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An Effective Two-Sided Assembly Line Balancing Approach for Large-Sized Products: A Real Life Application

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Abstract

This article addresses the assembly line balancing problem for the large-sized products in a real-world industry application. A two-sided assembly line is the effective method to assemble the large-sized products. In this study, the mathematical model was developed for the line balancing problem of a real two-sided assembly line. This study is carried out for a company which produces personnel elevating platforms. The new assembly line produces more platforms in the same time and ensures a regular material flow, makes maximum use of machine capacities and uses idle times. With the new developed assembly line, the daily production volume of the company is increased from 2 platforms/day to 7 platforms/day. Moreover, supporting the workforce on the line with robotic systems offers the opportunity of increasing the daily production volume to 12 platforms/day. The proposed model has significant application potential in the assembly line balancing problem for the large-sized products.

Keywords: Assembly line balancing, Integer programming, Large-sized product, Two-sided assembly line

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1. Introduction

The competitive environment between companies is constantly intensifying due to several reasons such as developing technology, increase in demands, product variety etc. To adapt this competitive environment and meet various demands of customers, companies have to use their resources efficiently and should be open to continuous improvement and development in their production systems. In many industries, assembly lines form the basis of production systems. An assembly line is a production system that employs a flow-line configuration, wherein workstations, or units responsible for performing assembly operations, are arranged in a serial sequence. With moving throughout the line by way of a conveyor belt or a similar transportation system, the workpieces visit workstations consecutively. The time interval between two consecutive entries to the station is referred to the cycle time (Boysen et al., 2007). The assembly line balancing (ALB) problem can be described as the assignment of tasks to workstations in a manner that optimises specific objectives while ensuring the satisfaction of certain constraints. These may include constraints related to the assignment of tasks, precedence relations, and other factors (Kara & Atasagun, 2013). In ALB problems several objectives are defined. Kim et al. (1996) classified ALB problems into five types based on the objective function. The reduction in the number of workstations and the reduction in cycle time are the most common objectives and are referred to as Type-1 and Type-2 problems, respectively. In Type-3 problems, the objective is to optimise the smoothness of the workload, whereas in Type-4 problems, the aim is to maximise the work-relatedness of the problem. In Type-5 problems the multiple objectives of Type-3 and Type-4 problems are considered simultaneously (Kim et al., 1996).

ALB problem has been sorted as NP-hard problem. Initially the ALB problem was presented for manual assembly lines, throughout the years the problem has been developed to fit robotic, machining and disassembly themes (Battaïa & Dolgui, 2013). Robotic assembly lines provide flexibility and automation in assembly lines (Levitin et al., 2006). In the robotic ALB problem assigning tasks to workstations and allocating robot for each station to increase the productivity of the line are critical (Gao et al., 2009).

Classification of assembly lines can be made by the shape of the line and the number of product models. According to the line shape classification, simple straight and U-shaped assembly lines are two common types. Single, mixed and multi-model assembly lines are of assembly line classes based on the number of product models. Single model straight ALB is the simplest form of the ALB problem and it was introduced by Salveson (1955) (Kara & Atasagun, 2013). Mixed-model assembly lines are utilized to produce several product models on a single assembly line at the same time. In multiple-model assembly lines, a number of product models are assembled in distinct batches (Jafari et al., 2019). Assembly lines can also categorized considering the usage of operation sides, one-sided and two-sided assembly lines. In one-sided assembly lines, tasks are operated only on left or right side of the line. Two-sided assembly lines employ both the left and right sides of the line. The utilisation of two-sided assembly lines is a common practice in the production of larger products, such as trucks. A further type of assembly line is the parallel assembly line. In this configuration, the objective is to optimise the utilisation of shared resources and tools. This is achieved by placing two or more lines in parallel with one another (Kucukkoc & Zhang, 2015).

Balancing and design problems have emerged in order to increase the efficiency of assembly lines and many researchers have studied different kinds of ALB problems within years. Also various types of solution approaches have suggested in these studies.

A number of studies considered mixed and multi-model assembly lines. In their study of a mixed-model assembly line, Roshani and Nezami (2017) observed the inclusion of multi-manned workstations. To address the identified issues, they developed a mixed-integer-programming model in conjunction with a simulated annealing algorithm. In addressing the balancing problem of mixed-model two-sided assembly lines, Hamzadayı (2018) employed the teaching-learning based optimisation algorithm. Harish et al. (2023) focused on multi-model assembly line and integrated simulation and lean techniques. Li et al. (2023) investigated the mixed-model ALB problem with uncertain demand. A heuristic method and a customised variable neighbourhood search method were proposed as potential solutions to the problem. Delice et al. (2023) studied mixed-model ALB problem joint with supermarket location problem and solved the problem using mixed integer mathematical model. For large-sized problem cases they proposed ant colony and simulated annealing algorithm based procedure.

Assembly line designing and balancing problem considering resource constraints finds broad coverage in the literature. Corominas et al. (2011) addressed the general resource-constrained ALB problem, which encompasses scenarios where a single, multiple, alternative, and/or simultaneous resource may be required for each task. In addition, an upper limit was considered for the available resources. An experimental study has been made for the developed mathematical model and the effectiveness of the model has been demonstrated. In their study, Mete et al. (2016) presented a mathematical model for the resource-constrained disassembly line balancing problem. The developed model was validated through two test problems in the literature. Kamarudin and Roshid (2017) studied an ALB with resource constraints for minimizing the number of workstations, machines and workers. They developed a genetic algorithm. Fang et al. (2020) discussed multi-robotic disassembly line balancing with resource constraints. They proposed a mathematical model and a constrained multi-objective evolutionary algorithm.

A number of studies focused on parallel ALB problem. Vilarinho and Simaria (2006) developed a mathematical model for the problems caused by zoning constraints for minimizing the number of stations. Buckhin and Rubinovitz (2003) proposed a linear mathematical model for the ALB problem with parallel stations. Akpınar and Bayhan (2011) developed an algorithm for ALB problem by considering the zoning constraints for parallel workstations to achieve a balanced distribution of the workforce between stations. Kara and Atasagun (2013) developed an integer linear programming model for ALB and parallel ALB problems. Özcan (2019) put forth a simulated annealing algorithm for the resolution of the balancing and scheduling issue in the context of parallel assembly lines.

Some researchers studied two-sided ALB problem. Özbakır and Tapkan (2011) aimed to minimize the idle time of stations on the line and to maximize the line efficiency by developing a multi-colony ant algorithm in two-sided assembly lines. In their research, Delice et al. (2018) investigated a two-sided U-type assembly line with sequence-dependent setup times. To address this issue, they devised a solution using an ant colony algorithm. Delice (2019) presented a particle swarm optimization algorithm in two-sided U-type ALB problem considering the zoning constraints. Kızılay and Çil (2021) studied the two-sided ALB problem. They proposed constraint programming and mixed-integer linear programming models.

A number of studies addressed parallel two-sided ALB problem. Tapkan et al. (2016) proposed an Artificial Bee Colony algorithm by including walking distances in parallel two-sided ALB problems. Yadav and Agrawal (2019) addressed the resource constrained multi-manned parallel two-sided ALB problem. They proposed a mathematical model for solution. Yadav et al. (2020) examined the case of allowing resource sharing for certain tasks between two parallel two-sided assembly lines.

Robotic ALB problem is one of the widely considered ALB problems. Rekiek et al. (2002) addressed the problem of optimal design of robotic assembly lines. Levitin et al. (2006) employed a genetic algorithm for assignment of robots to stations with the objective of maximising the production speed of the line. Gao et al. (2009) proposed a genetic algorithm for robotic ALB problem for minimizing cycle time. Mukund Nilakanta and Ponnambalam (2016) developed a particle swarm optimization algorithm to solve the robotic U-shaped ALB problem. Li et al. (2019) discussed the robotic two-sided ALB problem considering setup times. Because of the NP-hardness of the studied problem, metaheuristic algorithms were presented to solve the problem. Bakar et al. (2019) examined the studies carried out in the literature in terms of advanced heuristic, heuristic and exact solution methods for the robotic ALB problem. They stated that in robotic ALB problems, there are generally cycle time minimization applications. Hagemann and Stark (2020) reported robotic assembly system design and solved the problem with a search algorithm.

In this study, a platform assembly line belonging to a company that produces personnel elevating platform is discussed. For assembling the large-sized products as personnel elevating platform, two-sided assembly line design is the effective approach. The considered platform assembly line is classified as straight line with deterministic processing times. The main features of the studied assembly line problem are: (a) two-sided stations, (b) assignment constraints of workpieces, (c) station constraints. In order to reduce the number of stations required, a mathematical model has been developed which incorporates precedence relations and cycle time constraints.

As stated above ALB problem widely studied with various problem variants and solution approaches. This study contributes to ALB problem literature with a real-world industry application for the large-sized products. A mathematical model was developed for the line balancing problem of a real two-sided assembly line for a company which produces personnel elevating platforms with different working heights. The proposed model displays considerable potential for application in the area of ALB for products of a larger scale, and has been evaluated through a process of balancing the assembly line of a real-world personnel elevating platforms manufacturing company.

2. Material and Method

2.1 Problem definition

This study was carried out on a real-world assembly line problem for the large-sized products. In this study, the ALB problem of a company which is a manufacturer of personnel elevating platforms was investigated. The products of the company can be divided into three groups which are scissor lift, articulated platform and vertical platform. This study was conducted for the ALB problem of the scissor lift production line. The company needed to rebalance the line to meet customer demands with minimal labour costs. The assembly area consists of four main parts: (1) Mechanical assembly, (2) Electrical assembly, (3) Hydraulic assembly (4) Final assembly. All materials belonging to the chassis, scissors and balcony to be used in the mechanical assembly are kept in the mechanical assembly area. Most of the components to be utilized in electrical and hydraulic assembly are stocked in the warehouse and transported to the assembly line when used. Finished products are transferred from the assembly area to the testing area for calibration and quality checks. The products that pass the test are packaged and then transported to the finished product area. The illustration of the two-sided assembly line structure is shown in Figure 1.

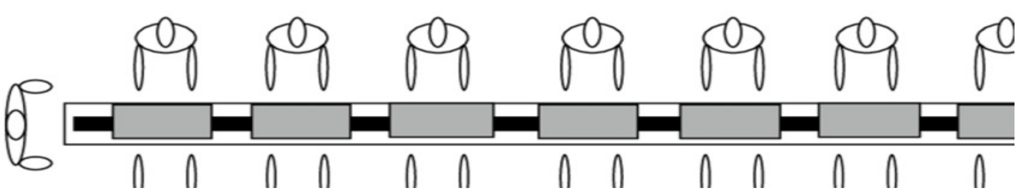

Figure 1. Illustration of the Two-Sided Assembly Line Structure

The general characteristics and assumptions of the ALB problem are as follows:

• The precedence relationships between the tasks are known.

• The work-piece is transported between stations in a fixed time without waiting.

• Some tasks have to be done together at the same station.

• Some tasks are done on the right side of the platform, some on the left.

Considering the assembly and disassembly processes of the machine, it is essential to identify the order of priority in order not to interfere with each other, to ease assembly and to use time in the most efficient way. The precedence relationships diagram showing the order of tasks is given in Figure. 2.

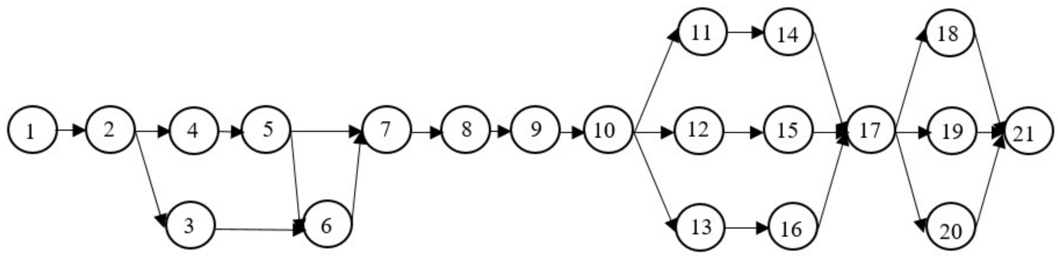

Figure 2. The Precedence Relationships Diagram for the Assembly Tasks

Processing times, the tasks that need to be done just before a task (predecessor tasks) and the platform standing position (right -left side) are given in Table 1.

The processing times were determined by a detailed time study. The precedence matrix among the tasks is given in Appendix A. The aim of this study is maximizing line efficiency while minimizing the number of workstations and thus the number of operators. In this problem, the constraint is related to the direction in which the work-pieces will be assembled during the execution of the operations. Therefore, the tasks on the right side of the assembly process should be grouped in separate stations and the tasks on the left side in separate stations.

Table 1. Times of Assembly Tasks, Predecessor Tasks and Position Information

Task	Predecessor tasks	Processing time (min)	Right-Side	Left-Side
1	-	27.3	✓	
2	1	27.27		✓
3	2	12.66	✓	✓
4	2	12.66	✓	✓
5	4	3.99		✓
6	3,5	3.21	✓	
7	5,6	1.68	✓	
8	7	8.97	✓	✓
9	8	8.07		✓
10	9	6.09		✓
11	10	9.6	✓	✓
12	10	10.71	✓	✓
13	10	11.79		✓
14	11	9.09	✓	
15	12	11.07	✓	
16	13	10.74	✓	
17	14,15,16	6.66	✓	✓
18	17	4.35		✓
19	17	4.53	✓	✓
20	17	5.94	✓	✓
21	18,19,20	3.72		

2.2 Mathematical formulation

In this section, a mathematical model is developed for the ALB problem in a platform producing company. The notations used in the proposed model are given as follows:

N	total number of tasks
J	maximum number of workstations
i, k	assembly tasks ($i - 1, \dots, N$)
j	workstations ($j - 1, \dots, J$)
C	cycle time
t_i	processing time of the task *i*
W	task pairs for precedence tasks (*i*, *k*)
$nmax$	maximum number of two-sided workstations
R	the set of right-side tasks
L	the set of left-side tasks

Decision variables

x_{ij}	1, if task *i* is assigned to workstation *j*; 0, otherwise ($i = 1, \dots, N, j = 1, \dots, J$)
r_j	1, if workstation *j* is used for the right-side tasks; 0, otherwise ($j = 1, \dots, J$)
l_j	1, if workstation *j* is used for the left-side tasks; 0, otherwise ($j = 1, \dots, J$)
d_j	1, if a two-sided station is opened to the workstation *j*; 0, otherwise ($j = 1, \dots, J$)

The proposed mathematical model is presented as follows:

$$Min \sum_{j=1}^{J} (r_j + l_j + d_j) \tag{1}$$

$$\sum_{j=1}^{J} x_{ij} = 1 \qquad \forall\, i \;\; (i = 1,2, \dots, N) \tag{2}$$

$$\sum_{j=1}^{J} x_{kj}.j - \sum_{j=1}^{j} x_{ij}.j \geq 0 \quad \forall\, (i,k) \in W \tag{3}$$

$$\sum_{i-1}^{N} x_{ij}.t_i \leq C \qquad \forall\, j \;\; (j = 1,2, \dots J) \tag{4}$$

$$r_j + l_j \geq d_j \qquad \forall\, j \;\; (j = 1,2, \dots J) \tag{5}$$

$$r_j + l_j \leq 1 \qquad \forall\, j \;\; (j = 1,2, \dots J) \tag{6}$$

$$\sum_{i \in R} x_{ij} \leq |R|.(1 - l_j) \qquad \forall\, j \;\; (j - 1,2, \dots J) \tag{7}$$

$$\sum_{i \in L} x_{ij} \leq |L|.(1 - r_j) \qquad \forall\, j \;\; (j - 1,2, \dots J) \tag{8}$$

$$\sum_{j=1}^{J} d_j \leq n_{max} \qquad \forall\, i, j \;\; (i = 1,2, \dots, N, j = 1,2, \dots J) \tag{9}$$

$$x_{ij}, r_j, l_j, d_j \in \{0,1\} \tag{10}$$

Equation (1) is the objective function of the model. It minimizes the number of workstations where the assembly tasks will be performed, according to the determined cycle time. Constraint (2) provides that each task to be done is assigned to only one workstation. Constraint (3) supplies that all precedence relationships among tasks are met. Constraint (4) ensures that the total time of the tasks assigned to station j is less than or equal to the cycle time. Constraint (5) can be used if the right-side or left-side workstation is turned on of the two-sided workstation. Constraint (6) ensures that, a station can be opened as a workstation with either right-side task or left-side task. Constraint (7) prevents the right-side tasks from being assigned to workstations with left-side restricted. Constraint (8) prevents the left-side tasks from being assigned to workstations with right-side restricted. Constraint (9) limits the number of two-sided workstations that can be opened. Constraint (10) states that the variables x_{ij}, r_j, l_j, d_j are binary variables.

3. Results

In the assembly processes of large-sized products made on fixed stands, production is carried out with high costs and long periods. In order to establish the assembly line in the platform producing company where the application is made, first, the ease of transportation of the materials to the workstations and the space constraints are considered. The most suitable place where the assembly line can be installed and the maximum number of workstations that can be opened are determined. In the installation of the line, the width and length of the line area, the space requirement for placing the materials, the suitability of the area where the assembly line will be installed in terms of conveying large-sized workpieces to the workstations are taken into account. It has been calculated that a maximum of five stations can fit in the area where the line is planned to be installed, considering the length of the platform, the location constraint and the working area space requirement that should be between the stations. During the assembly, it is decided that the space between stations should be 70 cm in terms of the required working area. By utilizing the experiences of technical personnel and assembly masters, assembly tasks are identified and then the processing time required for each task and the precedence relationships are determined as given in Table 1.

For calculating the daily production volume of the company Equation (11) is used. Before line balancing, the daily production volume of the company computed as 2.398≅2 platforms/day when the cycle time is taken as 200.1 min, which is total processing time. The developed mathematical model is run in the LINGO 18.0 optimization package to solve the studied ALB problem. Obtained solutions presented in Table 2.

$$\text{Daily production volume (platforms/day)} = \frac{60(\text{min}) \times \text{Daily Working Time}}{\text{Cycle Time}} \tag{11}$$

Table 2. Tasks Assigned to Workstations After Assembly Line Balancing

Workstation	Task	Processing time (min)	Total processing time assigned to workstation (min)
1	1	27.3	67.23
	2	27.27	
	3	12.66	
2	4	12.66	45.93
	5	3.99	
	8	8.97	
	10	9.6	
	12	10.71	
3	15	11.07	37.35
	16	10.74	
	17	6.66	
	18	4.35	
	19	4.53	
4	6	3.21	49.59
	7	1.68	
	9	8.07	
	11	6.09	
	13	11.79	
	14	9.09	
	20	5.94	
	21	3.72	

A total of four workstations are opened and the longest total processing time assigned to the stations belongs to the first station and it is 67.23 min, which is the cycle time of the line. The daily production volume of the company is computed as 7.139≅7 platforms/day after line balancing. Thus, by balancing the line the production capacity is increased without increasing the number of operators in the line.

For balancing the assembly line with heterogeneous workforce, the required datasets are reconstructed on the basis of precedence relationships and processing times in the existing assembly line dataset, and the developed mathematical model is run again. The coefficients used in the reconstruction of the data set are determined approximately on the basis of information provided by experts on robot and human-robot interactive systems and industry representatives. Table 3 shows the obtained results of the line balancing with robotic workforce.

As a result of supporting the workforce on the line with robotic systems, the daily production volume will be 12.253≅12 platforms/day. Considering the obtained profitability as a result of the increase in the company's production capacity, the robotic system investment cost to be made should be examined.

Table 3. Tasks Assigned to Workstations After Assembly Line Balancing with Robotic Workforce

Workstation	Task	Processing time (min)	Total processing time assigned to workstation (min)
1	1	15.015	39.171
	2	14.9985	
	4	6.963	
	5	2.1945	
2	3	6.963	24.3045
	6	1.7655	
	7	0.924	
	8	4.9335	
	9	4.4385	
	10	5.28	
3	11	3.3495	20.328
	14	4.9995	
	12	5.8905	
	15	6.0885	
4	13	6.4845	26.2515
	16	5.907	
	17	3.663	
	18	2.3925	
	19	2.4915	
	20	3.267	
	21	2.046	

Additionally, in order to contribute to the capacity increase in production; the losses that cause inefficiency are reduced, improvements are made in operations, processing times are shortened, the material flow is improved and the effect of time wastage is eliminated with material stocks.

4. Discussion and Conclusion

In this study, the ALB problem of the scissor lift production line is discussed and the integer programming model of the problem is developed. In the current system, the daily production capacity is able to produce an average of two products. The proposed assembly line system has the capacity to produce an average of seven products. Thus, with balanced assembly line, the production capacity is increased, and this increase is achieved without increasing the number of operators on the line. As a result of supporting the workforce on the line with robotic systems, it is seen that the daily production will be 12 products. Considering the increase in the company's production capacity, the profitability of the robotic system to be made as a result of the investment cost should be examined.

In assembly line design literature the simple assembly line problem is mainly center of attention. This study presents a mathematically formulated solution to the line balancing problem inherent to the assembly of large-sized products utilising a system comprising two-sided workstations. An integer programming model is proposed that performs the assignment of assembly tasks to the line, taking into account space constraints, process assignment constraints and precedence relationships for a specified cycle time. Results are compared according to the daily production amount. In real-world problems, job rotation is also examined with criteria such as a cost and profit-oriented objective function, equipment selection, alternative processes and mixed model production. In future research, it can be examined how real data will be combined with these additional features and how they will be analyzed and applied to practice.

Appendices

Appendix A. The precedence matrix among the tasks

Task No.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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