

## Assembly Line Worker Assignment and Balancing Problem by Considering Labor Cost

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### Abstract

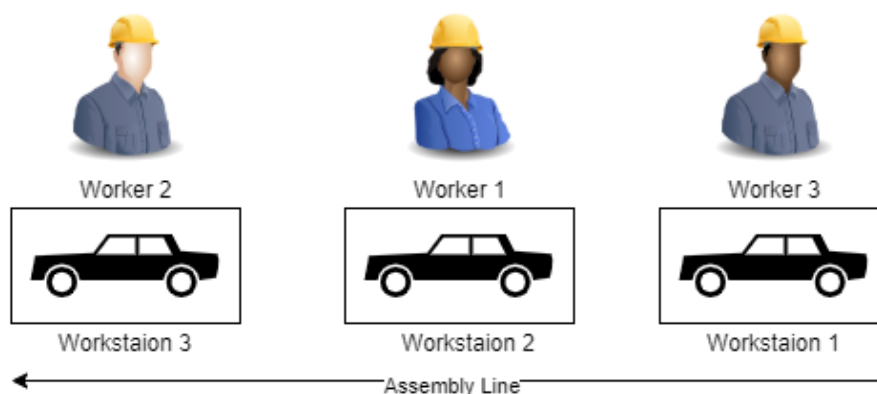
Assignment of worker appears as a new problem in the literature for assembly lines (AL) where the workforce is heterogeneously located. The difference of this line balancing from the traditional line is that the assembly task times of the workers to be assigned to the stations differ from each other. Especially assembly lines issues are generally a labor-intensive type of production. Therefore, for assembly line problems, balancing activity should be done considering the labor costs. Thus, the proposed solutions will be able to produce more realistic results for real life. For this purpose, in this study, a mixed-integer mathematical formulation is presented for assembly line worker assignment and balancing problems by considering the objective function of minimizing labor costs and cycle time. The efficiency of the proposed model and the improvements have been demonstrated by solving test instances in the literature.

**Keywords:** Assembly Line Balancing, Worker Assignment, Mathematical Modelling, Labor Cost.

## 1. Introduction

AL has been used frequently to produce products with high volumes in the industry and is one of the well-known and popular research areas in the production environment [1]. ALBP can be defined as assigning tasks to workstations, considering the constraints on the line. In addition, assembly lines are optimized for various objectives, such as cycle time minimization for a predetermined number of the workstations or workstation minimization for a predetermined cycle time. Regarding assembly lines, we can say that both solution methods and line properties are discussed in the literature in many ways and maintain their popularity [2, 3, 4]. And also, conventional ALBP is known as the NP-hard problem structure [5, 6]. The detailed reviews of studies related to line balancing problems are given by Scholl and Becker [7] and Becker and Scholl [8].

A different form of traditional assembly line problem is considering worker assignments and called assembly line worker assignment and balancing problem (ALWABP). It constitutes a major difficulty found in workstations for the disabled, e.g. some of the workers who will perform the assembly tasks at the station can perform some of the tasks in a longer period of time. In fact, there are some conditions such as the inability of some workers to perform certain tasks. Because of the growing respect and interest for the disabled, many of them are employed by various industries and companies are always concerned with assigning workers on assembly lines [9]. For this reason, there are workers at the station that can perform a task at different times. And this requires deciding which worker will be assigned at which workstation. ALWABP is an assembly line balancing problem involving worker assignment and task allocation sub-problems. Worker assignment aims to distribute tasks evenly across workstations by ensuring various constraints such as precedence and cycle time constraints while determining the assignment of workers to workstations as seen in Figure 1 [10, 11].



**Figure 1.** Worker assignment example for ALWABP

Assembly Line (AL) with sheltered work centres is introduced by Miralles et al. They presented a mathematical model formulation of the problem to minimize the cycle time [10]. The importance of assembly lines with disabled workers is mentioned by Chaves et al. and a search heuristic with clustering is proposed to solve ALWABP [12]. Subsequently, a mathematical model for ALWABP is formulated and an exact solution algorithm is presented to solve the problem [13]. In another study, ALWABP is solved with a hybrid method based on clustering search [14]. Also, for this problem, a beam search method is developed, and an exact solution procedure is introduced. [9, 29]. A heuristic

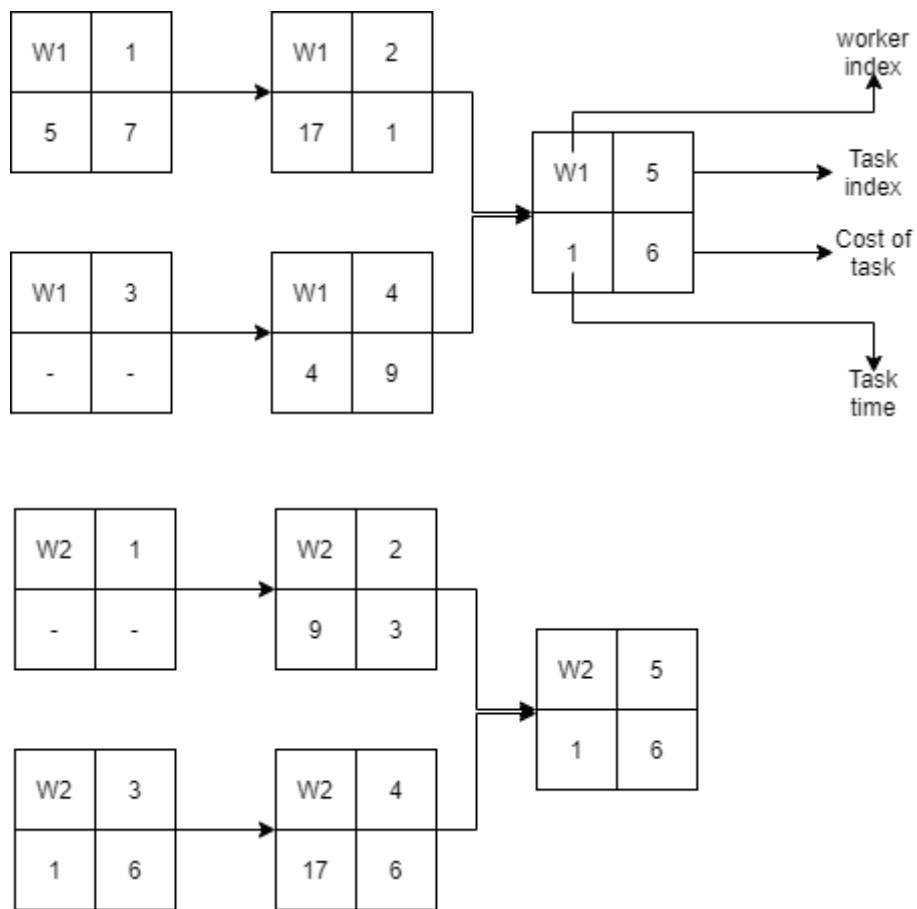
algorithm based on priority rules of task-worker is presented by Moreira et al. [15]. A genetic algorithm is developed to solve the problem. According to the algorithm, the method is very robust and effective for large test instances [16]. For the ALWABP, new lower bounds were calculated with an exact solution algorithm. And it is state-of-the-art in terms of creating solution quality for the problem [17]. Akyol and Baykasoğlu presented a heuristic approach and compared the performance of the algorithm on test instances. Experimental results show that the proposed algorithm is effective for the problem benchmark datasets [18]. In addition to these, the problem has also been addressed from different aspects. A mixed-model ALWABP is presented and goal programming is proposed to solve the problem [19]. However, a two-sided ALWABP is presented and a mathematical model is formulated to solve this ALBP [20]. Nevertheless, U-shaped assembly line worker assignment and balancing problem by considering the worker performance has been studied under different conditions [27, 28]. Akyol and Baykasoğlu, on the other hand, addressed the problem with different dimensions by considering ergonomic risk factors [30]. At the same time, the assembly line balancing problem has been studied under various constraints [31, 32].

When the literature is examined, it is seen that ALWABP is addressed from different aspects. In literature, the objective of the problem is usually to minimize the cycle time for each lines. Generally, minimization of the cycle time of assembly lines is aimed at time-oriented assembly lines, for example, by minimizing the number of operators with the number of workstations to minimize line length for a given cycle time. With only a view of time-oriented window for the problem, just worker number is considered, other cost factors such as wage rates or machines are neglected. However, the competition that emerged in the industry made production costs more meaningful. Even in successful industries' production systems with assembly lines, the effort to reduce production costs has become a necessity. From such an economic point of view, the aim of line designers in AL production systems should not only be cycle time or workstation minimization. Another factor for balancing AL in real life is labor costs. Therefore, in addition, targets such as minimizing the total cost per task should also be considered. A survey is provided by Amen on assembly line balancing problems with costs [21]. A mixed-integer mathematical model is formulated for cost-oriented ALBP [22]. For the cost-oriented two-sided assembly line balancing problem, a mathematical programming model is presented in order to minimize the costs of the assembly lines [23]. According to the qualification levels of workers and tasks, a mathematical programming formulation for cost-oriented ALBP is proposed with the objective of minimizing the total cost for a given cycle time [24].

As can be seen from the literature, many problems related to assembly lines have been investigated by including additional cost constraints. Generally, costs occurring on each assembly line can be divided into two groups: (1) labor costs and (2) invested capital [25]. In this study, a mathematical model has been proposed by considering the labor costs for ALWABP.

ALWABP is a form of the line where tasks and workers are assigned to the assembly line while minimizing the cycle time. While workers can complete assembly tasks at different durations, some workers cannot perform some tasks. A certain wage rate is accepted according to the difficulty level of each task, and the wage rate of a worker at a station is equal to the rate of the most difficult task's wage assembled at that station and this wage is paid for the total cycle time of workstation. In traditional assembly line balancing problems, task times are given together with priority relations.

However, among the data presented within the scope of this problem, in addition to task time and precedence relations, the labor cost should also be taken into consideration. As seen in Figure 2, ALWABP has a precedence diagram with 5 tasks and two (W1 and W2) workers and, also, each assembly durations and labor cost for the task change due to workers. For example, five tasks are defined for each of the 1st and 2nd workers with the same precedence constraints. In addition, the cost of each worker to perform a task may differ. While the 1st worker performs task 4 with 9 cost-unit, the 2nd worker assembly it with 6 cost-unit. According to the author’s best knowledge, there has not been any published study treating cost objective function and assembly line worker assignment and balancing together. For this purpose, this paper presents a mathematical model which minimizes both cycle time and cost of workers to address this research gap.



**Figure 2.** Precedence diagram and specifications for ALWABP.

The details of the study, which is divided into four sections, are as follows: In the first section, the specifications of the problem and the gap in the literature is shown. In the second, section the mathematical model formulation of the problem is presented. In the third section, traditional ALWABP problem solutions and proposed model solutions are discussed by comparing the findings obtained from the mathematical models. In the last section, results are discussed and references to further studies are given.

## 2. Material and Methods

### 2.1. Integer Programming Model

The presented mathematical model formulation is based on the model formulated by Yilmaz and Demir [26].

$i, h$ : index of task

$t$ : index of worker

$j$ : index of workstation

$I$ : tasks set

$T$ : available workers set

$J$ : workstations set

$c$ : cycle time

$M$ : a large number

$t_{it}$ : task time of  $i$  if worker  $t$  assemble it

$C_{it}$ : labor cost of  $i$  if worker  $t$  assemble it

$IP_i$ : A set for immediate predecessors of  $i$

$x_{ij}$ : 1 if the  $i^{th}$  task is assigned to the  $j^{th}$  workstation, otherwise 0

$y_{jt}$ : 1 when the  $t^{th}$  worker is assigned to the  $j^{th}$  workstation.

$max_t$ : maximum labor cost of the  $t^{th}$  worker.

$$\text{Min } c + \frac{1}{M} \cdot \sum_{t \in T} max_t \tag{1}$$

$$\sum_{j \in J} x_{ij} = 1, \forall i \in I, \tag{2}$$

$$\sum_{t \in T} y_{jt} \leq 1, \forall j \in J, \tag{3}$$

$$\sum_{j \in J} y_{tj} \leq 1, \forall t \in T, \tag{4}$$

$$max_t \geq C_{it} \cdot (x_{ij} + y_{jt} - 1), \forall t \in T, \forall i \in I, \forall j \in J, \tag{5}$$

$$\sum_{j \in J} x_{ij} \leq \sum_{j \in J} x_{hj} \forall i, h \in I \text{ and } IP_i \tag{6}$$

$$\sum_{i \in I} x_{ij} \leq M \cdot \sum_{t \in T} y_{jt} \forall j \in J \tag{7}$$

$$\sum_{i \in I} (x_{ij} + y_{jt} - 1) \cdot t_{ij} \leq c, \forall j \in J, \forall t \in T, \tag{8}$$

$$y_{jt} \in [0,1], x_{ij} \in [0,1], max_t \geq 0, c \geq 0, \forall i \in I, \forall j \in J, \forall t \in T \tag{9}$$

The objective function (1) first minimizes the cycle time and then minimizes the cost multiplying by a sufficiently small number. Constraint (2) ensures tasks are assigned to workers in one single workstation. Constraint (3) and (4) provide that in

every station there will be a worker, and every worker will be assigned to one workstation. The highest cost of the tasks in a station shows the labor cost of that station. Thus, the highest cost among the tasks assigned to a station will show the labor cost of that station. Constraint (5), is the cost rate of a station indicates that the tasks assigned to that station. For example, if  $x_{ij} = 1$  and  $y_{jt} = 1$ , the constraint will be active, and it will assign the highest cost to  $\max_t$  from the tasks assigned to the same station. Constraint (6) is precedence relations of tasks. Constraints (7) and (8) ensure assigning more than 1 task in a cycle time (c). Constraint (9) is binary and integer variables in the model.

## 2.2. Numerical Experiments

The main goal of this study is to analyze ALWABP with labor costs and cycle time minimization together. A new mathematical model formulation is presented for the problem. As a solution approach traditional ALWABP model [24] and presented mathematical model is compared with cycle time and total labor cost. In this study, the problem of ALWABP with minimizing cycle time and labor cost is presented for the first time. There is no study on the problem for comparison with the presented algorithm in the literature. Hence, the results of the proposed mathematical model are compared with traditional mathematical model solutions on small size test instances.

The proposed mathematical model is solved by GUROBI 8.1.1, algorithm is coded by C# 2015 and executed on a PC with Intel(R) Core(TM) i7, 2.20 GHz processor and 8.00 GB of RAM. Benchmark data is considered from the ALWABP benchmark data set and just considered small-size test instances [12]. The details of test instance characteristics are given in Table 1. There are 40 test instances which are named into Heskia and Roszieg. Each test instance family has 2 groups with different workers. Also, since there are no labor cost instances for this assembly line in the literature, random costs are generated using uniform distribution for each worker and each task.

**Table 1.** Characteristics of test instances.

Family	# of Tasks	# of Workers
Roszieg	25 (low)	Group 1(4 Workers) / Group 5 (6 Workers)
Heskia	28 (low)	Group 1 (4 Workers) / Group 5 (7 Workers)

## 3. Results and Discussion

In this study, a total of 4 groups, two groups from Heskia and two groups from the Roszieg family, were examined. Among the tests, Heskia has 4 and 6 different workers, Roszieg has 4 and 7 different workers. A total of 40 test problems have been examined with the traditional and proposed model. The cycle times and labor costs are given in Table 2.

**Table 2.** Computational results of test instances.

Family	Test Problem #	ALWABP Without Labor Cost			ALWABP With Labor Cost		Imp(%)
		W	C	LC	C	LC	
Heskia	1	4	94	338	94	338	0,00
	2	4	95	371	95	367	1,08
	3	4	102	341	102	341	0,00
	4	4	103	352	103	298	15,34
	5	4	92	377	92	377	0,00
	6	4	98	379	98	355	6,33
	7	4	116	375	116	345	8,00
	8	4	86	367	86	342	6,81
	9	4	95	345	95	345	0,00
	10	4	142	375	142	369	1,60
	11	7	35	514	35	403	21,60
	12	7	40	521	40	434	16,70
	13	7	35	512	35	369	27,93
	14	7	30	553	30	438	20,80
	15	7	40	581	40	454	21,86
	16	7	29	456	29	429	5,92
	17	7	25	580	25	562	3,10
	18	7	43	545	43	514	5,69
	19	7	38	642	38	471	26,64
	20	7	34	539	34	486	9,83
Roszig	1	4	20	42	20	40	4,76
	2	4	22	47	22	47	0,00
	3	4	18	46	18	46	0,00
	4	4	18	44	18	44	0,00
	5	4	17	48	17	44	8,33
	6	4	24	48	24	48	0,00
	7	4	21	50	21	45	10,00
	8	4	20	41	20	41	0,00
	9	4	22	47	22	45	4,26
	10	4	19	47	19	47	0,00
	11	6	10	68	10	58	14,71
	12	6	10	62	10	57	8,06
	13	6	10	65	10	60	7,69
	14	6	9	69	9	68	1,45
	15	6	12	62	12	48	22,58
	16	6	9	52	9	52	0,00
	17	6	10	68	10	51	25,00
	18	6	8	72	8	57	20,83
	19	6	10	64	10	53	17,19
	20	6	9	72	9	70	2,78

(W: Workstation, C: Cycle Time, LC: Labor Cost)

The improvement rates of each test instance vary between 0% and 27.93%. On all test problems, there is an average improvement of 8.67%. Out of 40 test problems, 29 test instances had better results in terms of labor costs. This covers

a rate of 72.5% among all test problems. However, equal labor costs were found for the other 11. Along with these improvement rates, production was carried out with the same cycle times for all problems. Statistical details of the results are given in Table 3.

**Table 3.** Comparison of results.

Family	Test Problem Size	# of Optimum Cycle	Improved Labor Cost	Average Improvement
Heskia	20	20	75%	9,96
Roszieg	20	20	65%	7,38

#### 4. Conclusion

In this paper, a mixed-integer mathematical model is formulated for the ALWABP considering labor cost. A proposed mathematical model is compared with the traditional ALWABP model by solving some small-size test instances using a GUROBI solver. Computational analyzes were made to show the efficiency of the proposed mathematical model. Computational results show that the proposed model is successful and effective in terms of labor cost and cycle times for the problem.

The presented paper is the first study for ALWABP by considering labor cost. This study is a good starting point for future studies. Future studies might extend the presented problem with positional, zoning constraints or different real-world constraints. The problem, which is the NP-Hard problem structure, cannot be solved by a mathematical model with a reasonable CPU time. For this purpose, effective meta-heuristic algorithms (simulated annealing, genetic algorithm, etc.) can be used to solve ALWABP (or line balancing problems).

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