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A New Cost-oriented Two-sided Assembly Line Balancing with Worker Assignment Problem

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Abstract

Two-sided assembly line are widely used in plants producing large-sized high-volume products such as trucks, automobiles or buses. During the production, cost is an essential part that can't be ignored. It contains equipment cost, wage cost and station establishment cost, especially, a worker's wage varies according to his/her worker qualification. In this paper, a new Cost-oriented Two-sided assembly line balancing problem is proposed and formulated. A mixed integer programming model is established to solve a single objective function consisting of minimizing the cost associated with equipment, worker wage, and station establishment. Computational results indicated that the proposed model can solve problems optimally and get the solution with the minimal cost of the assembly line in relatively small-scale problem.

Keywords

Two-sided Assembly Line; Line Balancing; Objective Function.

1. Introduction

In real production, the traditional unilateral assembly line cannot meet the production needs. With the intensification of market competition, many enterprises utilize some new assembly line layouts, such as parallel assembly line, U-shaped assembly line and Two-sided assembly line. The Two-sided assembly line was first proposed by Bartholdi in 1993[1]. Compared with the traditional single assembly line, it has left and right stations on an assembly line for processing tasks. With the advantages of shortening the length of the assembly line, shortening the off-line time of products, improving the utilization rate of tools and the labor productivity of workers, the Two-sided assembly line is now widely utilized in the large products assembly process of automobiles, trucks, buses and motorcycles. It is particularly common, especially in automobile engine pre-assembly line, automobile welding line and automobile final assembly line. Two-sided assembly line balancing is considered to be an important decision which affects the daily operation cost. In this type of configuration as shown in Figure 1, a pair of two directly facing single stations is called "mated station" and the two stations are called "companion stations" for each other [2].

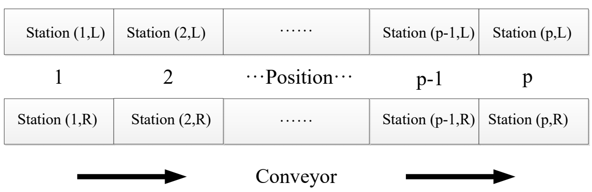

Figure 1. A configuration of Two-sided assembly line

At present, the optimization objective of the research on assembly line balance is to minimize the number of stations for a given cycle time (type-I) [1] or to minimize the cycle time for a given number of stations (type-II) [3]. In other words, both objectives are to minimize idle time

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on the workstation to maximize production efficiency. It is called time-oriented assembly line balancing problem. A large number of scholars study this type of problems[4][5] and expand it combined with more realistic problems, such as muti-constraints [6], mixed- model [7], robotic assembly line [8].

However, with the intensive competition among enterprises in recent years, enterprises need to construct their own production system in order to further improve output of products and reduce production costs. For enterprises, it is necessary to look for the possibility to cut down production costs. Under the above practical needs, the objective in assigning task to assembly line production systems should not be only to minimize the number of stations or minimize the cycle time, and objectives like minimizing the total production cost should also be considered. This is done in Cost-oriented assembly line balancing problem[9]. Cost-oriented assembly line problem is based on the classical balance problem and takes the existing production cost in practical application as the optimization goal. Therefore, the goal of Cost-oriented assembly line balance is to minimize the cost of unit product [10]. Some scholars have analyzed and studied the composition affecting the cost of unit product, established the corresponding model and proposed the solution algorithm. In 1992, Rosenberg and Ziegler [11] analyzed the wage of workers and put forward the concept of wage rate. Each task corresponds to a wage level according to different difficulty. A worker is assigned to a workstation, and its wage level is the highest of all the wage levels assigned to the workstation, The wage of the workstation depends on cycle time (CT) and the corresponding wage grade. Amen [9] extended the objective function proposed by Rosenberg, considered the cost that each workstation needs to invest in advance, and proposed the branch and bound method to solve the problem with the goal of the total wage of workers and the construction cost of workstations invested in advance. Later, it also analyzed the existing heuristic algorithm and two new heuristic algorithms, based on the previous work, the quality of solution time and solution is improved [12]. In 2006, Amen [13] improved the model so that the established mathematical model can be solved by standard solution software. The above research is carried out for Two-sided assembly lines, and the cost of Two-sided assembly lines also needs to be considered. Roshani [14] studied the Cost-oriented balance problem of Two-sided assembly lines for the first time, dividing the cost into labor cost and investment cost (mechanical equipment and transportation facilities), so taking the worker's wage, transportation equipment cost related to mated workstations and mechanical equipment cost related to companion workstations as the cost objective function, the MIP mathematical model is proposed for small-scale solution. For large-scale problems, the simulated annealing algorithm is used. Rashid et al. [15] This paper rethinks the composition of the total cost, and puts forward the total cost objective function including energy consumption cost, installation cost, labor cost and equipment cost. This paper is based on the Two-sided assembly line, and puts forward an improved (I-MFO) algorithm. Salehi et al. [16] improved the process of equipment allocation cost and workers' wages. The author pointed out that equipment allocation is related to the tasks assigned on the workstation. Different workers will receive different salary for performing the same task due to different qualification levels. The improvement of the above two points will increase the constraints of equipment allocation and workers' allocation, which is more realistic.

To sum up, the current research on Two-sided assembly line pays more attention to the time-oriented assembly line balancing problem, and there is a limited number of research on Cost-oriented assembly line balancing problem. There is only one paper considering Cost-oriented problem combined with Two-sided assembly lines, but its treatment of workers' wages does not include the factors of different time for workers with different qualifications to process the same task. Therefore, this paper reconsiders the treatment of workers' wages and proposes a new cost oriented Two-sided assembly line balance problem to address the previous research gap. First in Section 2, a Cost-oriented objective function is proposed for Two-sided assembly

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lines and then a mixed integer programming will be given to solve the problem optimally. In Section 3 presents a numerical example and gives computational results. Concluding remarks will follow in Section 4.

2. Problem Definition and Mathematical Formulation

Table 1. Model related notions

Indices	
i, h, p	Tasks index.
j, g	Station index.
k	Direction index.
(j, k)	Station index, side k of station *j*.
Sets	
I	Set of tasks, I = {1, ..., nt}.
J	Set of stations, J = {1, ..., nm}.
K	Set of Directions, K = {0,1}.
AL	Set of tasks that should be performed at a left station.
AR	Set of tasks that should be performed at a right station.
AE	Set of tasks that can be performed at either a left station or a right station.
P_0	Set of tasks that have no predecessors.
$P_a(i)$	Set of all immediate predecessors of task *i.*
$P(i)$	Set of immediate predecessors of task *i.*
$S(i)$	Set of immediate successors of task *i.*
$S_a(i)$	Set of all immediate successors of task *i.*
$C(i)$	Set of tasks that opposite to task *i.*
$K(i)$	Set of performed directions of task *i.*
Parameter	
t_i	Processing time of task *i*.
nm	The max number of stations.
M	A big enough positive integer.
K^{MSC}	The total costs of establishing for each of the stations.
K^{SSC}	The total costs of the machinery for each single station.
Decision variables	
CT	Cycle time.
m	The number of mated Station.
n	The number of total stations.
tf_i	Completion time of task *i.*
x_{ijk}	1 if task *i* is assigned to (j, k), 0 otherwise.
z_{ip}	1 if task *i* is assigned earlier than task p at the same station and same side, 0 otherwise.
F_j	1 if both side of a station is open,0 otherwise.
G_j	1 if only one side of a station is open,0 otherwise.
U_{jk}	1 if station (j, k) is open.

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In this section, a new mixed integer programming model for Two-sided assembly line balancing problem considering cost is proposed. This model minimizes equipment cost, worker wage cost and workstation construction cost, in which different workers have different wages for processing the same task. The relevant assumptions of the model are as follows:

- One worker can only be arranged on exactly one workstation.
- The establishing cost of each workstation is fixed.
- The total processing time on a workstation cannot exceed the cycle time.
- The processing precedence relationship between tasks has been given, and the precedence relationship between tasks cannot be violated.
- The machinery cost on each workstation is also a fixed value.
- The worker's wage to be paid for processing the same task depends on the worker level.

The model of this study is based on the notions shown in Table 1.

The proposed mixed integer linear programming model for this problem is expressed as follows:

$$Minimize\ Tcost = \sum_{w=1}^{W}\sum_{j=1}^{nt}\sum_{k=1}^{2} TCS_{wjk} + m * K^{MSC} + n * K^{SSC} \tag{1}$$

$$\sum_{j\in J} X_{ij0} = 1 \quad \forall i \in AL \tag{2}$$

$$\sum_{j\in J} X_{ij1} = 1 \quad \forall i \in AR \tag{3}$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijk} = 1 \ \forall i \in I \tag{4}$$

$$\sum_{g\in J}\sum_{k\in k(h)} g * x_{hgk} \le \sum_{j\in J}\sum_{k\in k(i)} j * x_{ijk} \ \forall i \in I - P_0 \ h \in P(i) \tag{5}$$

$$t_i^f - t_h^f + \psi(1 - \sum_{k\in k(h)} X_{hjk}) + \psi(1 - \sum_{k\in k(i)} x_{ijk}) \ge t_i$$
$$\forall i \in I - P_0,\ h \in P(i), j \in J \tag{6}$$

$$t_i^f - t_p^f + \psi\left(1 - X_{ijk}\right) + \psi\left(1 - X_{pjk}\right) + \psi * z_{ip} \ge t_i$$
$$\forall i \in I, p \in \{r | r \in I - \left(P_a(i) \cup S_a(i) \cup C(i)\right) and\ i < r\}, j \in J, k \in K(i) \cap K(p \tag{7}$$

$$t_p^f - t_i^f + \left(1 - X_{ijk}\right) + \psi\left(1 - X_{pjk}\right) + \psi * \left(1 - z_{ip}\right) \ge t_p$$
$$\forall i \in I, p \in \{r | r \in I - \left(P_a(i) \cup S_a(i) \cup C(i)\right) and\ i < r\}, j \in J, k \in K(i) \cap K(p \tag{8}$$

$$t_i^f \ge t_i \quad \forall\ i \in I \tag{9}$$

$$t_i^f \le CT\ \forall\ i \in I \tag{10}$$

$$\sum_{i\epsilon I} x_{ijk} - M * U_{jk} \le 0 \quad \forall j \in J, \forall k \in K \tag{11}$$

$$\sum_{i\in I} x_{ijk} - U_{jk} \ge 0 \quad \forall j \in J;\ \forall k \in K \tag{12}$$

$$\sum_{k=1,2} U_{jk} - 2 * F_j - G_j = 0 \ \forall j \in J \tag{13}$$

$$F_j + G_j \geq F_{j+1} + G_{j+1} \ \ \forall j = 1,2 \dots nm - 1 \quad (14)$$

$$m = \sum_{\forall j \in J} (F_j + G_j) \quad (15)$$

$$x_{ijk} + y_{wjk} - 1 \leq d_{iwjk} \ \ \forall i \in I, \forall w \in W, \forall j \in J, k \in K \quad (16)$$

$$x_{ijk} + y_{wjk} \geq 2d_{iwjk} \ \ \forall i \in I, \forall w \in W, \forall j \in J, k \in K \quad (17)$$

$$\sum_{\forall j \in J} \sum_{k \in K} y_{wjk} \leq 1 \ \ \forall w \in W \quad (18)$$

$$\sum_{w \in W} y_{wjk} = U_{jk} \quad \forall j \in J, k \in K \quad (19)$$

$$C_{iw} * d_{iwjk} \leq CS_{wjk} \ \ \forall i \in I, j \in J, w \in W, k \in K \quad (20)$$

$$TCS_{wjk} = CT * CS_{wjk} \ \ \forall j \in J, w \in W, k \in K \quad (21)$$

In this regard, the proposed model minimizes the total cost associated with purchasing necessary equipment, workers' wage, and station establishment cost in the assembly line, as shown in (1). Constraint (2) - (4) ensure that each task can only arranged on the workstation, constraint (2) mean that each task can only be arranged in one operation direction on each workstation, constraint (3) and (4) ensure that the task must be arranged in its specified operation direction. Constraints (5) and (6) ensure the task arrangement should satisfy task precedence constraints. A task can only be processed after its immediate task is finished. Constraints (7) - (8) ensure the arrangement of constrained tasks without precedence relationship constraints. When two tasks i and p without precedence relationship constraints are arranged in the same operation direction on the same workstation, these two constraints (7) and (8) will take effect, if i is arranged before p, formula (8) becomes effective as $tf_p - tf_i - t_p \geq 0$, otherwise formula (7) becomes effective as $tf_i - tf_p - t_i \geq 0$, so as to ensure the processing sequence of tasks in a workstation. Constraint (9) gives the lower bound of the variable tf_i and constraint (10) defines tf_i cannot succeed the cycle time. Constraints (11) and (12) define the relationship between task arrangement and the status of whether the workstation is opening or not. Tasks can only be arranged on the workstation that has been opened, and once the workstation is opened, there must be at least one task arranged on this workstation. Constraint (13) is used to determine whether the mated workstations are opened individually or both. Constraint (14) ensures that the workstation is continuously turned on. Constraint (15) defines the number of paired workstations. Constraints (16) and (17) define the relationship between task I i and worker w on the workstation (j, k). Constraint (18) ensures that a worker cannot work on more than one workstation at most. Constraint (19) ensures that a worker can only be arranged on workstations that have been turned on. Constraint (20) defines the total wage of workers on the workstation (j, k). Constraint (21) defines the total wage of workers on the whole Two-sided assembly line.

3. Computational Results

3.1. Test Problems Setting

In order to evaluate the correctness and effectiveness of the MIP model proposed in this paper, we use the classical example in TALBP to test. The MIP model is encoded in Python language, and the DOcplex interface is called by IBM ILOG CPLEX 12.10 0 solution results. All examples are run on a personal computer with Intel (R) core (TM) i5-10210u CPU processor. The classical problems in all TALBP are selected, including different scales. Four problems P9, P12, P16 and P24 are from Kim [3]. Each scale is given a different cycle time, we tested a total of 23 instances.

As for cost setting part, the wage of each worker for processing each task are randomly generated between [100, 200]. In order to compare the effects of different weights of establishing cost and machinery cost on final results, two groups of experiments were set. In the first group, the establishing cost of workstation is 25000 and the machinery cost is 20000. While in the second group, and the establishing cost of workstation is 10000 and the machinery cost is 20000. Because the Two-sided assembly line balancing problem is NP-hard problem, its solution complexity is higher than that of single assembly line balancing problem. Moreover, this paper also considers the cost factor, in which the worker cost processing further improves the complexity of the problem.

3.2. Experiment Results

In addition, in order to control the solution time, this paper sets the maximum computing time of all instance solution to 3600 seconds. If the MIP model fails to find the optimal solution within 3600 seconds, it is represented by "-" , and the upper bound output when it reaches 3600 seconds is the approximate optimal solution result of the current problem. The details of solution results are shown in the table below. The optimal number of the mated-stations (NM), the optimal number of the single-stations (NS) and the optimal total cost of the whole assembly line (Cost) found by the MIP model and its needed CPU time are shown in Table 2.

From Table 2, it can be found that all instances in P9, P12 and P16 of the two groups can find the optimal solution within a given time by MIP model. However, it is obvious that the solution time of MIP model increases rapidly as the problem scale becomes larger. For example, the average solution time of P9 problem in the first group is 14.219 seconds while that of P16 problem is 482.515 seconds Even when solving a slightly large-scale problem P24, MIP model can't find the optimal solution within 3600 seconds, and its output upper bound value is far away from the minimum number of stations (NS_{LB}), and the performance is poor, such as, in instance 21-18-8, NS_{LB} has 8 workstations, and the output results are 9 mated workstations and 11companion workstations. More effective solution methods are needed in the future.

In addition, by comparing the establishment costs of the two groups of different workstations, it can be found that the assembly line planning results obtained by different cost settings are different. For example, 12-5-5 example, the best scheme of the first group is 3 mated workstations and 6 companion workstations, while the best scheme of the second group is 4 mated workstations and 5 companion workstations. Enterprises can different best layout scheme according to their own actual needs.

4. Conclusion and Further Researches

This paper takes the Two-sided assembly line as the object, studying the Cost-oriented Two-sided assembly line balance problem, and proposes a new Cost-oriented mathematical model. Combined with the workstation construction cost, machinery cost and workers' wage, the goal of the model is to minimize the total cost of the Two-sided assembly line, in which the wage levels of workers performing the same task are different. Workers' wages are determined

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according to the highest wage level on their workstation. In order to verify the feasibility of the model proposed in this paper, Python language coding is used to call CPLEX to solve numerical examples of different scales. The results show that the model can obtain the optimal solution on a small scale and obtain the balance scheme with the lowest cost, which proves the correctness and effectiveness of the model. The experimental results of two groups of different cost settings show that different weights of construction cost and machinery cost will affect the final result, and enterprises can set according to their own needs. As the problem scale becomes expended and the combined cost increases the complexity of the problem, the solution performance of CPLEX on a large scale is not good, the optimal solution cannot be obtained within the specified time, and the output upper bound solution is also poor. In the future, metaheuristic method can be utilized to solve large-scale problems, which can meet the actual needs.

Table 2. Computational results of all instances

Problem	CT	NS_{LB}	Mated Stations Cost:25000, Station Cost:20000			Mated Stations Cost:10000, Station Cost:20000		
			NM[NS]	Cost	Time	NM[NS][C]	Cost	Time
P9	3	6	3[6]	197178	14	3[6]	152178	20.031
	4	5	3[5]	177456	16.047	3[5]	132456	51.765
	5	4	2[4]	132530	21.563	2[4]	102530	44.125
	6	3	2[3]	112388	5.266	2[3]	82388	3.813
Avg					14.219			29.934
P12	4	7	4[7]	243284	87.36	4[7]	183284	71.906
	5	5	3[6]	198625	111.609	4[5]	143505	160.375
	6	5	3[5]	178702	148.14	3[5]	133702	92.218
	7	4	2[4]	133990	68.5	2[4]	103990	95.578
	8	4	2[4]	134160	95.531	2[4]	104160	62.875
Avg					102.228			96.590
P16	15	6	4[6]	230830	757.453	4[6]	170830	1366.23
	16	6	3[6]	206920	186.891	3[6]	161920	1259.3
	18	5	3[6]	207438	426.296	4[5]	151520	493.375
	19	5	3[5]	186837	457.703	3[5]	141837	433.609
	20	5	3[5]	187260	509.187	3[5]	142260	723.75
	21	4	3[5]	187747	759.359	4[4]	131424	511.36
	22	4	2[4]	141616	280.719	2[4]	111616	354.235
Avg					482.515			734.551
P24	18	8	9[11]	477580	3600	7[9]	274678	3600
	20	7	9[11]	477580	3600	9[10]	318660	3600
	24	6	4[6]	239872	3600	6[7]	227000	3600
	25	6	6[7]	318275	3600	4[6]	184025	3600
	30	5	3[5]	198550	3600	-	-	3600
	35	4	3[5]	201040	3600	4[5]	169480	3600
	40	4	4[7]	282680	3600	3[5]	155585	3600
Avg					-			-

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