Multi-objective balancing of Parallel Mixed-Model assembly lines by Considering Machine and Worker Constraints

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***Abstract*—Assembly line balancing has been a focus of interest to academics in operation management for the last decades. Despite diverse research works in this field, many problems still remained unsolved. Given the importance and attractiveness of the mixed product parallel lines balancing problem and the importance of the human factor in the development process and also very few studies in relation to several simultaneous objectives that is a new approach in the field of parallel assembly lines, this paper presents a two-objective combined integer mathematical model for balancing mixed-model parallel assembly lines. By assigning variables in the form of zero-one and considering the limitations of both machinery and manpower at the same time, called Dual-Resource Constrained (DRC), it seeks to reduce the number of stations required in lines and minimize the total cost of human resources. The proposed model is evaluated by solving two numerical examples. Results reflect the good performance of the model and improved objectives.**

Keywords—assembly line balancing, parallel assembly lines, Mixed-Model, dual resources constraints, type I.

I. INTRODUCTION

An assembly line is a production system consists of a number of related workstations which handle assembled products through a conveyor belt or similar systems. A set of tasks is performed at each workstation and finally, the assembled product is delivered at the end of the line [1]. Many problems in the production and assembly lines are mainly due to their imbalance. The assembly line balancing is defined as assigning activities to stations in order to minimize or maximize an objective function. It is considered an essential step in the planning of production systems. Imbalance will lead to the loss of useful capacities of the system and exorbitant costs for the system. This issue has become more important because of increasing global competition and rapid technological development [2].

A variety of different products can be assembled on an assembly line. An important feature is the assembly line balancing problem. Thanks to intelligent customers who seek diversity and have a high understanding of technology and provide opportunities for manufacturers to compete in today's market, mixed production lines (including simple, mixed and multi-product lines) have been considered [3]. The mixed model is used in many manufacturing systems. In this system, the line can produce several models in low volume or small groups in order to rapidly respond to diverse customer demands without large inventory [4].

Another characteristic of assembly lines which affects the classification of assembly line balancing problems is the line layout. Due to many advantages such as ease of balancing the workload among stations, higher reliability, more flexibility in scheduling, job enrichment and employee satisfaction, parallel lines were used which make further improvements in flexibility and sensitivity to failure. Therefore the use of mixed-model parallel lines will improve the system performance and productivity [5]. The design of parallel lines leads to reduced number of workstations by combining neighboring stations in adjacent lines [6].

Most research has focused on the balance problems type I and type II. In type I, the assembly line duration is known as an input and the objective is to minimize the number of workstations [7, 8]. In type II, the number of assembly stations is known as an input and the objective function is to minimize the working cycle time [9-11].

We studied type I, so our goal is to reduce the number of workstations. But the problem approach is based on the DRC. It follows two purposes: the first is to minimize the number of workstations and the second is to minimize total cost of

manpower which is a novel goal in this context. Given the fact that the present world is undoubtedly the world of organizations and the custodians of these organizations are people who embody, move and manage organizations. Organizations without manpower have no meaning, so they are impossible to manage. Human capital is the highest, most valuable and the greatest asset of any organization and country, and the greatest competitive advantage of countries and organizations is having capable workforce. It is importance due to the important role the human factor plays in the development process, so we selected to reduce total cost of manpower in addition to reducing the number of stations. Systems that consider both machinery and manpower constraints simultaneously can fall in the DRC group [12-14]. The DRC systems are more complicated than single-constrained ones. During scheduling, additional resources are challenged because different aspects of worker allocation must be considered at the same time such as location and time of worker allocation, and the evaluation of the effects of components on each other. The performance of workers should be determined according to the type of their station which was assigned based on their skill levels. In general, there are four skill levels which use a series of factors adopted from Techawiboonwong teams [15]. Workers can be assigned to a workstation in one shift. Due to differences in workers' skills and capabilities, tasks assigned to them vary from worker to worker.

Given above, the importance of mixed-model assembly lines in modern industries and the benefits of parallel assembly lines are specified. In such an environment, production processes are more reliant on workers, and resource planning must be done for different types of machines and human in order to provide optimal plans. This paper presents a model for balancing a mixed-model assembly line through Parallel Mixed-Model Assembly Line Balancing with the approach of Dual-resource constrained, which is called (PMMALB/D). This study is organized in six sections: after the introduction, Section 2 reviews the literature, Section 3 describes the mathematical model presented for the line balancing problem, Section 4 presents numerical experiments based on a set of standard data with computational results, Section 5 contains the results and some suggestions for future research and finally, Section 6 lists references.

II. Literature Review

Most of the research on the assembly line balancing problem has been allocated to modeling and solving the simple assembly line balancing problem. The analysis of the assembly line balancing problem was first modeled by Brayton [16] and the mathematical model was published by Salveson [17]. The assembly line balancing problem has been extensively studied [4, 18-20]. Moreover, in order to adapt to customer demand with high variability, mixed-model assembly lines are widely used in a wide range of industries. The mixed-model lines have two important problems. The first relates to line balance and the second relates to the model sequence problem. In this regard, several studies have been reported [9, 21-26]. In the parallel assembly lines balancing, the goal is to balance more than one assembly line. In designing such lines, several methods and heuristic dynamic algorithms have been proposed to determine the number of lines and configuration. Sure and Dagli [27] studied alternative strategies for line design for a single product. Their studies on the parallel lines are different in terms of logic from the approach of Gokcen et al. [28]. Gokcen et al. [28] studied parallel lines with a different logical approach and proposed a new parallel assembly line balancing problem which contains balancing more than one assembly line with a common resource and also developed mathematical models and two heuristic methods for solving the parallel assembly line balancing problem. Benzer et al. [29] proposed a network model to solve the balancing parallel assembly lines problem. Lan [30] presented a two-phased approach for setting a list of possible layouts of elements, for a production line, determining the number of parallel machines to assign to each workstation, production rate and operation duration. Detailed review about balancing parallel assembly lines was done by Lusa [31]. He summarized his various studies on balancing parallel assembly lines and compared objectives and approaches. Esmaeilian [32] developed a heuristic algorithm for initial allocation and allocated tasks in the mixed production model for reconfiguration through parallel assembly lines. Scholl [33] proposed a solution for line layouts in order to increase the efficiency of production systems through combining neighboring stations for the parallel assembly line balancing problem, which was extended by Gokcen et al. [28]. Scholl and Boysen [3] provided a precise definition of the parallel assembly lines balancing problem. They introduced this problem as a parallel assembly lines balancing problem and divided into two subsections: 1. allocation of products to parallel lines, and 2. balancing these lines simultaneously. Kara et al. [34] proposed two goal programming approaches for balancing parallel assembly lines with fuzzy sets and objectives. Ozcan et al. [35] introduced a method for balancing mixed-model parallel assembly lines and the sequence line problem using simulation. Esmaeilian et al. [11] proposed the meta-heuristic Tabu search algorithm for allocating tasks in order to balance mixed products on parallel assembly lines.

During several decades, many studies have been done on DRC systems pioneered by Nelson [36]. Later, two literature review papers were published by Treleven [12] and Hottenstein and Bowman [13]. Researchers in previous studies found five major dimensions for DRC including: 1. worker's flexibility, 2. the transfer time of a worker, 3. the location where a worker is transferred, 4. queue order (job dispatch), and 5. Cost of worker transfers [13]. The main element in DRC systems is labor flexibility which is considered one of the dimensions of production flexibility. In these production systems, two important decisions must be taken: 1) time and 2) place where workers have to move [13, 14, 37]. Hax and Candea [38] proposed several options for production planning related to changing demand patterns and also changing workforce, overtime, seasonal inventory and backlogs in the plan. Silva et

al. [39] proposed a mass production programming model which considers a constant employment level. Lagodimos and Leopoulos [40] presented a programming model based on a heuristic method for changing labor planning. The goal is to determine the minimum number of workers required for each available period. Elmaraghy et al. [41] used the genetic algorithm for scheduling DRC production systems. Hopp et al. [42] provided a context so that workers can work at different speeds and then analyzed by defining the speed factors for each worker relative to the standard worker. Zhang et al. [43] proposed a method based on random numbers for the assembly lines balancing problem by worker allocation. By focusing on the capabilities of virtual production systems and using DRC settings, Hamedi et al. [44] proposed a multi-objective mathematical model with the goal programming approach. It is solved by the Tabu search algorithm and finds the optimal or near-optimal solution. Nakade and Nishiwaki [45] provided an optimization problem for the allocation of workers to lines so that the total cycle time is minimized. Using the genetic algorithm, Chaudhry and Drake [46] minimized the total delay for machine scheduling and solved the labor allocation problem for similar parallel machines.

There are a wide variety of assembly line balancing problems. Table 6 summarizes some of the activities conducted in the field of parallel assembly lines or mixed-model production. For simpler comparison, the literature classifies the assembly line balancing problems and the defined problem into four main categories (type of assembly line, number of products, type of problem and objective). For the notation of the first class (S: single assembly lines, W: single assembly line with parallel stations, U: U-shaped assembly line and P: a parallel assembly lines). In the second part: (SM: single product, MP: multi-product and MM: mixed-product assembly lines). The third group includes symbols BA and SE which represent the assembly line balancing problem and the sequence problem, respectively. The forth group refers to the study goal (A: minimization of workstations, B: minimization of cycle time or maximization of production rate, C: maximization of the productivity of lines, G: minimization of the response time to the system, E: maximization of profits and minimization of design costs, and F: minimization of labor costs). As was observed, there is no study on the PMMALB/D despite its importance and necessity. It further indicates the importance of the subject.

III. Mathematical Model

Traditionally, each line is separately balanced due to the precedence relations between tasks and cycle time in order to minimize the number of workstations, but the design of parallel lines reduces the number of workstations considering neighboring (adjacent) lines.

In order to provide the said mathematical model with the aim of reducing the number of stations within a line (type I) and minimizing the total cost of manpower, the following constraints and assumptions are considered:

- Two direct mixed assembly lines, which are located parallel to each other.
- The precedence graph is used which is one of known different models, and the concept of the Thomopoulos combined-priority chart [21] is separately used for each lines.
- Only permanent workers are used without temporary workers.
- Workers work during normal working hours without overtime hours.
- Only the balancing problem is considered without production sequence.
- One worker is assigned to a station and only performs the tasks of that station.
- All parameters and variables are deterministic.
- Parallel tasks and parallel stations are not considered.
- Machine failure (downtime) is not considered.
- Walking time of workers is not considered.

Parameters and Symbols:

i: index of task; $I_m = 1 \ldots\ldots |N_m| \quad i \in I_m$

m: index of model; $m = 1 \ldots\ldots |M| \quad m \in M$

k: index of workstations; $k = 1 \ldots\ldots k_{max}$

k_{max} : maximum number of stations;

c: cycle time; $C = max\{C_1, C_2, \ldots, C_m\}$

h: line number; $h = 1 \ldots\ldots H$

s: index of period; $s = 1 \ldots\ldots T$

o: work skills category; $o = \{1, 2, 3, 4\}$

w : number of operators;

t_{im}: time of task i in the *m* model;

p_h : set of precedence relationships in precedence diagram of line h;

A_{hk}: total number of tasks (that can be) assigned to station k in line h;

L^o: number of workers of skill category o;

L_s^o: number of workers of skill category o working in period s;

b_{so}: regular time rate for temporary workers of skill category o during period s;

x_{imhk}: 1 if task i from the *m* model in the *h* parallel line is assigned to workstation *k*; 0 otherwise;

V_{ks}^o: equals 1 if worker from skills category o is allocated to station k in period s;

R_k: equals 1 if workstation k is used for assembly and 0 otherwise;

U_{hk}: 1 if station k is utilized in line h; 0 otherwise;

μ_{ro} :equals 1 if workers of skill category o can work at processing stage r and zero otherwise;

Objective Functions:

$$\text{Min } k \tag{1}$$

$$\text{Min } \sum_{k=1}^{k_{max}} \sum_{o=1}^{4} \sum_{s=1}^{T} (V_{ks}^{o} \times b_{so}) \tag{2}$$

Constrains:

$$\sum_{h=1}^{H} \sum_{k=1}^{k_{max}} \sum_{m=1}^{M} \sum_{t=1}^{N_m} x_{tmhk} = 1 \tag{3}$$

$$\sum_{h=1}^{H} \sum_{k=1}^{k_{max}} \sum_{m=1}^{M} \sum_{t=1}^{N_m} x_{tmhk} \times t_{tm} \leq c \tag{4}$$

$$\sum_{h=1}^{H} \sum_{k=1}^{k_{max}} \sum_{m=1}^{M} i \times x_{rmhk} \leq \sum_{h=1}^{H} \sum_{k=1}^{k_{max}} \sum_{m=1}^{M} k \times x_{gmhk} \tag{5}$$

$$\forall (r,g) \in p_h \ | r < g$$

$$\sum_{h=1}^{H} \sum_{k=1}^{k_{max}} \sum_{m=1}^{M} \sum_{t=1}^{N_m} x_{tmhk} - A_{hk} \times U_{hk} \leq 0 \tag{6}$$

$$\sum_{h=1}^{H-2} \sum_{a=2}^{H-h} \sum_{k=1}^{k_{max}} U_{hk} + U_{(h+a)k} = 1 \tag{7}$$

$$w = \sum_{k=1}^{k_{max}} R_k \tag{8}$$

$$\sum_{k=1}^{k_{max}} \sum_{o=1}^{4} \sum_{s=1}^{T} V_{ks}^{o} \times \mu_{ko} = 1 \tag{9}$$

$$w = \sum_{k=1}^{k_{max}} \sum_{o=1}^{4} \sum_{s=1}^{T} V_{ks}^{o} \tag{10}$$

$$\sum_{k=1}^{k_{max}} \sum_{o=1}^{4} \sum_{s=1}^{T} V_{ks}^{o} \times \mu_{ko} \leq L_s^o \tag{11}$$

$$\sum_{o=1}^{4} \sum_{s=1}^{T} L_s^o \leq \sum_{o=1}^{4} L^o \tag{12}$$

The objective functions are shown in equations (1 and 2) which are the minimization of the number of workstations and the total cost of workers. Constraint 3 ensures that all tasks of models are assigned only once to each workstation in parallel lines. Constraint 4 ensures that the total operation time assigned to each workstation cannot be greater than the cycle time. Constraint 5 ensures that task i cannot be assigned earlier than its previous tasks to the workstation. Constraints 6 and 7 ensure that the operator in workstation k and line h can perform the tasks of lines h and h+1 (in this model, we assumed there are two lines). Constraint 8 calculates the total number of workers. Constraint 9 ensures that only one of workers can be assigned to any station at any period. Constraint 10 ensures that the total number of workers is equal to the estimated total number of workers calculated in Constraint 8 (w). Constraint 11 ensures that the total number of workers used from each skill category at each period are less than or equal to the total number of workers in that skill category. Constraint 12 ensures that the total number of workers allocated to each workstation is less than or equal to the total number of workers available.

IV. Numerical Example

Workers are assigned to each workstation using a matrix in which rows represent workstations and columns represent types of workers (4 skill categories) allowed to operate in each station.

Workers are assigned to the appropriate workstation according to their productivity in order to save the cost of direct labor. With regard to the activities that occur at each station, the type of worker that can be allocated to each station is determined, and a signage at each station specifies the type of authorized workers in that station. For the worker assignment problem, workers are randomly selected based on skill level and are assigned to the appropriate workstation. Workers can be assigned to one workstation at one period. In this paper, the maximum cycle time is considered in various models [47].

A. Example 1

This dataset is known as Jackson dataset [48] which includes three models (M=3) and 11, 10, and 9 tasks (obtained from datasets in this context adopted from the website [48]). Table 1 shows the theoretical minimum number of workstations and cycle time at the independent lines status for the problem test according to Gokcen et al. [28]. Table 2 shows the task processing time determined for each model. The matrix of allocating workers to stations is considered as follows:

$$\mu_{ko} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$

Moreover, the wage costs of workers from skill category o in period s are assumed as follows:

b_{11}=550, b_{12}=400, b_{13}=470, b_{14}=600

With regard to the labor allocation matrix and the considered parameters and constraints, 3160 was obtained for the second objective, which is the least cost for workers.

TABLE I. CYCLE TIME AND WORKSTATION IN JACKSON DATA SET [48]

Theoretical min.no.of workstation			Cycle time		
Model 1	***Model 2***	***Model 3***	***Model 1***	***Model 2***	***Model 3***
11	9	7	8	10	13

Finally, the combined priority diagram for models 1 and 2 is located on line 1 and for model 3 on line 3. For more simplicity, the final balance is graphically shown in Figure2.

TABLE II. JACKSON DATA SET TASKS PROCESSING TIME[48]

i	1	2	3	4	5	6	7	8	9	10	11
t_{i1}	6	2	5	7	1	2	3	6	5	5	4
t_{i2}	6	2	5	7	1	2	3	6	5	5	---
t_{i3}	6	2	5	7	1	2	3	6	5	---	---

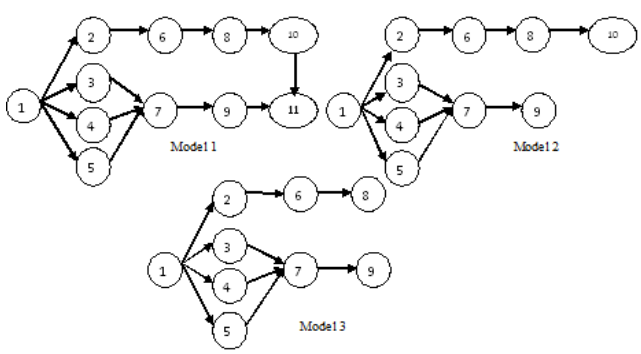

Fig. 1. Jackson data set precedence diagrams[48]

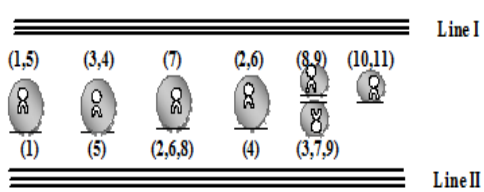

Fig. 2. Schematic of final balancing arrangement for the Jackson's test problem

B. Example 2

Jaeschke dataset [48] is the most famous dataset in testing the line balancing problems. It includes three models (M=3) and 9, 8 and 7 tasks. Table 3 shows the theoretical minimum number of workstations and cycle time at the independent lines status for the problem test according to Gokcen et al. [28]. Table 4 shows the task processing determined time for each model. The matrix of allocating workers to stations is considered as follows:

$$\mu_{ro} = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 \end{bmatrix}$$

Moreover, the wage costs of workers from skill category o in one period are assumed as follows:

b_{11}=600, b_{12}=400, b_{13}=480, b_{14}=550

With regard to the labor allocation matrix and the considered parameters and constraints, 2710 was obtained for the second objective, which is the least cost of workers.

TABLE III. CYCLE TIME AND WORKSTATION IN JAESCHKE DATA SET [48]

Theoretical min.no.of workstation			Cycle time		
Model 1	***Model 2***	***Model 3***	***Model 1***	***Model 2***	***Model 3***
8	7	6	9	11	13

TABLE IV. JAESCHKE DATA SET TASKS PROCESSING TIME[48]

i	1	2	3	4	5	6	7	8	9
t_{i1}	5	3	4	5	4	5	1	4	6
t_{i2}	5	3	4	5	4	5	1	4	---
t_{i3}	5	3	4	5	4	5	1	---	---

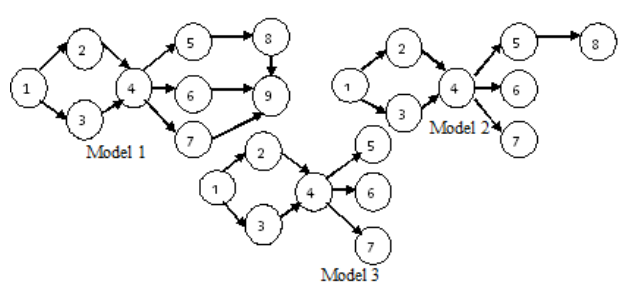

Fig. 3. Jaeschke data set precedence diagrams[48]

The combined priority diagram for models 1 and 3 is located on line 1 and for model 2 on line 2. For more simplicity, the final balance is graphically shown in Figure 2.

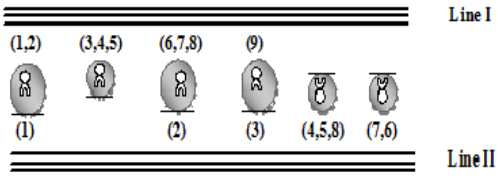

Fig. 4. Schematic of final balancing arrangement for the Jaeschke's test problem

Finally, Table 5 compares the data provided by the test problems and the final balance results (PMMALB/D). Moreover, results indicate that balancing the Jackson mixed-model dataset and the Jaeschke mixed-model dataset on parallel assembly lines will reduce the number of workstations. Table 5 clearly shows that the final number of workstations in the model data has improved 74/07% and 71/42%.

TABLE V. COMPARISON RESULT OF DATA SET

	Independent assembly line	Mixed model parallel assembly lines	Workstation Improvement (%)
Jackson	27	7	74/07%
Jaeschke	21	6	71/42%

CONCLUSION

Many problems in the production and assembly lines are mainly due to their imbalance. Today the assembly line balancing is an essential step in the production system planning. Failure to achieve this important step only leads to a loss of useful capacities of the system and the exorbitant costs for the system. Because of increasing global competition and rapid technological development, this issue has become more important [2]. In this paper, we studies and modeled the PMMALB/D problem with two objectives: reducing the number of workstations required (type I) and reducing the cost of labor. Moreover, a computational test, which was done using the prominent dataset in this field, was evaluated [48]. Clearly, in the end, as shown in Table (6), two numerical examples achieved improvements of 74/07% and 71/42% in workstations, respectively. This paper is important because there are no studies on the PMMALB/D, which is a new approach in balancing parallel assembly lines, and that there is no comparable result for the second objective of this problem.

Given the above, the following recommendations are offered for further investigation in the future: all parameters used in this paper are considered deterministic. To consider the random operation time and fuzzy data and compare it with the results of this study can be a good option for future research. The mixed-model parallel assembly line balancing problem is a NP-hard problem, and solving these problems through traditional methods is very difficult due to the formulas, high computational power needed and the high volume of data. Thus, moving towards meta-heuristic methods is inevitable. Moreover, meta-heuristic techniques are more flexible than allocation rules with the exact method in terms of planning power and can be considered an interesting subject for future research. One can achieve significant improvement methods considering the demand of each model, transfer time between workstations, downtime of each workstation, and their sequence. Given the importance of considering human factors such as character, fatigue and team structure, it is expected that future research is done in this area, and more accurate models are developed for solving the problem.

TABLE VI. CLASSIFICATION OF THE LITERATURE

	Type of Line(s)				Number of Product(s)			Problem (s)		Objective (s)
	S	***W***	***U***	***P***	***SM***	***MP***	***MM***	***BA***	***SE***	
[21]	√						√	√		*A,C*
[49]		√					√	√		*E*
[50]	√						√	√		*A*
[23]	√						√	√		*B*
[7]			√				√	√	√	*A,B*
[51]	√						√	√		*A*
[9]	√						√	√		*B,C*
[52]	√						√	√		*E*
[53]		√					√	√		*E,B*
[54]	√						√	√		*C*
[55]	√						√	√		*C*
[28]				√	√			√		*A,C*
[29]				√	√			√		*G*
[32]				√	√			√		*C*
[35]				√			√	√	√	*C*
[34]				√	√			√		*C*
[56]				√	√			√		*A*
[11]				√			√	√		*B*
[57]				√	√			√		*A*
[58]				√	√			√		*B*
The presen t study				√			√	√		*A,F*

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