Designing a New Layout for a Balanced Production Line: A Practical Application

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Abstract: In most manufacturing companies, the layout designs and line balancing problems are often based on personal experience and made without following a theoretical methodology. By applying those ad-hoc solutions, various problems may arise when quick changes of capacity or any other constraints occur. This work was developed for a Portuguese SME in the electronics industry, that had some changes at the production level, which caused limitations in terms of space on the factory floor. Furthermore, it was also revealed that an existing production line with high production rates was gradually losing efficiency. Bringing these two issues together, the idea was to design a new plant layout to improve the performance of this production line, considering the new space constraints. To increase the production line efficiency, decisions such as the number of workers and assembly task assignment to stations need to be optimized to increase its throughput and decrease cost. An integer linear programming model was developed and used to solve the balancing problem. Considering six different optimization criteria, five variants of the model were tested. Using the best solution according to predefined Key Indicators Performance, the layout was developed using the Systematic Layout Planning approach.

1 INTRODUCTION

The layout design problem is a strategic issue and has a significant impact on the efficiency of a manufacturing system (Islam et al., 2014). Layout design is considered one of the keys elements to operations management since it maximizes the resource usage and the overall system throughput (Yemane et al., 2017). A good layout determines the efficiency of all operations in a system.

This work presents a case study that takes place in a Portuguese Small and Medium-sized Enterprise (SME) in the electronics industry. To insert a new production line on the factory floor, the company needs to relocate an existing production line - Induction Cooking Plates (ICP) production line - whose efficiency has been decreasing due to lack of continuous improvement. Considering the product production process, the company resources, and the available shop floor area, a new layout for the ICP production line was studied. The idea is, when designing the new layout, to improve the efficiency of the production line through its balancing and, simultaneously, adapt it to the new available area. For this, two of the problems that were addressed and solved were the layout design and the assembly line balancing problems.

One of the most applied and successful methodology used to plan a proper layout is the Systematic Layout Planning (SLP) technique. SLP is a procedure layout design approach (Yang et al., 2000) developed in 1973 by Richard Muther (Muther, 1973), and successfully implemented in SMEs, existing several studies of its application (Naqvi et al., 2016; Fahad et al., 2017; Tak and Yadav, 2012; Wiyaratn et al., 2013). The SLP is a technique used to arrange a workplace in a plant by locating two areas with high frequency and logical relationships close to each other. It involves the collection of information for the development of a relationship chart (step 1). This chart highlights the desirability levels of adjacency between pairs of resources, classifying them with the code A (absolutely necessary), E (especially important), I (important), O (ordinary), U (unimportant), and X (undesirable). Through the analysis of this information, a relationship diagram is elaborated. This diagram shows the resources connected through lines, in which the desirability levels of adjacency between the resources, dictates the lines characteristics

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– thickness and color. The latter is analyzed in order to elaborate the layout solutions (step 2). Finally, depending on the predefined Key Performance Indicators (KPIs), the most favorable layout is chosen (step 3).

Production activities in manufacturing industry are closely related to the assembly line balancing (Syahputri et al., 2018). The combination of layout design with line balancing techniques has already proven to be quite advantageous (Syahputri et al., 2018; Buchari et al., 2018). Therefore, a virtuous layout can be designed, and productivity can be increased through an appropriate assembly line balancing (Yemane et al., 2017). An assembly line is a set of workstations arranged sequentially and interconnected by a material conveyor system. At each workstation, a set of predefined tasks (or operations) are executed in an assembly process. Each task is defined by its processing time (the time required to execute a given task) and its precedence constraints (the set of constraints that determines the sequence according to which tasks can be executed).

The Simple Assembly Line Balancing Problem (SALBP) was initially formulated by (Salveson, 1955). This problem consists of assigning a set of tasks to a set of workstations, intending to minimize the number of workstations or the cycle time of the production line. The assignment of tasks to workstations is done to ensure that the assembly line can meet the costumers' demand. (Scholl and Becker, 2006) states that there are four formulations for the SALBP: SALBP-1 (minimizing the number of workstations for a given cycle time), SALBP-F (establishing whether a feasible line balance exists for a given combination of workstations and cycle time), SALBP-2 (minimizing the cycle time for a given number of workstations), and SALBP-E (minimizing the cycle time and the number of workstations considering their interrelationship).

There are some considerations that can be incorporated in the assembly line balancing models: assignment constraints (Task-related or zone constraints, Workstations constraints, Positioning constraints and Operators' constraints), parallel lines, parallel workstations, and U-shaped assembly lines.

So many researchers, over the last decades, have studied the SALBP in many ways, depending on the constraints and the goals considered. Most of the published papers are focused on SALBP where the performance measure is either minimizing the number of stations or the cycle time. Using different preference criteria to assign tasks to the workstations, results in different heuristics. A simple heuristic refers to sorting the tasks in descending order (MaxTime Heuristic) or ascending order (MinTime Heuristic) of their processing time. After this ordering, the tasks are assigned to the workstations according to the established order, considering that the defined cycle time cannot be exceeded. In the heuristic designated by the notation MaxG, the assignment of tasks to workstations is carried out in decreasing order of each task processing time divided by the upper bound. Another heuristic example is the MaxS (or Greatest), in which the allocation is made by prioritizing the tasks with the greatest number of successors. Finally, in the Ranked Positional Weight (RPW) heuristic, the assignment of tasks is made in descending order of the ranked positional weight of each task.

The paper is divided into four sections. This one (section 1) is a brief introduction to the problem and a review of approaches and studies available in the literature. In section 2, the case study is presented, as well as the production line under study.It is followed by the layout design approach explanation in section 3, in which the obtained results are showcased and analyzed. Finally, in section 4, conclusions on the comparison of the solutions effectiveness are provided as well some future work remarks.

2 CASE STUDY: PROBLEM DESCRIPTION AND CHARACTERIZATION

The practical case under study takes place in a SME belonging to a group in the electronic industry. This group develops and produces efficient, sustainable, and suitable solutions for the Smart Cities/Utilities, Smart Buildings/Installations, and Smart Homes/Appliances. The company is dedicated to the production of Induction Cooking Plates (ICP), LED Lights and, more recently, a new product, that for the sake of disclosure, will be referenced throughout this paper as MWMs.

The insertion of the new production line for the MWM production was an excellent opportunity to study the optimization of the existing production line whose efficiency has been decreasing, the ICPs production line. The shop floor is divided between two floors. With the insertion of the MWM production line on the upper floor, there was a reorganization of the remaining space on the same floor. With this reorganization, the opportunity to separate the processes of automatic insertion of electronic components from the processes of manual insertion of electronic components and ICP encapsulation arose. Therefore, at the company's request, the space available on the upper floor (Figure 1) was studied, to insert the final processes of manual insertion of components and encapsulation of the ICP production line.

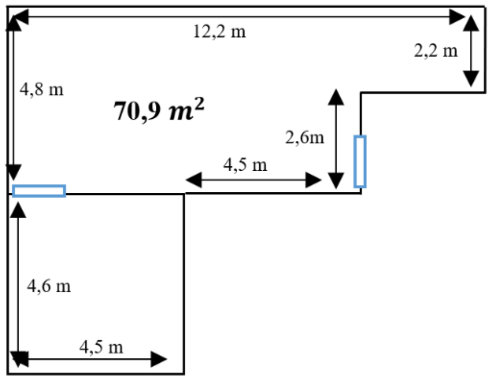

Figure 1: Available space in the upper floor.

It is important to reinforce that there are processes that will remain on the lower floor due to the sharing of machines with other production lines. Therefore, these processes will not be included in this study.

There are several models of induction cooking plates available. The data used in this study correspond to a model that, for the sake of disclosure, will be referenced throughout this paper as PB. This model uses all the available resources to produce any model of ICPs.

The Induction Cooking Plates are composed by an electronic components module called Main ICP, a set of magnetic induction exchangers (MIEs), a support base, a display module designated by IURI with an interface called TecBit, and finally, a glass.
According to the ICP production process, a precedence diagram was drawn and is presented in Figure 2.

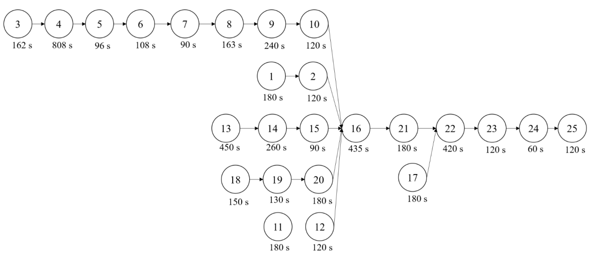

Figure 2: ICP precedence diagram.

Considering the costumers' demand, the company aims to produce 5 units/hour, which implies a cycle time of 720 seconds/unit. This means that each workstation will have a cycle time of 720 seconds in which all the tasks assigned to it must be carried out. However, when the precedence diagram is analyzed, it can be seen that there is a task that has a processing time greater than the desired cycle time (Task 4 - 808 seconds). This means that whatever workstation this task is assigned to, will have to be duplicated. Besides this, there are some tasks assignment constraints that must be considered, more specifically, task-related or zone constraints. At the company's request, the resources associated with tasks 21 and 23 cannot be in the same workstation due to safety conditions. Tasks 3 to 6 need to be in the same workstation due to resource constraints, and for the same reason, the same happens for tasks 18 to 20. It is important to mention that although these tasks require the same resources, they are performed by different workers.

3 ICP LAYOUT DESIGN

The layout design methodology was divided into two steps: line balancing and layout design (Figure 3).

In the first step, it was solved an assembly line balancing problem using an integer linear programming model (Section 4.4.1). Based on this base model (BM), 5 variants were also used and tested, using different preference criteria (PC) to assign task to the workstations: PC1-shortest Processing Time (MinTime); PC2-longest Processing Time (MaxTime); PC3-Greatest RPW (RPW); PC4-Greatest G (MaxG) (maximum processing time divided by the upper bound); PC5-Greatest S (MaxS or Greatest) (Greatest number of successors). The line balancing results were compared using the following KPIs:

- Number of Workstations;
- Line Efficiency (LE): is the ratio of workstations time and the cycle time multiplied by the number of workstations;

$$LE(\%) = \frac{\sum_{i=1}^{N} t_i}{C \times W}; \quad (1)$$

where t_i is the processing time of task i in seconds ($i \in \{1,...,N\}$), N is the number of tasks and W is the number of workstations.

- Balance Delay (BD): is the ratio between the idle time in the production line balancing and the time available;

$$BD(\%) = \frac{C \times W - \sum_{i=1}^{N} t_i}{C \times W}; \quad (2)$$

- Smoothness Index (SI): is an index that becomes the relative refining index of a production line balance.

$$SI = \sqrt{\sum_{j=1}^{w} (T_{max} - T_j)^2} \quad (3)$$

where T_{max} is the maximum workstation time, and T_j is the time of the j_{th} workstations.

In the second stage, using the best solution found in the previous stage, the facility layout problem (FLP) was resolved using the Systematic Layout Planning (SLP) approach. The layout was evaluated using the standard KPIs related to production time - workers' movement time, workers' movement distance, and production lead time.

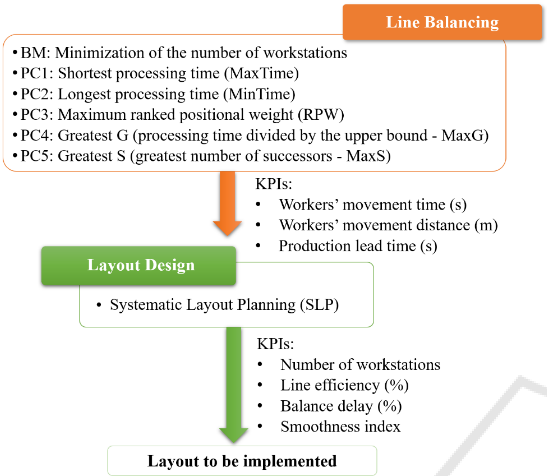

Figure 3: ICP layout design.

3.1 ICP Production Line Balancing Approach

This study deals with a SALBP-1 problem, that is related to allocation of tasks to workstations in a predefined cycle time, while minimizing the number of workstations needed. As presented in the Section 2.1, this problem deals with some features related to the tasks processing time, precedence relations and zone constraints.

Considering the product characteristics, the precedence diagram and all the constraints presented in the Section 2.1, an integer linear programming model was developed to solve the balancing problem of this production line.

3.1.1 Mathematical Model

The proposed integer linear programming model is a simple assembly line balancing model with parallel jobs and zone constraints. This model is based on the following assumptions:

- The line is dedicated to the production of a single product;
- According to the production volume and the time interval for production, there is a predefined cycle time;
- The product assembly follows a set of tasks, each with a predetermined execution time and with precedence rules between them;
- The tasks are processed at a set of workstations;
- A task can only be allocated to a single station;
- There are zone constraints, which are related to the compatibility and incompatibility of performing certain tasks in the same workstations;
- A workstation can be parallelized at most once, but only if the processing time of one of the tasks, assigned to that station, exceeds the predefined cycle time;

A possible line balance, i.e., an assignment of tasks to workstations, can be done according to different objectives, but the most common is to minimize the number of workstations for a given cycle time and simultaneously balancing the workloads between the workstations.

The following notations and variables are used for the proposed model:

Notations:

- N: Set of tasks, $i \in \{1,...,n\}$;
- W: Set of workstations, $j \in \{1,...,w\}$;
- P: Set of all immediate predecessors;
- *(pre, post)*: Pair of precedence relations among tasks, where task *pre* should immediately precede task *post*;
- t_i: Processing time of task i, in seconds;
- C: Cycle time, in seconds;
- AC: Assignment compatibility, set of tasks that must be assigned to the same workstation;
- *(tC1, tC2)*: Pair of compatibility relations among tasks;
- AI: Assignment incompatibility, set of tasks that cannot be assigned to the same workstation;
- *(tI1, tI2)*: Pair of incompatibility relations among tasks;
- $MaxDW$: Maximum number of stations duplication;
- M: Very high positive integer number.

Decision variables:

$$x_{ij} = \begin{cases} 1, \text{if the task i is assigned to workstation j} & i \in N, j \in W \\ 0, \text{ otherwise} \end{cases}$$

$$r_j = \begin{cases} 1, \text{if the workstation j is duplicated} & j \in W \\ 0, \text{ otherwise} \end{cases}$$

Considering all the assumptions, variables and data, the idea is to assign all the tasks to workstations, ensuring all the constraints, while minimizing the number of needed workstations. The mathematical model can be written as:

$$Min \sum_{j=1}^{W} j \times x_{nj} \tag{4}$$

subject to:

$$\sum_{j=1}^{W} x_{ij} = 1; \forall i \in N \tag{5}$$

$$\sum_{j=1}^{W} j \times x_{i.pre\,j} \leq \sum_{j=1}^{W} j \times x_{i.post\,j}; \forall i \in P \tag{6}$$

$$x_{i.tC1j} = x_{i.tC2j}; \forall i \in AC; \forall j \in W \tag{7}$$

$$x_{i.tI1j} + x_{i.tI2j} \leq 1; \forall i \in AI; \forall j \in W \tag{8}$$

$$\sum_{i=1}^{N} t_i \times x_{ij} \leq C \times (1 + r_j \times (MaxDW - 1)); \forall j \in W \tag{9}$$

$$r_j \leq \sum_{i=1, t_i > C}^{N} x_{ij}; \forall j \in W \tag{10}$$

$$M \times r_j \geq \sum_{i=1, t_i > C}^{N} x_{ij}; \forall j \in W \tag{11}$$

$$x_{ij} \in \{0, 1\}; \tag{12}$$

$$r_j \in \{0, 1\}; \tag{13}$$

The objective function given in Eq. (4) minimizes the number of workstations.

According to Eq. (5), each task must be assigned to only one workstation. Eq. (6) is associated with the operations precedence, and prevents that a successor task of task i, be assigned to a workstation before task i is processed. Eq. (7) and (8) are the zone constraints that define the sets of task pairs that must be allocated to the same workstation (compatible tasks) and task pairs that cannot be allocated to the same workstation (incompatible tasks). If there are tasks that must be performed at the same workstation, this is guaranteed by Eq. (7). Eq. (8) ensures just the opposite, that is, incompatible tasks are not assigned to the same workstation.

Eq. (9), (10) and (11) are constraints concerning parallel workstations: Eq. (9) ensures that the capacity of each station is not exceeded; Eq. (10) ensures that the predefined number of parallel workstations is not exceeded; and Eq. (11) ensures that only workstations with assigned tasks, whose processing time exceeds the cycle time, can be replicated.

Eq. (12) and (13) define the domain of the decision variables.

3.1.2 Different Criteria Approaches

In addition to this model, it was intended to test other approaches to the problem using the well-known preference criteria (PC) presented in section 1. Each of these PCs is a different way of assigning tasks to workstations, each corresponding to a typical heuristic of balancing problems. Considering five PC, five variants of the previous model (named Base model - BM) were created. For that, the following additional notations must be considered:

Additional Notation:

- S: is the set of all immediate successors;
- $RPW_i = t_i + \sum_{r \in S} t_r$: is the Ranked positional weight of task i;
- $G_i = \frac{t_i}{UB_i}$: is the Greatest of task i, defined by the processing time divided by the workstations upper bound $((UB_i = N + 1[\frac{t_i + \sum_{r \in S} t_r}{C}]^+)$;
- S_i: is the number of Successors of task i;

As mentioned before, it is important that the number of workstations is as small as possible, due to the existing workforce in the company. However, the fair distribution of work between the several workstations is also important. So, since minimizing the number of workstations (Eq. (4): $Min \sum_{j=1}^{W} jx_{nj}$) is one of the company's main priority and the main goal for the plant layout, the optimal solution obtained by the BM will be considered as an upper-bound for the number of workstations.

Each PC approach has an objective function that corresponds to the related preference criteria, which dictates what tasks are preferred when assigning to stations. As such, five more models were tested (PC1, PC2, PC3, PC4 and PC5), differing only in the objective function.

- PC1, tasks with shortest processing times are given priority:

$$\text{Min} \sum_{j=1}^{W} \sum_{i=1}^{N} t_i x_{ij} \tag{14}$$

- PC2, tasks with longest processing times are given priority:

$$\text{Max} \sum_{j=1}^{W} \sum_{i=1}^{N} t_i x_{ij} \tag{15}$$

- PC3, tasks with bigger RPW are given priority:

$$\text{Max} \sum_{j=1}^{W} \sum_{i=1}^{N} RPW_i x_{ij} \tag{16}$$

- PC4, tasks with bigger G are given priority:

$$\text{Max} \sum_{j=1}^{W} \sum_{i=1}^{N} G_i x_{ij} \tag{17}$$

- PC5, tasks with bigger S are given priority:

$$\text{Max} \sum_{j=1}^{W} \sum_{i=1}^{N} S_i x_{ij} \tag{18}$$

An upper-bound on the number of workstations is added to each model and settled to 8 workstations. The mathematical model (BM) and its variants (from PC1 to PC5) were implemented using the CPLEX Studio IDE 20.1.0. The six models were tested with different problems instances and the results related to the ICP production line are presented in Table 1.

Table 1: Models variants quantitative results.

Approach	No. of workstations	LE (%)	BD (%)	SI
BM	8	89,6	10,4	274,6
PC1	8	89,6	10,4	384,6
PC2	8	89,6	10,4	296,8
PC3	8	89,6	10,4	391,4
PC4	8	89,6	10,4	274,6
PC5	8	89,6	10,4	301,5

All the model variants achieved the optimal solution of 8 workstations, having also the same line efficiency and balance delay. One way to evaluate this solution is by comparing it with the theoretical minimum number of workstations. This value is computed according to the cycle time and the summation of the tasks processing time. The theoretical minimum number of workstations is 7 (workstations lower-bound). However, when computing this value, theoretically, it is not consider all the problem constraints. As this problem has a large set of constraints, the fact of obtaining 8 workstations with the models we can consider it a very good solution. So, it could be stated that in all the 6 approaches, the tasks are fairly divided by all the workstations, and the line efficiency is relatively good.

Table 2: Set of workstations resulting from the BM and PC4.

Workst.	Task No.	Workst. Proc. Time (s)	Resource required
1	1	600	CT1 w/ computer
	2		CT2 w/ platform 1
	11		CT6
	12		CT6 w/ platform 3
2 and 3	3	632	CT3 w/ supporting tool
	4		CT3 w/ supp. tool and wind. machine
	5		CT3 w/ supp. tool
	6		CT3 w/ supporting tool
	7		**CT4 (CT4.1)**
4	8	523	**CT4**
	9		**CT4**
	10		CT5 w/ platform 2
5	17	640	CT8
	18		CT9 w/ platform 4
	19		CT9 w/ platform 4
	20		CT9 w/ platform 4
6	13	710	**CT7 (CT7.1)**
	14		**CT7 (CT7.1)**
7	15	705	**CT7**
	16		**CT7**
	21		CT13; WR1; WR2; HP
8	22	720	CT10
	23		CT12 w/ platform 5
	24		CT11
	25		CT11

The minimum value of the smoothness index is 0 which indicates a perfect balance, i.e., a smaller smoothness index indicates a production line closer to a perfect balance. Therefore, by analysing the results, it was possible to conclude that the best solution is achieved when considering both the BM and the PC4 model, i.e., considering only the minimization of the number of workstations, and when the priority is given to the tasks with bigger G (processing time divided by the upper bound). Both approaches have the same solution related to the number of workstations, and these workstations also have the same assigned tasks (Table 2). For any of the models the processing times were quite short, always reaching the optimal solution in less than one minute.

In order to implement the solutions obtained by the BM and its variants (PC1 to PC5 models) on the shop floor, it turns out that, according to the task grouping, some resources (marked in bold in Table 2) must be duplicated. That is, there were tasks that need the same resources, but they were allocated to different workstations (Table 2). To solve this problem, a duplication of resources (CT4 and CT7) was carried out. Important to mention that this duplication did not incur in significant costs for the layout implementation.

3.2 ICP Layout Design Approach

As mentioned previously, the Facility Layout Problem was solved through the application of the Systematic Layout Planning method.

3.2.1 Systematic Layout Planning

As explained in Section 1, after some information collection, the SLP methodology can be divided into three major phases. In the first phase, occurs the analysis of production processes information. The layout design take place in the second phase, in which the information related to the needed resources and the production workflow are used to elaborate a relationship chart. In this study, it was also created a code that depicts the reason for the respective degree of proximity (Table 3).

Table 3: Numerical Code used in the ICP relationship chart.

Numerical Code	Reason
1	Resources used in the same task
2	Workflow within the same workstation
3	Workflow between workstations
4	Resources from the same workstation
5	Resources that cannot be close to each other for safety reasons

Figure 4 shows the relationship chart obtained for the ICP production line.

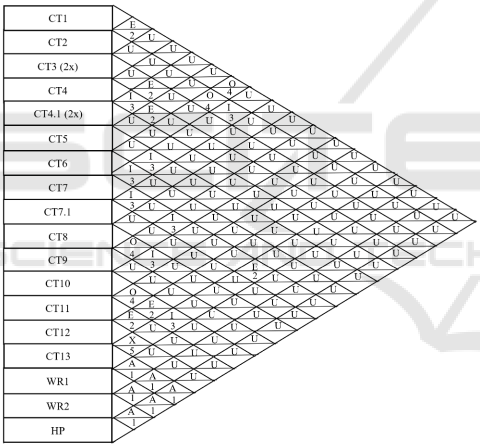

Figure 4: ICP relationship chart.

Through the analysis of this relationship chart, the relationship diagram was drawn (Figure 5). Considering this last one, the necessary resources and the available space, the layout options were elaborated.

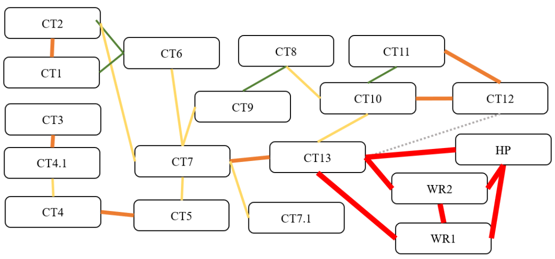

Figure 5: ICP relationship diagram.

In the third and last phase, the developed layouts options were evaluated and the most suitable one was chosen (Figure 6). The orange line represents the workflow into the same workstation, and the green line represents the workflow between workstations.

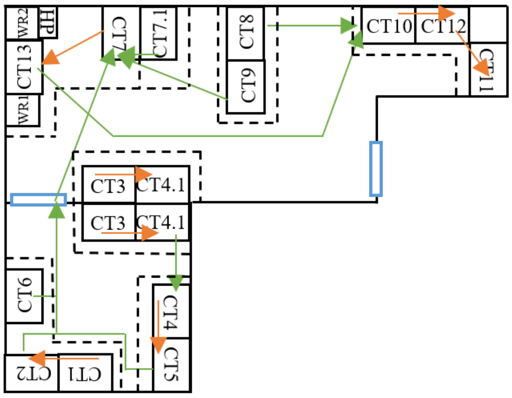

Figure 6: ICP production line layout resulting from the SLP approach.

The previously defined KPIs were measured for the obtained layout, being the results present in Table 4. Analyzing the KPIs, it is noticeable that the workers' movement time represents a small percentage of the production lead time, only 1,7%. This means that the workers' movement time can be considered insignificant in the production lead time, being the layout obtained evaluated as efficient.

Table 4: KPIs results from the SLP layout.

KPI	SLP
Workers' moving distance (m)	41,1
Workers' moving time (s)	88,3
Production lead time (s)	5079,2

3.3 Final Layout

Table 5 summarizes the KPIs obtained for the ICP production line layout.

Table 5: KPIs summary from the ICP production line layout.

KPI	SLP
No. of workstations	8
Line efficiency (%)	79
Balance delay (%)	21
Smoothness index	301,5
Workers' moving distance (m)	41,1
Workers' moving time (s)	88,3
Production lead time (s)	5079,2

Regarding the balancing KPIs, the results are considered satisfactory. The number of workstations obtained is very close to the theoretical minimum number of workstations, i.e., 7 workstations. This lower-bound calculation does not consider any constraint present in this problem (for example, zone restrictions and parallel workstations), having this in mind, we can consider that the number of stations obtained is quite satisfactory. The high efficiency of the production line is reflected into an uniform distribution of the workload among the workstations. This also means a decrease in the risk of bottlenecks occurring in production. Consequently, and as expected, the balance delay obtained is low, which implies a low idle time, caused by some not so good job assignments due to the problem constraints. The KPIs related to production time are also considered satisfactory, since the percentage of workers' movement time is insignificant compared to the production lead time. Therefore, the layout obtained can be considered efficient both in terms of resource/space optimization and line optimization.

4 CONCLUSIONS

A case study of a production line layout design was presented. The idea was to take advantage of the need to optimize the efficiency of an existing production line, by redesigning and studying a new production line. The methodology implemented was divided into two major steps: line balancing and layout design.

In the first step, an assembly line balancing problem was solved, using an integer linear programming model. Besides this BM, five variants, based on different preference criteria to assign task to workstations, were created. All the models variants achieved the optimal solution of 8 workstations, with an efficiency of 79% and balance delay of a 21%. Since the theoretical value of the number of workstations - lower bound is 7, and considering the existing constraints, it could be stated that the production line has a relatively good efficiency. Comparing the smoothness index, it was possible to conclude that the best solution was achieved when considering the BM and the PC4 variant model.

In the second step, the facility layout problem was solved by applying the SLP method. The final layout obtained was evaluated using KPIs related to production time. When the results were analysed, it was concluded that the KPI that was thought to be most important - the workers' movement time, only represented a small percentage of the production lead time (1,7%), which can be considered an insignificant percentage.

It is important to note that, with the new layout, the space is optimized and the production efficiency increases. However it is advisable that the company maintains a Lean culture and whenever possible the layout should be revised. Having this in mind, as future work, other layout design methodologies can be tested to see if further improvements can be made.

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