where, x_j production rate from station j. This condition indicates that the station j would not be blocked until the buffer space between station j and station $j+1$ is not filled up to its maximum capacity of B_{pq}. Similarly if $WL_j > WL_{j+1}$ then after time $(WL_j - WL_{j+1})$ the parts which have completed tasks on station $j+1$ will move to the next buffer. It depends on the storage capacity or the buffer size of buffer between the two stations j and $j+1$ which will decide the starvation of the station $j+1$. The station $j+1$ will not starve until following condition remains true, $x_{j+1}(WLj - WL_{j+1}) \le B_{pq}$

Suppose the situation when station j is not blocked and station $j+1$ is not starved, then the production rate of these stations will be same and will be equal to the production rate of the station which is located first, therefore the situation when buffer is full, production rate will be given in (10).

$$x_j = \frac{B_{pq}}{|WL_j - WL_{j+1}|} \qquad (10)$$

The production rate x_j, if used in (9) can give the throughput for the situation when the station j will be deciding the production rate of the assembly line and the buffer between station j and $j+1$ is full, from (11)

$$TP_j \cong \frac{\frac{B_{pq}}{|WL_j - WL_{j+1}|}}{1 + \frac{\lambda}{\mu} + \frac{\{(m-1)\lambda/\mu\}}{\{1 + (m/4)(1+2\lambda/\mu)(\mu \times |WL_j - WL_{j+1}|/B_{pq}\}}} \qquad (11)$$

Suppose, K indicates the set of throughput values TP_j obtained using production rates of each station j in the assembly line. Then, throughput of the current problem is considered as

$$TP = \min TP_j \text{ from } \forall\ K = \{TP_1, TP_2, ..., TP_j, ...TP_{m-1}\}$$

III. Interdependency between Buffer Sizing and Assembly Line Balancing

In assembly line balancing problem, tasks are divided among stations in such a way that certain objectives are optimized. For example, cycle time is minimized, workload variations are minimized or line efficiency is maximized [31]. In assembly lines, due to different workload of stations, there is possibility of starvation or blocking between stations on assembly lines and therefore, buffers are used between the stations to store the semi-finished parts of the stations. Buffers can regulate and smooth the production in assembly lines but incur storage cost and therefore it is desired to optimize the size of buffers between the stations. The total sum of size of all buffers in line is limited due to the fixed size of the assembly workshops and the size of buffers between two consecutive stations can be affected by the workloads between these stations. The buffer size can also affect the throughput of the assembly line as can be seen from (11). In real assembly lines, the balancing solutions are desired but at the same time maximum throughput is also desired in the assembly lines. The assembly line balancing solution and buffer sizing can collectively affect the throughput of the assembly lines and therefore assembly line balancing solutions which can give more throughput values are significant. The collective contribution of a balancing solution and buffer sizing can be cleared from a simple example as given below:

Simple Example

In order to describe the interdependency between the balancing solutions and buffer sizing problem, a simple assembly line problem is taken from a simple assembly line example from [31] and the task time data is randomly taken. The precedence diagram of the considered assembly line problem is shown in Fig. 1 and task time data is shown in Table I. The tasks of the assembly line problem are allowed to divide in 5 stations and it is assumed that λ and μ has same values and equals to 1.

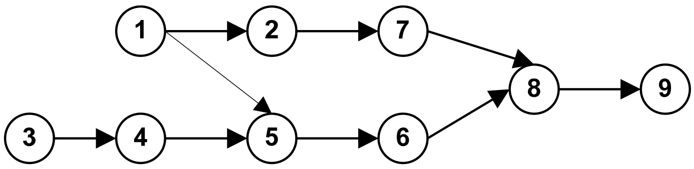

Fig. 1 Precedence Relation in Tasks in an Assembly Line

TABLE I
TASK TIME DATA FOR THREE SCENARIOS

Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9
6	6	4	5	4	5	4	2	9

Some of the possible balancing solutions of the considered assembly line balancing problem are indicated in Table II. The numbers in Table II represents the tasks assigned to different stations in the considered assembly line balancing solution. The workload of the stations for each of the balancing solution is given in Table III.

TABLE II
SOLUTIONS FOR THE CURRENT ASSEMBLY LINE BALANCING PROBLEM

Solution	Station 1	Station 2	Station 3	Station 4	Station 5
1	1, 3	2, 4	5, 6	7, 8	9
2	3	1,4	2,5	6,7	8,9
3	1,3	4,5	2,6	7,8	9

TABLE III
WORKLOAD ON STATIONS FOR EACH BALANCING SOLUTION

Solution	Station 1	Station 2	Station 3	Station 4	Station 5
1	10	11	9	6	9
2	4	11	10	9	11
3	10	9	11	6	9

For each assembly line balancing solution, there are different settings to assign buffer sizes between any two consecutive stations in the assembly line. For each balancing solution, different buffer sizes between the stations and their corresponding throughput values are indicated in Table IV. It can be seen from Table IV that, for each balancing solution, the size of buffers between the stations can affect the throughput value of the assembly line balancing solution. The buffer size assignments with overall minimum size and which can give maximum throughput values can be the better choice to select for an assembly line balancing solution. It can be seen from Table IV that the considered three balancing solutions are observed and different settings of the buffer sizes between the stations are analyzed. From the results shown in Table III, the balancing solution 1 is better choice to consider because it needs small size of buffers and the total size of buffer i.e., sum of buffers between all stations is 9, and it is highlighted in Table IV.

TABLE IV
BUFFER SIZES AND THROUGHPUT OF ASSEMBLY LINE FOR DIFFERENT BALANCING SOLUTIONS

Balancing solution	Size of Buffer				Total Buffer Size	Throughput after Buffer				Bottleneck Station	Throughput of Assembly Line
	1	2	3	4		1	2	3	4		
1	1	1	1	1	4	0.352	0.147	0.088	0.088	3 and 4	0.088
	1	1	2	2	6	0.352	0.147	0.2121	0.2121	2	0.212
	1	2	2	2	7	0.352	0.352	0.2121	0.2121	3 and 4	0.212
	1	2	3	3	9	0.352	0.352	0.352	0.352		0.352
2	1	1	1	1	4	0.031	0.352	0.352	0.147	1	0.031
	4	1	1	1	7	0.174	0.352	0.352	0.147	4	0.147
	4	1	1	2	8	0.174	0.352	0.352	0.352	1	0.174
	5	1	1	2	9	0.231	0.352	0.352	0.352	1	0.231
	7	1	1	2	11	0.352	0.352	0.352	0.352		0.352
3	1	1	1	1	4	0.352	0.147	0.046	0.088	3	0.088
	1	1	2	1	5	0.352	0.147	0.111	0.088	4	0.147
	1	2	3	2	8	0.352	0.352	0.185	0.212	4	0.212
	1	2	5	3	11	0.352	0.352	0.352	0.352		0.352

IV. Multi-Objective Assembly Line Balancing and Buffer Sizing

The interdependency between balancing solution and buffer sizing indicates that the objective of maximizing throughput of an assembly line and minimization of the buffer size are confliction objectives. Furthermore, the balancing objective considered in current research is the minimization of the variation of workload of stations from the average workload of stations. The objectives shown in (1), (2) and (3) are conflicting objectives and these objectives are significant to consider simultaneously. The solution of multi objective problems is in the form of set of tradeoff solutions called Pareto set of solutions and these problems does not give one solution. The multi objective optimization problems are solved by different approaches in literature to get better Pareto set of solutions. There are two main methods to optimize multi objectives. In one method, objectives are combined into a single objective and optimization is performed on the combined objective by giving some weightages to each objectives. However, it is hard to decide the weights for each objective precisely. In this method, a single solution is obtained. In another method, an entire Pareto front is obtained in which each solution is non-dominated with others and the optimization problem is focused to determine the set of non-dominated solutions. In literature different optimization approaches have been used to determine non-dominated solutions and selection of some solutions from this set of non-dominated solutions or Pareto set of solutions. The most famous among them are fast non-dominated sorting genetic algorithm (NSGA II) [32] and strength Pareto evolutionary algorithm (SPEA II) [33]. These algorithms search the non-dominated set of Pareto solutions from the search space. Deb et al. [32] introduced the concept of crowding distance and crowding comparison operator which is used to decide on the selection or rejection of a Pareto solution from non-dominated set of Pareto solutions. Zitzler et al. [33] used strength value of the non-dominated Pareto solutions and based on their strength values, Pareto solutions are selected or rejected from the non-dominated set of Pareto solutions.

In Pareto front there are many solution points from which one solution is desired to use and without the decision maker input, it is difficult to decide which solution can be given preference on the other Pareto solution, based on the values of the objective functions in that Pareto solution. Furthermore, the two corner points on the Pareto front can give extreme value of one of the objective and in the absence of the decision maker the middle Pareto Points on the Pareto front can be a little more reliable then the corner Pareto points because they can give less or middle values of the objectives on the Pareto front. The Pareto front, its corner points and middle points are shown in Fig. 2.

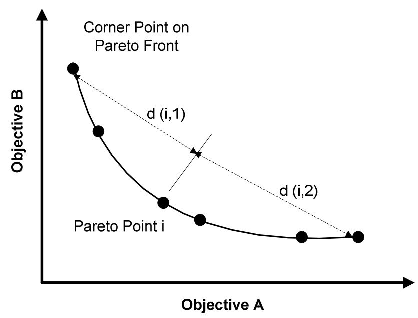

Fig. 2 Pareto front indicating corner points and middle points

In the current research, the Pareto points which are on the middle of the front are given preferences for selection. This preference is given based on the objective function shown in (12). The objective function shown in (12) gives the product of the Euclidean distance of the Pareto point from one corner Pareto point and its Euclidean distance from the second corner point on the front. This product has maximum value for the Pareto solutions which are on the middle of the front and its value is less for the Pareto points which are more towards the corner Pareto points on the front. These points can be seen in Fig. 2 and the objective function indicated in (12) is significant to identify Pareto solutions which are in the middle portion of the front and can help to give search direction.

$$Objective = Max(d_{i,1} \times d_{i,h}) \; \forall 1 < i < h \tag{12}$$

The current problem of multi objective assembly line balancing and buffer sizing is solved using proposed method.

Example Problem

In order to test the proposed method, a simple assembly line problem used in the previous section is considered for assembly line balancing and buffer sizing problem, as shown in Fig. 1. The task time data is used the same which is used in the previous section, shown in Table I and it is assumed that λ and μ has same values and equals to 1. The balancing solutions of the considered assembly line balancing problem are indicated in Table V. The numbers in Table V represents the tasks assigned to different stations in the considered assembly line balancing solution. The workload of the stations for each of the balancing solution is given in Table VI. The buffer sizes, total buffer size, throughput value and the variation of workload from average workload (i.e., value of the objective shown in (2) for each Pareto solution as indicated in Table VII. These solutions in Table VII are the solutions of the considered problem. From these solutions the Pareto solution 7 is highlighted in Table VII and it obtained based on objective shown in (12). It can be seen from Table VII that solution 7 gives lower values of all the objectives, i.e., it gives relatively smaller size of the buffer.

TABLE V
BALANCING SOLUTIONS FOR THE CURRENT ASSEMBLY LINE BALANCING PROBLEM

Solution	Station 1	Station 2	Station 3	Station 4	Station 5
1	1, 3	2, 4	5, 6	7, 8	9
2	3	1,4	2,5	6,7	8,9
3	1, 3	2, 4	5, 6	7, 8	9
4	1,3	4,5	2,6	7,8	9
5	1,3	4,5	2,7	6,8	9
6	1,3	4,5	2,7	6,8	9
7	1,2	3,4	5,7	6,8	9
8	1,2	3,4	5,7	6,8	9
9	1,2	3,4	5,7	6,8	9
10	3	1,4,5	2,7	6,8	9
11	1,3	4	2,5	6,7	8,9
12	3,4	1,2,5	6,7	8	9

TABLE VI
WORKLOAD ON STATIONS FOR EACH BALANCING SOLUTION

Solution	Station 1	Station 2	Station 3	Station 4	Station 5
1	10	11	9	6	9
2	4	11	10	9	11
3	10	11	9	6	9
4	10	9	11	6	9
5	10	9	10	7	9
6	10	9	10	7	9
7	12	9	8	7	9
8	12	9	8	7	9
9	4	15	10	7	9
10	4	15	10	7	9
11	10	5	10	9	11
12	9	16	9	2	9

TABLE VII
BUGGER SIZES, 1/THROUGHPUT AND WORKLOAD VARIATION FOR DIFFERENT SOLUTIONS

Solution	Size of Buffer				Total Buffer Size	1/Throughput	Workload variation from average workload
	1	2	3	4			
1	1	2	3	3	9	2.84	17.88
2	7	1	1	2	11	2.84	21.16
3	1	2	2	2	7	4.71	17.88
4	1	2	5	3	11	2.84	17.88
5	1	1	3	2	7	2.84	17.66
6	1	1	2	2	6	4.71	17.66
7	3	1	1	2	7	2.84	16.85
8	2	1	1	1	5	4.71	16.85
9	4	2	2	3	11	2	16.85
10	11	5	3	2	21	2.84	21.9
11	5	5	1	2	13	2.84	18.11
12	1	1	1	1	4	32	20.54

V. CONCLUSION

Assembly line balancing and buffer sizing problems are significant and solution of both of these problems can affect the throughput of the assembly lines. However, in literature, assembly line balancing and buffer sizing problem are mostly addressed separately. Due to collective contribution of balancing solutions and buffer sizing solutions in throughput rate of assembly lines, balancing and buffer sizing problem are desired to study simultaneously and therefore they are considered here simultaneously. Current research is aimed to maximize throughput, minimize total size of buffers in assembly line and minimize workload variations from average workload in assembly line simultaneously. A multi objective optimization objective is designed which can give better Pareto solutions from the Pareto front and a simple example problem is solved for assembly line balancing and buffer sizing simultaneously.

Current research is significant for assembly line balancing research because it can be used to assign differ tasks to the station and at the same time it can decides the sizes of buffer storages required between the stations for the considered balancing solution. Moreover, Pareto optimization shows the solution which can give a balancing solution desiring smaller storages between stations and which can give less variation in the workload of stations from average workload. Current research can be extended to introduce current Pareto optimization approach in some optimization algorithms to optimize current multi objective problem in future.

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