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Optimal Assignment of Machine Operators to Enhance Productivity and Skill Efficiency in Assembly Lines in Apparel Industry Using Two-Phase Integer Linear Programming Model: A Case Study

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Abstract

Assembly line balancing (ALB) in the apparel industry is crucial for optimizing production efficiency. It requires an optimum assignment technique for machine operators (MOs) based on their skills and availability to minimize production delays and enhance productivity. This study aims to optimize the line layout and production throughput by applying a bottleneck-oriented resource allocation framework that combines the Rank Positional Weight Method (RPWM) with a two-phase Integer Linear Programming model (ILPM). Once the line layout is determined by the RPWM, the next stage is to assign MOs to operations by solving a two-phase ILPM. In the first phase, an ILPM is applied to maximize the total production rate by assigning MOs to operations, based on their efficiency, identifying bottleneck operations which contribute to the lowest production rate. In second phase, the total skill level of the assembly line is minimized. The predetermined bottleneck production rate is used as an indicator, ensuring that the production rate which is maximized in the first phase is kept fixed. The reassignment of the remaining MOs is based on their skill levels, while the bottleneck operations and operators are kept aside in the second phase. The bottleneck operation, identified in the first phase, ensures that the most efficient MOs are assigned where needed, while other operations are conducted by MOs based on a compromise solution between their skill levels and availability. This approach emphasizes the importance of line balancing and operator assignment in the apparel industry and determining the ideal number of MOs needed to perform the set of operations. Additionally, this proposed method can be adopted to any production line with necessary modifications.

Keywords: Assembly line balancing, Bottleneck operation, Integer linear programming, Machine operator, Production rate

Introduction

Sustainability assessment has become a rapidly developing topic with a growing number of concepts and tools which are being developed during the last decades. This has been particularly relevant for industries to continuously and effectively optimize the design of manufacturing systems to economize the processing time. The general meaning of “manufacturing” can be stated as “producing of products by manual labor or by machinery.” “Manufacturing is the transformation of raw material into useful products through the use of the easiest and least expensive methods. It must be mentioned that not only must the product be manufactured by the easiest and least expensive method, but also it must have the desired quality in performance as well as reliability” (Becker & Scholl 2006). In the 21st Century, the garment industry has become a large-scale manufacturing industry. The industry has made

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breakthrough changes, from costumes that are sewn according to individual measurements at an expensive cost to the production for mass demand at low cost, from designs, models, materials, color and the time of use, and the development of new products are also constantly being changed. However, Competition among the garment industries has increased with the globalization, forcing industries to increase the productivity, which is one of the most significant factors affecting the competitiveness of the garment industry. As one of the sectors that utilizes a significant amount of human resource and various activities at production line, the garment industry is one that places a high priority on increasing productivity and reducing production costs (ur Rehman et al., 2019). The production line is a critical component of the entire manufacturing process, as it is where the final product is assembled. As such, improving the efficiency of the production line is essential to the overall success of manufacturing operations. One of the key challenges faced in this regard is known as the assembly line balancing (ALB) problem. Optimizing the assembly line directly impacts production efficiency, making it a vital focus area for manufacturers aiming to stay competitive. Assembly lines, consist of a sequence of tasks, each having an operational processing time and a set of precedence relations, are widely used in manufacturing plants (Salveson, 1955). The aim is to allocate the optimal number of operators to the production line and assign them to specific operations according to their skill levels for each operation, task requirements and productivity goals. This ensures that the production process is properly balanced and highly efficient (Fathi et al., 2018). ALB is one of the techniques that can be used to enhance the productivity in production lines. It is a simple and effective technique which does not consume any cost in addressing the problem of low efficiency. Line balancing means balancing the production line, or any assembly line. The main objective of line balancing is to distribute the task evenly over the production line so that idle time of the operator and hence, the machine can be minimized. Line balancing aims at grouping the facilities or workers in an efficient balance of the capacities and flows of the production or assembly processes (ur Rehman et al., 2019). It helps the garment industries to survive in global competitive market and focus their manufacturing strategies on minimizing their production costs, increasing productivity, improving product quality, resources utilization, and increasing customer satisfaction. Having a balance in an assembly line will help the industry to achieve its targets on time to meet the customer demands. Workforce play a very important role in all the process involved in the industry and there is always a room for improvement for their effective utilization. The process of balancing the assembly line matches the output from each operation to maintain constant flow of materials which results in reduction of wastes, lead time, workforce and improves the overall efficiency of the system (Ahmad et al., 2024). By combining RPWM with a two-phase ILPM, this study proposes an optimum line layout by carefully managing the bottleneck operations.

Material and methods

In the literature, it can be found that ALB problems have been solved using many different methods and techniques. These can be grouped into three main categories: heuristic methods, analytical methods, and simulation techniques. Some examples of these methods include mathematical programming, branch-and-bound algorithms, dynamic programming, and position weight techniques. Heuristic methods are useful because they can provide a near optimal solution with less computational time. However, the downside is that they don't always perform the same way and can't guarantee the exact optimal solution. Some examples of heuristic methods are the rank positional weight method, Hoffmann heuristic, and Kilbridge and Wester heuristic. Simulation techniques focus on understanding how the system works, developing strategies, and mimicking the system's operation. As the number of tasks in assembly line balancing problems increases, the degree of difficulty in solving the problem also increases. In such cases, heuristic methods are often used. For this reason, heuristic methods, here The Ranked Positional Weight Method (RPWM) was chosen for this study to find the best assembly line layout.

RPWM which was developed by Helgeson & Birnie in 1961, is widely used in the literature as a heuristic approach to solve assembly line balancing problems (Ghutukade & Sawant, 2013). To calculate the position weight of each task, the total time to perform all the tasks that follow it, including itself, is calculated. The key idea is that during the initial assignment process, the task with the highest position weight is chosen first. To select and determine the appropriate method for line balancing, it is necessary to develop an analytical method to assess the performance of each existing method concerning the production task characteristics. This allows the identification of the most efficient workstation arrangement method. The implementation steps of RPWM are as follows:

1) Determining the precedence operation matrix
2) Calculating the positional weights for each operation
3) Obtaining the results of the positional weight calculations
4) Assigning the operations in the workstation design
5) Precedence diagram resulting from the design.

The main objective of this study is to propose a novel method aimed at improving the efficiency of the ALB problem. By addressing key factors such as task allocation, operator skills, and production flow, the proposed method seeks to enhance the overall productivity of the assembly line. This approach aims to maximize total production, minimize bottlenecks, and optimize the use of resources, ultimately leading to a more balanced and efficient production process.

A. *Assumptions*

- The number of Machine Operators (MOs) is at least equal to the number of operations.
- Each MO is either assigned to a single operation or left unassigned.
- Each operation can be performed by multiple MOs.

The following ILPM is proposed to determine optimal assignment of MOs to operations in the assembly line. The proposed method consists of two phases:

B. *Phase 1 : Maximize the Production Rate*

The max approach uses the skill-based times to allocate operators to operation, aiming to achieve maximum output. This allocation is determined using an integer programming model. The mathematical model is formulated with the objective of maximizing the production rate (1).

Decision Variables

$$y_{kj} = \begin{cases} 1, & \text{if operator } k \text{ is assigned to operation } j \\ 0, & \text{otherwise} \end{cases}$$

R – Production rate

Parameters

a_{kj} - Number of units operator k can process if assigned to operation *j* per unit time
n - Number of operators
m - Number of operations
f_k - Set of operations that operator k can perform
f_j - Set of operators who can perform operation *j*

Index

k - Operator
j - Operation

Objective Function

$$\text{Maximize } Z = R \tag{1}$$

Subject to

$$\textstyle\sum_{k\in f_j} a_{kj}\, y_{kj} \geq R, \qquad \text{where } j = 1, 2, \dots, m \tag{2}$$

$$\textstyle\sum_{j\in f_k} y_{kj} \leq 1, \qquad \text{where } k = 1, 2, \dots, n \tag{3}$$

$$\textstyle\sum_{k\in f_j} y_{kj} \geq 1, \qquad \text{where } j = 1, 2, \dots, m \tag{4}$$

$$y_{kj} \in \{0, 1\}, \qquad \text{where } j = 1, 2, \dots, m \text{ and } k = 1, 2, \dots, n \tag{5}$$

Constraint (2) specifies which operators are assigned to each operation determining the production rate for each operation in the process using, $\sum_{k\in f_j} a_{kj}\, y_{kj}$. Constraint (3) ensures that each operator is assigned to at most one operation. Furthermore, constraint (4) guarantees that each operation is assigned to at least one operator. Constraint (5) indicates that y_{kj} is a binary variable. This assignment model is solved for each product using the COIN-OR Branch and Cut algorithm which was coded in Python programming language. To identify the most critical bottleneck operation in the assembly line, "(6)" and "(7)" are used. Equation (6) will determine the production rate for each operation:

$$R_j = \textstyle\sum_{k\in fj} a_{kj}\, y_{kj}, \qquad \text{where } j = 1, 2, \dots, m \tag{6}$$

Equation (7) given below will identify the most critical bottleneck operation:

$$R_b = min\{R_j\}, \qquad \text{where } j = 1, 2, \dots, m \tag{7}$$

For the above approach, max-min principle is adopted. The max-min principle keeps the operator assignment unchanged for the bottleneck operation, but reassign other operators to non-bottleneck operations. This minimizes the overall skill requirements while maintaining the optimal rate of output.

C. Phase 2 : Re-balance Production Line

A mathematical model is formed, where the objective function is to minimize the total skills for the remaining low skilled operators as given in (8) below. Constraint (9) ensures that the original production rate is maintained with the lowest rate being the bottleneck rate identified by the Phase 1. The constraint (10) establishes the highest production rate by multiplying the bottleneck rate by a positive factor η, setting as the upper bound. The value η, a positive real number, can be determined based on the required production rate, and it serves as the upper limit for the highest production rate of non-bottleneck operations. The constraint (11) is introduced to track whether an operator k is used (assigned to any task) or not. Constraint (12) imposes that each operator is assigned to operation with the possibility of no assignment. Constraints (13) and (14) respectively guarantee that y_{kj} and Z_k are binary variables. $Z_k = 1$ indicates whether operator k is assigned to any operation or not (other than the bottleneck operation).

Parameters

R_b - Production rate of bottleneck operation
S_{kj} - Skill level of operator k for operation j

Objective Function

$$\text{Minimize } Z = \textstyle\sum_{k\in f_j} \sum_{j\in f_k} S_{kj}\, y_{kj}, \tag{8}$$

where j non-bottleneck operation, k non-bottleneck operator

Subject to

$$\textstyle\sum_{k\in f_j} a_{kj}\, y_{kj} \geq R_b \quad \text{for } j = 1, 2, \dots, m \text{ and } j \text{ non-bottleneck operation} \tag{9}$$

$$\textstyle\sum_{k\in f_j} a_{kj}\, y_{kj} \leq \eta \times R_b \quad \text{for } j = 1, 2, \dots, m \text{ and } j \text{ non-bottleneck operation} \tag{10}$$

$$1 < \eta < \text{positive real number}$$

$\sum_{j \in f_k} y_{kj} \leq Z_k$ where $k = 1, 2, \ldots, n$ and k not in bottleneck operation (11)

$\sum_{k \in f_j} y_{kj} \geq 0$ where $k = 1, 2, \ldots, n$ (12)

y_{kj}Î {0,1} (13)

Z_kÎ {0,1} (14)

Results

Data from a previous study (Süer & Alhawari, 2012) were considered to validate the proposed technique, with an emphasis on the two-phase ILPM computation. The dataset consists of information on 12 MOs and 6 operations. A skill level is identified, rated on a scale from 1 (highest skill level) to 5 (lowest skill level) and an operation rate is estimated for each MO. Each operator was assumed to be capable of performing 3 operations. The skill levels were modeled assuming they follow a normal distribution. The bottleneck operation, defined as the operation with the lowest production rate across the entire production line, effectively determines the overall production rate. Thus, the bottleneck rate can be interpreted as the production rate of the entire system. Since production rates are measured on an hourly basis, the total production rate represents the **hourly production efficiency** of the production line. The table below summarizes the results, comparing the outputs from the previous study by Süer and Alhawari (2012), who employed the Max-Min and Max assignment strategies to evaluate operator performance in dynamic cellular environments, with those obtained using the proposed method

Table 1: *Comparison between the previous study and the proposed method*

	Previous Study	Proposed Method
	Phase I	
Production/ Bottleneck rate	273.68	273.68
Operator	MO assignment	
1	Operation 3	Operation 3
2	Operation 4	Operation 4
3	Operation 2	Operation 2
4	Operation 6	Operation 6
5	Operation 5	Operation 5
6	Operation 4	Operation 4
7	Operation 5	Operation 5
8	Operation 4	Operation 4
9	Operation 2	Operation 2
10	Operation 4	Operation 4
11	Operation 1	Operation 1
12	Operation 3	Operation 3
	Phase II	
Bottleneck operation	2	2
Bottleneck operators	3, 9	3, 9
Minimized skill	42	42
Non-bottleneck operators	1, 2, 4, 5, 6, 7, 8, 10, 11, 12	1, 2, 4, 5, 6, 7, 8, 10, 11, 12

	Previous Study	Proposed Method
	Phase I	
	MO assignment	
Operator	Operation	
1	Operation 4	Operation 4
2	Operation 4	Operation 4
4	Operation 6	Operation 6
5	Operation 5	Operation 5
6	Operation 4	Operation 4
7	Operation 5	Operation 5
8	Operation 4	Operation 4
10	Operation 3	Operation 3
11	Operation 1	Operation 1
12	Operation 3	Operation 3
Extra MOs	NA	NA
	Output rates	
Operation 1	857.14	857.14
Operation 2	273.68	273.68
Operation 3	316.6	316.6
Operation 4	280.3	280.3
Operation 5	324.1	324.1
Operation 6	285.71	285.71

Discussion

Table 1 shows the MO allocation for each operation in the line layout, showing that both the previous study and the proposed technique produce identical results. However, to further validate the significance of the proposed method, a simulation was performed. During the data generation process, production rates were modeled using a distribution from the exponential family, specifically the exponential distribution (Johnson et al., 1995). A summary of the results is presented in Table 2.

Table 2: Simulation Results

No of MOs	No. of tasks	Bottleneck operation	Production/Bottleneck rate	Min skill (Before)	Min skill (After)	Extra MOs
20	12	6	94.94	43	41	10, 13, 19
		11	149.49	62	55	8, 11, 14
		1	77.34	47	36	5, 6, 10, 13, 16
15	9	8	118.25	42	42	-
		4	93.85	32	32	1, 10, 15
		7	171.66	40	39	15
12	7	1	176.22	34	33	1
		6	252.22	34	33	1
		5	111.23	32	32	-
10	6	1	153.75	18	18	-
		3	78.94	19	17	9
		6	166.0	29	24	3, 4, 9

The table above summarizes the key results from these simulations. The bottleneck operations and the corresponding bottleneck operators were identified for each scenario, while the bottleneck rate, minimum skill levels (from both the previous and proposed methods), and the number of extra operators were also computed. The simulation results show that the proposed method consistently produces solutions with lower skill levels compared to the previous approach. This is evident across different scenarios, where the "Min Skill (New)" column exhibits a reduction in the minimum skill required for bottleneck operations, as compared to the "Min Skill (Previous)" column. Furthermore, the “Extra MOs” column highlights an additional benefit of the proposed method; the ability to identify surplus machine operators in the production team, offering a possibility for better resource allocation or reallocation. The reduction in skill levels and identification of excess personnel underscores the efficiency and effectiveness of the proposed method.

Conclusions

The primary objective of this study was to develop an optimization technique for ALB problem. The proposed method effectively determines an optimal production line layout and subsequently allocates MOs. MO allocation is the most critical task in ALB problem, as it involves assessing the availability of operators and their skill levels. To demonstrate the significance of the proposed method, a dataset from a previous study was used for a comparison. The results showed that the previous study and the proposed method produce identical results when skill levels were insufficient to enhance production. However, the strength of the new method lies in its ability to improve efficiency when the operator skills are sufficient. In such cases, the proposed method identifies extra MOs that are not necessary for maintaining the production rate. Thus, the new method has the ability to determine the exact number of MOs required to sustain production while simultaneously maximizing the overall production rate. This provides flexibility to reassign these surplus operators to other production lines or retain them as a backup to be used when the production efficiency decreases over time. Furthermore, if these extra operators have the capability to perform bottleneck operations, assigning them to these critical tasks could significantly boost the overall production rate. Overall, the results of the simulation demonstrate that the proposed technique not only optimizes production by lowering required skill levels but also helps in improving resource management within the production system. This capability is crucial for better resource allocation and adapting to changes in production demands over time.

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