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Integrated Resource Optimization in a Multi-Product Separated Line Collaborative Assembly Line Balancing Problem (MPSLC-ALBP)

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Abstract: The traditional assembly line which produces a single-model product is not efficient for today's competitive industry and it cannot respond the customers' expectations. This drives companies toward multi/mixed-model products. In addition, the assembly lines' layout is of great importance for realizing such products and achieving the expected productivity improvement and capacity increase. In the current industrial context integration of Collaborative Robots (Cobots) in the assembly lines can be considered an effective way to increase the productivity while ensuring job security and flexibility. Thus, this study proposes a new Multi-Product Separated Line Collaborative Assembly Line Balancing Problem (MPSLC-ALBP) mathematical model to optimize resource assignment among lines. Besides the multi-product aspect, comparing to traditional ALB, the proposed model embraces the particular scenarios of Human and Cobot interaction as well as the diversity of workers such as experience level and its impact on task completion times. Through an illustrative case, it is shown that integrated resource optimization for all lines is more beneficial than individual resource optimization. Moreover, the effect of integrated resource optimization will be significant in the case that there are a limited number of resources available.

Keywords: collaborative assembly line, multi-product, cobot, separated line, Industry 4.0.

INTRODUCTION

Nowadays, customer needs are constantly evolving, and mass production is being gradually replaced by mass customization. Therefore, flexibility is considered one of the most valuable characteristics of production systems and especially of assembly lines (Kim et al. 2020). Assembly line consists of assigning a set of tasks which are characterized by their processing time and by a set of precedence relations to workstations in such a way that precedence constraints are fulfilled, the time of each workstation does not exceed the cycle time and a given objective is optimized.

The traditional assembly line, which produces the single-model product, is only suitable to produce a type of standardized product (Ramezanian and Ezzatpanah, 2015). Therefore, in mass production context, different assembly systems design is required to improve productivity, quality and customer satisfaction. In this regard, balancing the assembly line considering multi/mixed-model products can solve the product variety problem, and increase flexibility (Hamzadayi et al., 2012). On the other hand, workers' differences, and human factors play an important role in increasing flexibility in assembly systems since a wide range of tasks are still human centred in assembly systems (Katiraee et al., 2021). Thus, more attention is given to the human factors to create opportunities for improving the work conditions such as safety and reduce the risks brought by new technologies (Keshvarparast et al., 2022).

Meanwhile, Industry 4.0 offers new ways to facilitate this issue by introducing human-robot collaboration (Cobots) to industries (Keshvarparast et al., 2021). Industry 4.0 allows communication and interaction between human workers and machines, and it enables interaction between operators and machines to adapt to ever-increasing production variability (Çil et al., 2020). Therefore, integration of multi/mixed product models in Collaborative (human-robot collaboration) Assembly Line Balancing Problem (C-ALBP) can be considered as an important issue to not only respond to product variability and customer satisfaction but also improve flexibility and efficiency in assembly systems. Considering this issue, there are few studies which have addressed the multi-product problems in C-ALBP. For example, Çil et al. (2020) investigated the mixed-model assembly line balancing with collaboration between human workers and robots in a straight assembly line. In existing literature, the multi-product models were mainly addressed in parallel assembly lines (i.e Vilarinho and Simaria, 2006), two-sided assembly line (i.e Özcan, and Toklu, 2009) or straight assembly line. If a company does not have enough capability to apply the mentioned layout designs, it is forced to implement different assembly lines separately. Unlike other types of designs, the implementation of separate lines for multi-product manufacturing systems need more resources (human and cobot). Shortage of any resource may result in cycle time increment due to lack of adequate resources. Therefore, resource limitation in terms of human and cobot in C-ALBP can bring a company some problems. to avoid such a problem, an integrated resource optimization model can be applied to use the available resources more effectively.

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To the best of our knowledge, none of the existing contributions consider an integrated resource optimization in a multi-product collaborative assembly line balancing with a separate layout design. Therefore, to address this drawback in the literature, this study proposes a new mathematical model in multi-product separated line C-ALBP to investigate the effectiveness of integrated resource optimization throughout all lines. The remainder of this paper is structured as follows. Section 2 provides a literature review of studies related to multi/mixed products in simple assembly line balancing problem (SALBP) and C-ALBP. Section 3 presents the problem description and model formulation. Section 4 describes the model application to an illustrative case and discusses the obtained results. Finally, Section 5 presents conclusions and future perspectives.

2. LITERATURE REVIEW

According to a performed study by Boysen et al. 2007, the assembly lines can be classified as straight lines, and U-shaped lines in terms of line layout, and they can also be classified into single-product model lines and multi/mixed product lines based on the number of models and products produced on the line. Studies on assembly line balancing are rather extensive, particularly in a single product in a straight assembly line. However, in the literature, the studies on multi-product model U-shaped lines are relatively small (Özcan et al., 2010). Based on the basic mixed-model assembly line balancing problems (MALBP), several studies considered different layouts like U-shaped, two-sided, or additional constraints like parallel workstations, robot assignment, worker assignment and robustness (Meng et al., 2022). For example, for the U-shaped assembly line, Kara, and Tekin (2009) presented a mixed-integer programming for MALBP, to optimize the number of workstations. Özcan et al., 2010 developed a simulated annealing (SA) approach for the parallel MALBP and model sequencing. Their proposed approach maximized the line efficiency and distributed the workload smoothly across stations. Rabbani, et al. (2012) proposed a mathematical model for the same problem to maximize line efficiency and minimize the variation of workload.

For the mixed-model two-sided assembly line balancing problem (MTALBP), Özcan, and Toklu (2009) proposed a simulated annealing (SA) algorithm and a mathematical model to minimize the number of workstations. The same objective is also addressed by Delice, et al. (2014) and Yuan, et al. (2015) by designing a modified particle swarm optimization algorithm and a honeybee mating optimization algorithm respectively to solve the MTALBP. Recently, for MTALBP, Huang, et al. (2021) proposed a combinatorial Benders decomposition-based exact algorithm to optimize the number of workstations.

Many articles solved MALBP by considering additional constraints. For example, Vilarinho and Simaria (2006) proposed an algorithm to minimize number of operators for balancing the mixed-model assembly line with zoning and parallel workstations constraints. In this regard, Kucukkoc, and Zhang (2016) proposed a parallel mixed-model assembly line balancing problem and designed a flexible agent-based ant colony optimization algorithm to solve it. For the mixed two-sided assembly line balancing problem with robot assignment, Aghajani, et al. (2014) presented a mixed-integer programming model to minimize the cycle time. For the mixed-model assembly line balancing with worker assignment, Ramezanian, and Ezzatpanah (2015) proposed a mathematical model and an imperialist competitive algorithm to minimize the total cycle time and the operating costs.

Table 1. Multi-product collaborative assembly line

Reference	Problem	Assembly layout	Objective	Methods
Yaphisar et al. (2019)	Multi-product C-ALBP	Straight assembly line	Minimize investment and operational cost	Mathematical model
Samouei and Ashayeri (2019)	Multi-product C-ALBP	Straight assembly line	Minimize cost and cycle time	Multi-objective robust optimization model
Çil et al. 2020	Multi-product C-ALBP with scheduling	Straight assembly line	Minimize cycle time	Bee algorithm and artificial bee colony
Steck and Mokhtarzadeh (2021)	Multi-product C-ALBP with scheduling	Serially arranged stations	Minimize cycle time and ergonomic risk	Constraint programming, Bender's decomposition
Suer et al. 2021	Two-product C-ALBP	Single station	Minimize cycle time Maximize output	Simulation and a heuristic method
This work	Multi-product C-ALBP	Separated stations	Maximize normalized cycle time	Mathematical model, real solution

In the area of C-ALBP, there are also few studies which consider multi/mixed-products for assembly line balancing problems as listed in Table 1. Yaphisar et al. 2019, proposed a mathematical model for multi-product problem for straight assembly line to minimize investment and operational cost. Samouei and Ashayeri (2019) developed a multi-objective robust optimization model under demand uncertainty for multi-product straight assembly lines to minimize the number of stations along with human/robot costs. Çil et al. 2020, solved the mathematical model by Bee algorithm and artificial bee colony to minimize cycle time for multi-product straight assembly line balancing and scheduling. Moreover, for assembly line balancing and scheduling problem Steck and Mokhtarzadeh (2021), proposed a mathematical model for multi-product serially arranged stations to minimize both cycle time and ergonomic risk. Recently, Suer et al. 2021 proposed simulation and a heuristic method for two-products straight assembly line to address the assembly line balancing and scheduling problem. To the best of our knowledge, no one of the existing contributions considers the multi-product in C-ALBP with separate layout design. Previous studies considered the multi-product models in either parallel layout, two-sided or straight line. While in this study, the multi-product models in C-ALBP are studied in separated lines to fully optimize the resources among different lines.

3. PROBLEM DEFINITION

In a real-world situation, usually, more than one product assembles in a manufacturing system. In some cases, they are the same product with different models, but in other cases, the products are different. Also, it frequently happens that a new product replaces an old one. If there is only one assembly line in a manufacturing system, optimizing the new assembly line and performing task assignment, resource allocation, and equipment distribution would be simple. However, if a manufacturing system contains some separated assembly lines that each of them assemble a different product, optimizing the new assembly line as an independent line from the system may be questioned. For example, if the new assembly line needs a specific skill and workers with the same skill are all busy in other assembly lines, the new assembly line cannot be designed due to lack of experienced workers. Therefore, in multi-product manufacturing systems with multiple separate assembly lines, it is essential to optimize resources in an integrated and comprehensive manner. This resource optimization will be more critical when there are limitations on the number of resources. This limitation can be the limited number of cobots in the manufacturing system or the number of experienced workers. These two are the most important resource constraints in assembly lines. To solve this problem, we propose a new mixed-integer linear model and optimized resources in a multi-product separated line collaborative assembly line. The main assumptions of the model are as follow:

- Cobots can be used only in independent or simultaneous (parallel) scenarios.
- Only one cobot and one worker can be assigned to a station.
- A limited number of cobots are available.
- The task completion times and task precedence relations for all products are deterministic and known in advance.
- Workers have different experience levels; thus, the task completion times for a single task vary among workers.
- A higher experience level means a quicker task completion time.
- Loading and unloading time of worker and cobot are ignored and not included in the model.
- Each line assembles a different product, and it will be final product.

Some minor assumptions are considered to reduce the complexity of the mathematical model.

- All lines have the same number of stations.
- Walking among stations is not possible.
- All cobots have the same function and there is no difference between them.

3.1 Model formulation

A single-objective Mixed-Integer Linear Programming (MILP) model is developed for the MPSLC-ALB problem considering the mentioned assumptions. The objective function (Equation 1) aims to minimize the difference between the best possible cycle time and the obtained cycle time for each line divided by the best possible cycle time for each line. This objective function ensures that cycle time reduction is equally important for all lines. Because if one product has a very short cycle time while the other has a very long cycle time, minimizing the sum of the cycle time may result in significant increase of the former's cycle time. Since a different product is assembled in each production line, the mathematical model only uses a single index l to represent both the line and the product.

In the following, the model notations are presented:

Sets, indexes, and parameters:

L	Set of assembly lines, $l \in L$
I^l	Set of tasks for line l
i, j	Tasks' indexes, $i, j = 1,2, \dots, I^l$
R	Set of resources $R = W \cup C, r \in R$
C	Set of cobots, $c \in C$
W	Set of workers, $w \in W$
S	Set of stations, $s \in S$
T_{irl}	Completion time of task i of assembly line$l$ performed by resource i
TP^l	Set of task precedencies for line l
$MinCT_l$	Minimum possible cycle time for line l

Decision Variables:

X_{irsl}	1= if task i from line l is assigned to resource$r$ in station s; 0= otherwise.
Y_{rsl}	1= if resource r is assigned to station s from line l; 0= otherwise.
Z_{il}	Station number to which task i from line l was assigned.
ST_{il}	Start time of task i form line l
CT_l	Cycle time for line l

Mathematical model:

$$Minimize: \sum_{l}^{L} \frac{(CT_l - MinCT_l)}{MinCT_l} \tag{1}$$

Subject to:

$$\sum_{r}^{R} \sum_{s}^{S} X_{irsl} = 1, \quad \forall\, l \in L, i \in I^l \tag{2}$$

$$X_{irsl} \le Y_{rsl}, \quad \forall\, l \in L, i \in I^l, r \in R, s \in S \tag{3}$$

$$\sum_{s}^{S} \sum_{l}^{L} Y_{rsl} \le 1, \quad \forall\, r \in R \tag{4}$$

$$\sum_{r}^{C} Y_{rsl} \le 1, \quad \forall\, l \in L, s \in S \tag{5}$$

$$\sum_{r}^{W} Y_{rsl} \le 1, \quad \forall\, l \in L, s \in S \tag{6}$$

$$\sum_{r}^{R}\sum_{s}^{S} X_{irsl} \times s = Z_{il}, \quad \forall\, l \in L, i \in I^{l} \tag{7}$$

$$\sum_{r}^{R}\sum_{s}^{S} X_{irsl} \times s \le \sum_{r}^{R}\sum_{s}^{S} X_{jrsl} \times s, \quad \forall\, l \in L, (i,j) \in TP^{l} \tag{8}$$

$$ST_{il} + \sum_{r}^{R}\sum_{s}^{S} X_{irsl} \times T_{irl} - bigM\left(Z_{jl} - Z_{il}\right) \le ST_{jl}, \quad \forall\, l \in L, (i,j) \in TP^{l} \tag{9}$$

$$ST_{il} + \sum_{s}^{S} X_{irsl} \times T_{irl} - bigM * \left(2 - \sum_{s}^{S} X_{irsl} - \sum_{s}^{S} X_{jrsl}\right) \le ST_{jl}, \quad \forall\, l \in L, r \in R, i,j \in I^{l} \text{ and } i < j \tag{10}$$

$$ST_{il} + \sum_{r}^{R}\sum_{s}^{S} X_{irsl} \times T_{irl} \le CT_{l}, \quad \forall\, l \in L, i \in I^{l} \tag{11}$$

$$X_{irsl}, Y_{rsl} \in \{0,1\} \tag{12}$$

$$Z_{il} \in \mathbb{N}^{+} \tag{13}$$

$$ST_{il} \ge 0, CT_{l} \ge 0 \tag{14}$$

Equation 2 ensures that each task from each line is assigned to exactly one resource. Equation 3 calculates the Y_{rsl}. Y_{rsl} shows which resource is assigned to which station and line. Equation 4 ensures that each resource will be assigned to only one station. Equation 5 guarantees that only one cobot can be assigned to each station. Equation 6 ensures only one worker can be assigned to each station. Equation 7 calculates Z_{il}. Variable Z_{il}, which is the station that task i from line l assigned to i, and it will be used to calculate the start time of the tasks. Equation 8 ensures the respect of precedence relations between tasks for all products. Equations 9 and 10 calculate the start time for all tasks. Equation 9 ensures that if there is any precedence relation between task i and task j, start time of task j should be more than finish time task i. Equation 10 guarantees that if task i and j are assigned to the same resource, one should be performed after another. Equation 11 calculates cycle time for every line. Finally, Equations 12 to 14 set the decision variables and variables of the mathematical model.

4. NUMERICAL ANALYSIS

An illustrative case study was developed based on Keshvarparast et al. (2022) to validate the proposed mathematical model. The original case study was related to a vehicle front-end in the automotive industry, with 29 tasks and four stations (see Figure 1). We considered three parts of the original task precedence as the three imaginary products, A, B and C (see Figure 2). As indicated by color in Figures 1 and 2, only a fraction of tasks can be performed by cobots. Each assembly line has three stations. To analyze the resource optimization in separated lines collaborative assembly line problem, various resource states were considered, from insufficient for all stations to entirely sufficient. The case was solved using Pyomo, an extensible Python-based open-source optimization modelling language, on a standard computer with AMD Ryzen 7 4800H, 2.90 Ghz, and 16GB RAM. The proposed model run time was nearly 2 hours for this case study.

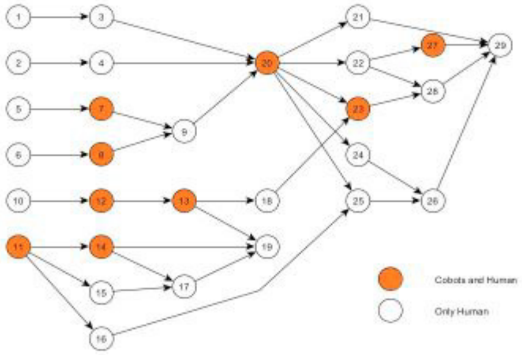

Figure 1. The precedence diagram for original case

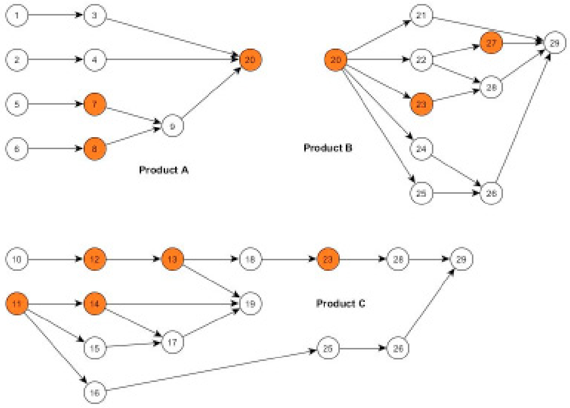

Figure 2. The precedence diagram for three imaginary products

4.1 Analysis of integrated resource optimization

The initial analysis should be the solution of the mathematical model using the presented case study. However, just optimizing the proposed model cannot show the benefits of integrated resource optimization. Therefore, conditions where different lines are optimized separately are considered for comparison with the integrated version. As shown in Table 2, there are six different arrangements for the separated optimization. The order of the lines is important and has a significant effect on the cycle time obtained in each line. For example, looking at the first row in Table 2, line one is optimized first with a cycle time of 2.4 minutes considering all resources. Then, the second line is optimized by leftover resources with a cycle time of 3.9 minutes. At the end, the third line is optimized by remaining resources with a high cycle time value of 11.4 minutes. These values have been changed in the second arrangement due to the lines' order. The results show that integrated optimization generally finds better solutions compared to the separated optimization in terms of cycle time. In separated optimization, the first optimized line will be the best one, the second line has a slight difference in cycle time compared to its optimum solution, while the last line's cycle time is significantly higher than the optimum solution. Therefore, the integrated model provides more reasonable solutions in terms of cycle time for all three lines. For example, in the first two rows (see Table 3), when the first line is optimized by all available resources, the obtained cycle time is equal to 2.4 minutes which is almost the same as the obtained by the integrated model (2.5 min). The same can be observed for lines 2 and 3, whose cycle time are 3.1 and 7.2 minutes and are close to the solution obtained from the integrated one.

Table 2. Integrated vs separated optimization

	problem	Cycle time		
		Line1	Line2	Line3
Separated	1 ► 2 ► 3	2.4	3.9	11.4
	1 ► 3 ► 2	2.4	5.2	8.5
	2 ► 1 ► 3	2.9	3.1	11.9
	2 ► 3 ► 1	4.3	3.1	8.2
	3 ► 1 ► 2	3.2	4.9	7.2
	3 ► 2 ►1	4.7	4.3	7.2
	Integrated	2.5	3.4	7.6

4.2 Cycle time improvement and resource reassignment

The presented model has another important application. It often happens that a manufacturer stops producing a product and replaces it with a new one. In this case, other assembly lines may already be available and operational. Therefore, the new assembly line can be designed either with the existing resources or by using the presented model for an integrated resource optimization approach. However, sometimes there are limitations on the number of resources that can be reassigned. Figure 3 demonstrates the cycle time for product C in the case of integrated resource optimization with limited resource reassignment for lines 1 and 2.

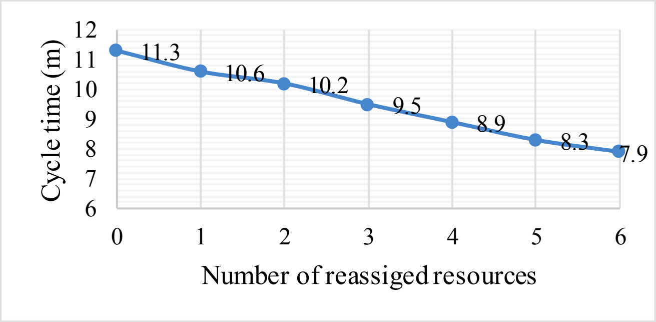

Figure 3. Cycle time of product C, with limited number of resource reassignment

In Figure 3, the first node represents the scenario where the number of reassigned resources is equal to zero, which is the same as designing the new assembly line using the separate method (with leftover resources). As shown, increasing the number of reassigned resources leads to a decrease in the cycle time for line C.

4.3 Cycle time and limited resource number

As a final analysis, the effect of resource limitation on cycle time is studied. In addition, a comparison between separated and integrated models has been done to see the effect of resource limitations on cycle time in each model (See Table 3). To perform this analysis, only one of the six separated problems from Table 2 (problem 1) was used.

Table 3: The cycle time comparison between separated and integrated model in case of resource limitation

Number		Separated (1 ► 2 ► 3)			Integrated		
W	C	Line1	Line2	Line3	Line1	Line2	Line3
6	1	2.4	4.8	-	4.1	6.4	16.9
6	2	2.4	4.3	-	3.9	6.1	15.7
7	1	2.4	4.8	24.7	3.7	5.7	14.5
7	2	2.4	4.3	24.7	3.6	5.5	13.8
7	3	2.4	3.9	24.7	3.3	5.1	12.4
7	4	2.4	3.9	19.8	2.9	4.6	10.8
8	2	2.4	4.3	13.7	3.1	4.6	9.9
8	3	2.4	3.9	13.7	3.1	4.3	8.7
8	4	2.4	3.9	10.5	2.7	3.9	8.5
9	2	2.4	4.3	12.9	2.8	3.7	7.9
9	3	2.4	3.9	11.4	2.5	3.4	7.6
9	4	2.4	3.9	9.7	2.5	3.4	7.4
9	5	2.4	3.9	8.2	2.5	3.1	7.4

According to Table 3, when the number of resources in a system are limited, separated optimizing may not work optimally. For example, when we have only six workers and one or two cobots, we cannot find any feasible solution for line 3 (the first two rows in Table 3). But under the same condition, in the integrated model, feasible solutions have been equal to 16.9 and 15.7 minutes, respectively. Looking at Table 3, it can be seen, by increasing the number of resources gradually (from row 3 in Table 3), a feasible solution for line 3 can be obtained in the separated model, however; the value is significantly high, for example equal to almost 25 minutes which is far from the optimal solution. However, this value has gradually decreased with resources increasing. The same trend can be observed for the integrated model. Based on the results, we can conclude that the integrated model can be very effective when we have limited resources, since it provides us feasible solutions with better cycle time value.

5. CONCLUSIONS

In this study, a new mixed-integer mathematical model is proposed for Multi-Product Collaborative Assembly Line Balancing Problem (MPSLC-ALBP) to optimize resource in an integrated way among lines. The main aim of this study is to increase flexibility and efficiency in assembly line by taking into account (1) Collaborative assembly line, (2) integrated resource optimization in separated line layout which is more beneficial than individual resource optimization (3) workers' diversity in terms of experience level that affect tasks completion time (Katiraee et al., 2021). The proposed model is solved by Pyomo and applied in an illustrative case. The model has been analysed in terms of three aspects: (1) analysis of integrated resource optimization versus separated optimization; (2) cycle time improvement by integrated resource optimization; and considering cycle time with limited number of resources. According to the obtained results, when the resources are optimized for each line separately, the first line is fully optimized in terms of cycle time while the last line has a considerable distance to the optimal solution. However, when the lines' resources are optimized in an integrated way, the obtained cycle times are more reasonable for all lines (Table 2). Furthermore, integrated resource optimization does not bring us any specific benefit when we have unlimited resources. On the contrary, in the case of constrained resources, integrated optimization can be considered as a practical solution (Table 3).

For future the model needs to be applied in more real-life case studies with higher number of tasks to assess its performance and behaviour more precisely. Since the problem is NP-hard by extension of the model, large instances might not be solved in a reasonable amount of time and consequently, heuristic approaches will be developed to tackle such instances. Besides, different levels of workers' skills must be considered since each worker may be able to perform a specific range of tasks. Finally, in this study, it is assumed that all lines are equipped equally, while in real cases lines may have different equipment that can be considered in future models.

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