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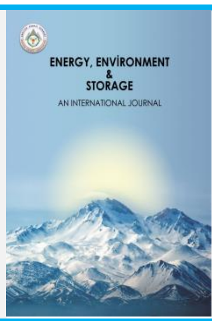

Grey Parallel Assembly Line Balancing

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ABSTRACT.

Purpose: The purpose of this paper is to solve a grey parallel assembly line balancing problem with type-I (G-PALBP-I) to minimize the number of stations under the major constraints and restrictions of the PALs.

Design/methodology/approach: A manufacturing system with parallel assembly lines (PALs) consists of at least two assembly lines placed next to each other in the facility layout. To design real-life PAL applications, the processing durations of the tasks may not always be fixed due to workers getting tired or making mistakes. In addition, the variability in customer demands may also affect the cycle duration called the total processing duration of a station. To better reflect the real-life applications of PALs, task and cycle times are expressed with grey system theory and grey numbers. A binary integer linear programming model is proposed to solve the G-PALBP-I.

Findings: The proposed model is implemented to the PAL systems designed by using a simple assembly line data in the literature. The results show that considering precedence relationships and variability in task and cycle durations provides a more flexible and consistent perspective.

Originality/value: The grey system theory and grey numbers, to the best of the authors' knowledge, have not been considered to describe the uncertainty of task and cycle times in PALBPs. Therefore, this study provides important insight to both researchers and decision-makers in practice.

Keywords: Parallel assembly line balancing, grey numbers, uncertain processing times, uncertain cycle time, mathematical model, binary integer linear programming

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Abbreviations:

ALBP: Assembly line balancing problem
BILP: Binary integer linear programming
PAL: Parallel assembly line
PALBP: Parallel assembly line balancing problem
G-PALBP-I: Grey parallel assembly line balancing problem with type-I
SALBP: Simple assembly line balancing problem
SA: Simulated annealing

1. INTRODUCTION

Assembly lines have been an indispensable element of production facilities for over a century. To meet the variable demands of the customers and compete in the global economy, an assembly line system can be designed in different ways depending on the nature of the product, the capacity demand of the firm, and various restrictions. One of these design types is the parallel assembly lines (PALs) placed next to each other to produce the same or similar products within a single facility. In real-life applications of PALs, there may be common stations, i.e., common workers, on two adjacent parallel lines. Thus, both the length of the assembly line is shortened and the installation of more stations is prevented. Due to the common stations between the adjacent lines, the idle/waiting times in the separate stations are converted to value-added periods. The most important advantage of PALs is the increase in the facility's production capacity. In addition, since a problem occurring on one line will not prevent other parallel lines, this provides a great advantage in terms of production continuity.

The parallel assembly line problem (PALBP), which deals with the task assignment processes to stations, was first introduced by Gökçen et al.[1]. They presented a binary integer linear programming (BILP) model. Since then, many papers have been published on different versions and restrictions of the PALBPs such as single-model [2,3,4,5,6,7,8,9,10,11,12,13,14] mixed-model [15, 16, 17, 18], U-shaped [19, 20, 21, 22, 23, 24, 25, 26], two-sided [27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41], uncertainty in task durations [42, 43, 44] and operator capabilities [45, 46, 47, 48, 49, 50, 51, 52].

The academic studies and evaluations implemented on the PALBPs usually have some general assumptions. The most important of these assumptions is that the task processing durations are considered within a deterministic framework. Deterministic and fixed task durations, especially in worker-focused assembly lines, mean that human factors such as workers getting tired, having trouble concentrating, and making mistakes are not considered. That is, treating workers working on PALs as robots and making such assumptions prevents the decision-makers from obtaining consistent results in real-life applications. Therefore, taking an approach that considers the uncertainties of the task processing times in PALBPs would provide a more realistic approach.

According to the aforementioned studies, only three publications are identified on the uncertainty of the task and/or cycle durations. The first one of these papers is presented by Baykasoğlu et al. [42]. They propose a multi-objective ant colony optimization algorithm to minimize the number of stations by addressing the uncertainty of cycle and task durations with a fuzzy logic approach. The second one is published by Özcan [43]. He presents a chance-constrained, piecewise-linear, mixed integer programming formulation and a tabu search algorithm to minimize the number of stations by addressing the stochastic task durations. The last paper is presented by [44]. They, like [43], consider the stochastic task durations. In addition, they also take into account the equipment cost to minimize the number of stations by proposing a hyper-heuristic approach based on a simulated annealing (SA) algorithm. In conclusion, while the fuzzy logic or statistical distribution approaches are used for the uncertainties of task and cycle durations in the PALs, no study addresses grey system theory and grey numbers for the task and cycle durations. Based on the grey system theory [53], the uncertain processing time is expressed as interval grey numbers [54]. Unlike the fuzzy method and the interval method, the interval grey number defines an unknown actual value with a definite range and limits the specified upper and lower bounds of the uncertain processing time [54]. The authors' findings show that only two papers address the task or cycle durations with grey numbers in the assembly line balancing problems (ALBPs). The first paper that considers grey demand and grey task times for the simple ALBP (SALBP) is presented by Arık et al. [55]. They propose a BILP model to minimize the number of stations and evaluate the results of a numerical example solved by the proposed model. In the second paper, Dang and Xie [54] build a mathematical model and design the SA algorithm based on a neighborhood search strategy to solve the ALBP with interval grey processing durations. However, there is no PALBP where the uncertainty in cycle time and task durations is defined by grey numbers. Accordingly, the main contributions of this paper are as follows; (1) this paper introduces the parallel assembly line balancing problem considering grey task processing and cycle durations to minimize the number of stations (G-PALBP-I), (2) this paper proposes a new BILP model to solve the G-PALBP-I.

The remainder of this paper is designed as follows. The problem definition and the proposed BILP model are presented in Section 2. Section 3 includes a numerical example. The last section is the conclusion and future directions.

2. GREY PARALLEL ASSEMBLY LINE BALANCING PROBLEM WITH TYPE-I

2.1 Problem definition

In PAL systems, at least two assembly lines ($\boldsymbol{h = 1, ..., H; H \geq 2}$) are placed parallel to each other. One or similar product models can be manufactured in the production facility. Each product model is manufactured on one assembly line. The set of tasks ($\boldsymbol{i = 1, ..., N_h}$) and task precedence relationships ($i \in P_{ih}$) for each product model are known in advance. Each line can have its own separate station or common stations can be established on two adjacent *h* and *h+1* lines (*k=1,...,K*). At common stations, tasks on both assembly lines are performed. The processing durations of tasks performed entirely by workers are defined as grey numbers. The task durations may include uncertainty due to human factors such as workers getting tired or making mistakes. Therefore, the processing duration of task i on any line h has a closed interval with lower and upper bounds ($\boldsymbol{t_{hi}^{LU} = [t_{hi}^{L}, t_{hi}^{L}]}$). The cycle time C of all stations established in PAL systems is the same. According to the classical approach, the cycle time depends on the product demand. Fluctuations in demand can lead to uncertainty in cycle times. For example, if demand forecast or order quantity information is insufficient to provide insight into the sales status of any product, there may be uncertainty in demand and therefore in cycle times. Therefore, the demand of the product model on line *h* ($\boldsymbol{D_h^{LU}} = [\boldsymbol{D_h^L, D_h^U}]$) and the cycle time of the PAL system $\boldsymbol{(C^{LU} = [C^L, C^U])}$ are defined through grey data with lower and upper bounds. The relation between grey demand and grey cycle time is given in equation (1). In equation (1), $\boldsymbol{AC_h}$ represents the time-dependent annual capacity of the line *h*. The joint cycle time is obtained by dividing the total of $\boldsymbol{AC_h}$ $\boldsymbol{(AC^{total})}$ by the demand value of the product models to be produced on the lines. The objective is to minimize the number of stations by considering some PAL constraints and task and cycle durations with grey numbers.

$$C^{LU} = [C^L, C^U] = \left[\frac{AC^{total}}{D_h^{LU}}\right] = \left[\frac{\sum_{h=1}^{H} AC_h}{D_h^{LU}}\right] = \left[\frac{\sum_{h=1}^{H} AC_h}{D_h^{U}}, \frac{\sum_{h=1}^{H} AC_h}{D_h^{L}}\right] \quad \textbf{(1)}$$

2.2. Mathematical model

The proposed BILP model for the G-PALBP-I is as follows:

$$\min \sum_{k=1}^{K} Z_k \quad (2)$$

$$\sum_{k=1}^{K} X_{hik} = 1 \quad \forall i = 1, \dots, N_h \text{ and } \forall h = 1, \dots, H \quad (3)$$

$$\sum_{k=1}^{K} X_{hik} \le M \cdot Z_k \quad \forall h = 1, \dots, H \text{ and } \forall i = 1, \dots, N_h \quad (4)$$

$$Z_k \ge Z_{k+1} \quad \forall k = 1, \dots, K-1 \quad (5)$$

$$\sum_{k=1}^{K} (K - k + 1) \cdot (X_{hik} - X_{hjk}) \ge 0 \quad \forall h = 1, \dots, H \text{ and } \forall i \in P_{jh} \quad (6)$$

$$\sum_{i=1}^{N_h} X_{hik} \le M \cdot U_{hk} \quad \forall h = 1, \dots, H \text{ and } k = 1, \dots, K \quad (7)$$

$$\sum_{i=1}^{N_h} X_{hik} \ge U_{hk} \quad \forall h = 1, \dots, H \text{ and } k = 1, \dots, K \quad (8)$$

$$U_{hk} + U_{(h+l)k} = 1 \quad \forall h = 1, \dots H-2;\ \forall l = 2, \dots, H-h \text{ and } k = 1, \dots, K \quad (9)$$

$$\sum_{i=1}^{N_h} t_{hi}^{LU} \cdot X_{hik} + \sum_{i=1}^{N_{h+1}} t_{(h+1)i}^{LU} \cdot X_{(h+1)ik} \le C^{LU} \quad \forall h = 1, \dots, H-1 \text{ and } \forall k = 1, \dots, K \quad (10)$$

$$X_{hik}, U_{hk}, Z_k \in \{0,1\} \quad \forall h = 1, \dots, H;\ \forall i = 1, \dots, N_h \text{ and } \forall k = 1, \dots, K \quad (11)$$

The objective function (2) minimizes the number of stations on the PAL systems. Constraint (3) ensures that each task i on line h is assigned to only one station. Constraint (4) states that if any task i on line h is assigned to station k, that station must be established. Constraint (5) prevents the next station from being established before the previous station is established. Constraint (6) ensures that tasks are assigned to stations by checking the precedence relationships between tasks i and j on line h. Constraints (7) and (8) state that if task i on line h is assigned to station k, that station serves line h. Constraint (9) guarantees that station k can only be assigned to two adjacent lines, i.e., assembly lines h and $h+1$. Constraint (10) ensures that the total grey processing times of tasks assigned to a station do not exceed the grey cycle time of the PAL system. Constraint (11) defines the binary decision variables. In constraint (10), the closed lower and upper bounds of total grey task durations must satisfy the closed lower and upper bounds of the grey cycle duration, respectively. Accordingly, satisfying the lower and upper bounds means satisfying all possible alternatives in that range. Therefore, constraint (10) can be updated as constraints (12) and (13).

$$\sum_{i=1}^{N_h} t_{hi}^{L} \cdot X_{hik} + \sum_{i=1}^{N_{h+1}} t_{(h+1)i}^{L} \cdot X_{(h+1)ik} \le C^{L} \quad \forall h = 1, \dots, H \text{ and } \forall k = 1, \dots, K \quad (12)$$

$$\sum_{i=1}^{N_h} t_{hi}^{U} \cdot X_{hik} + \sum_{i=1}^{N_{h+1}} t_{(h+1)i}^{U} \cdot X_{(h+1)ik} \le C^{U} \quad \forall h = 1, \dots, H \text{ and } \forall k = 1, \dots, K \quad (13)$$

3. A NUMERICAL EXAMPLE AND DISCUSSIONS FOR G-PALBP-I

In this section, the numerical example of the SALBP presented by Arık *et al*. [55] is converted to two adjacent parallel assembly lines. Annual capacity information is given in Table 1. Also, grey processing times and precedence relationships are given in Table 2. It is assumed that the same product is produced in both lines. Since there are two assembly lines in the PAL system, the AC^{total} and C^{LU} is calculated as follows:

$$AC^{total} = AC_1 + AC_2 = (300 \cdot 60 \cdot 8 \cdot 1) + (300 \cdot 60 \cdot 8 \cdot 1) = 288000 \text{ minutes/year.}$$

$$C^{LU} = [C^L, C^U] = \left[\frac{288000}{36000}, \frac{288000}{24000}\right] = [8, 12] \text{ minutes/unit}$$

Table 1. Product and annul production information

Parameters	**Value**
Number of PALs	2
Number of tasks on one assembly line	14
Annual uncertain demand (unit/year)	[24000,36000]
Number of working days per year (day/year)	300
Number of shifts in a working day	1
Working hours in a shift (hour/day)	8

Table 2. Grey task durations and precedence relationships (Arık *et al*. 2019)

Tasks (i)	**Grey processing times ($[t_{hi}^L, t_{hi}^U]$)**	**Predecessor (P_{jh})**	**Tasks (i)**	**Grey processing times ($[t_{hi}^L, t_{hi}^U]$)**	**Predecessor (P_{jh})**
1	[1,1.3]	-	8	[8, 12]	5
2	[2,2.6]	1	9	[2, 3]	7, 8
3	[3,4.5]	2	10	[3, 4.5]	9
4	[4,6]	2	11	[4, 7.6]	10
5	[2,3.6]	1	12	[5,8.5]	10
6	[4,4.4]	3, 4, 5	13	[6,9.6]	11
7	[6,6.6]	6	14	[7,10.5]	12, 13

For comparison, each line is solved both as SALBP and PALBP. The task assignments obtained for SALBP and PALBP are given in Tables 3a and 3b, respectively. According to Tables 3a and 3b, 18 stations are established for SALBP and 17 stations for PALBP. For the PALBP, stations 4, 5, 6, and 9 are the common stations. Stations 1, 2, 3, 11, and 14 are established for the line 1, and stations 7, 8, 10, 12, 13, 15, 16, and 17 are established for the line 2. As a result, despite the gray numbered demands and duty periods, G-PALBP-1 contributes to energy conservation with one station lower installation cost.

Table 3a. Task assignments for SALBP with two assemble lines

	Stations	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***

Line 1	**Tasks**	1, 2, 3, 5	4, 6	8	7	9, 10	11	12	13	14
	Grey duration of station	[**8, 12**]	[**8**, 10.4]	[**8, 12**]	[6, 6.6]	[5, 7.5]	[4, 7.6]	[5, 8.5]	[6, 9.6]	[7, 10.5]
	Stations	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***
Line 2	**Tasks**	1, 2, 3, 5	4, 6	8	7	9, 10	11	12	13	14
	Grey duration of station	[**8, 12**]	[**8**, 10.4]	[**8, 12**]	[6, 6.6]	[5, 7.5]	[4, 7.6]	[5, 8.5]	[6, 9.6]	[7, 10.5]

Table 3b. Task assignments for PALBP with two assemble lines

Stations	***1***	***2***	***3***	*4**	***5****	*6**	***7***	***8***	*9**	*10*	*11*	***12***	*13*	*14*	*15*	*16*	*17*
Tasks of line 1	1, 2, 3, 5	8	4, 6	7	9, 10	12			11		13			14			
Tasks of line 2				1	5	2	8	3, 4	6	7		9, 10	11		13	12	14
Grey duration of station	**[8, 12]**	**[8, 12]**	[**8**, 10.4]	[7, 7.9]	[7, 11.1]	[7, 11.1]	**[8, 12]**	[7, 10.5]	**[8, 12]**	[6, 6.6]	[6, 9.6]	[5, 7.5]	[4, 7.6]	[7, 10.5]	[6, 9.6]	[5, 8.5]	[7, 10.5]

*****Common station

3. CONCLUSION AND FUTURE DIRECTIONS

This paper introduces the parallel assembly line balancing problem considering the grey task and grey cycle durations to minimize the number of stations (G-PALBP-I). To better reflect the real-life applications of PALs, task and cycle times are expressed with grey system theory and grey numbers. A BILP model is proposed to solve the G-PALBP-I. The proposed model is implemented to the PAL systems designed by using simple assembly line data in the literature. The results show that considering precedence relationships and variability in task and cycle durations provides a more flexible and consistent perspective.

In order to contribute to the literature and application processes of the PAL systems, the following topics may be addressed in future studies: State-of-the-art approaches such as heuristics, meta-heuristics, and hyper meta-heuristics may be proposed for G-PALBP-I including large-sized task sets. On other suggestion is that, in the PALs, worker assignment and line balancing may be solved together by considering different worker capabilities with the grey system theory. In addition, the ergonomic concerns of the workers may be considered as the grey system theory to better handle the real-life applications of the PALs systems.

In future studies, grey robotic PALBP and grey robot/human collaborative PALBP may be considered in terms of energy consumption, energy saving, and energy cost.

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