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Optimization of an Air Conditioning Pipes Production Line for the Automotive Industry—A Case Study

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Abstract: The following work aims to show how a combination of continuous improvement (CI) and Lean tools can reduce waste and process variability along an air-conditioned pipe production line (PL), calculate its capacity, and improve its efficiency to achieve the expected productivity. A variability study focused on the PL's balancing was conducted to identify and reduce possible bottlenecks, as well as to evaluate the line's real capacity. Several layout improvements were made to upgrade the line's operational conditions and reduce unnecessary movements from the workers. The Constant Work-In-Progress (CONWIP) methodology was also applied to ease the component's production management in the preparation stage. Additional modifications were implemented to support production and to contribute to the increases in efficiency, quality, and safety on the line. The results revealed an increase in the line's capacity, associated with an efficiency rise from 28.81% to 47.21% from February to June 2023. The overall equipment effectiveness (OEE) in the same period increased by 18%. This demonstrates that, by interactively applying a mix of tools and methodologies, it is possible to achieve better performance of production lines. This knowledge can help scholars and practitioners to apply the same set of tools to solve usual problems in cell and production lines with performance below expectations.

Keywords: lean; layouts; balancing; continuous improvement; CONWIP; efficiency; OEE

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1. Introduction

In a constantly evolving business context, organizations operate in increasingly complex environments, with the need to develop different and better-quality products, ensuring even more demanding temporal commitments [1]. Considering most business areas and industries throughout the world, the automotive sector represented an annual turnover equivalent to the sixth-largest economy in the world in 2020. In 2017, the employment directly related to this type of industry was estimated at approximately 14 million employees [2]. In 2022, just in Portugal, this industry was associated with about 350 companies and 63,000 direct jobs. Its economic significance is also of extreme relevance, since it represents about 5.4% of GDC (gross domestic product), with a business volume of 13.0 billion euros [3].

With a fierce competitive presence, the increased equipment availability is one of many crucial aspects to provide an efficient response from an organization to a customer, since "The competitiveness and demands of the automotive industry increasingly require improvements and the elimination of waste" [4] (p. 1417). For companies in this type of market, with production areas mostly organized in assembly lines, actions that will ultimately lead to the reduction of losses and waste levels in their processes will be valued.

Multiple case studies whose main purpose is to increase the efficiency and capacity of production lines, mostly in the sector at hand, often fulfill these requests by implementing

Lean philosophy and Lean tools, along with Kaizen [5–10]. Antoniolli et al. [5] explored the application of the standard work methodology, supported by Lean and Kaizen philosophy, in a production line of a company in the automotive sector. The main objectives were the standardization of operations and the elimination of wasteful activities through the implementation of CI (continuous improvement) actions, promoting increased productivity. Ultimately, the efficiency values usually translated by OEE (overall equipment efficiency) increased, on average, from 70% to 86% [5]. Azevedo et al. [6] also performed a study in the automotive industry based on a project associated with the installation of seven final production lines and seven pre-assembly lines, which were analyzed to assess how waste reduction could be achieved in the production scenario. It was concluded that eliminating unnecessary activities, along with the optimization of work, resulted in large savings, namely around 10.9% of the initial investment cost considered for the project or, in other words, EUR 2,159,000 [6]. Also, in the context of a CI operation of a company manufacturing electronic components for automobiles, the production lines were analyzed to reduce waste and variability through the application of lean production tools, which are implemented to decrease cycle times and balance the lines in question. In this firm, the results found were quite positive and were revealed through the reduction in occupied space of 22%, the reduction in the number of employees of 38%, and the increase in productivity of around 50%, which culminated in an increase in earnings of approximately 125,300 unit coins per year [7]. A study concerning the implementation of Lean techniques also revealed sustainable improvement achievement through Lean implementation at a leading automotive manufacturer, engaging managers and stakeholders, and other developing countries in the contribution of excellent techniques to achieving sustainable goals [9]. The common focus of all these studies was that Lean and CI tools were applied independently to improve the production line's performance cumulatively.

The study described below took place at a company whose business was oriented to the manufacturing of car air conditioning pipes for the automotive industry. The main objectives were to determine the production line's capacity, analyze the main bottlenecks within the process, and apply a combination of Lean and CI tools in an interactive way to optimize it, in favor of identifying and reducing the main sources of waste exposed during this analysis. The final goal would be to compare the OEE results before and after this work. There is a gap in terms of information regarding the concrete application of these tools in an industrial context, with only short studies being found in conference proceedings, which do not provide the necessary detail to understand the methodology and application of certain Lean tools in an industrial context, mainly in component production for the automotive industry. This work intends to provide a comprehensive analysis of the application of some Lean tools in an industrial context.

In total, this study consists of five sections. The introduction, presented in Section 1, contains the general framing of the work, providing a concise explanation of the automotive industry and the main objectives for this work. Section 2, Background, presents the theoretical principles used in the practical work through relevant concepts, like Lean philosophy, Kaizen, Heijunka, Kanban, CONWIP (Constant Work-In-Progress), and OEE, among others. The methodology is presented in Section 3, describing the methods and the main environment found in the company used to perform this work. Section 4 describes the main results achieved and dissects them, functioning as the core of this work, and analyzes the impact of the improvements according to those problems. Section 5, Discussion, provides an overview of the implementation performed. The conclusions and contributions of this study to the automotive industry are highlighted in Section 6.

2. Background

Lean Production and continuous improvement, also known as Kaizen, contribute to a culture of continuous learning and an environment that promotes change [11]. Moreover, Lean Thinking focuses on Muda (waste), eliminating activities that consume resources, but do not create value for an organization [12]. Eight types of waste exist in Lean systems:

transportation, inventory, motion, waiting, over-production, over-processing, defect, and knowledge disconnection [8,9]. CI and Lean tools, such as Just-In-Time (JIT), the Kanban method, Heijunka, and standardized processes, are usually used to solve industrial problems [13]. The definition of JIT is to keep a fast and continuous flow of material throughout the processes, ensuring that the part is in the right place at the right time. However, this concept may be proven unfounded in cases where it is necessary to stop the production flow to connect two distinct processes (e.g., a machine that manufactures in batches between carrying out setups). Under these circumstances, the use of "supermarkets" is a usual option. This consists of maintaining a pre-determined level of inventory to guarantee the continuous run of the process. The supply of the "supermarket" can be performed using the Kanban method [8,13]. Kanban means a card or sign. and the kanban method contributes to the management of stocks throughout the supply chain, providing information regarding the products' status in each process stage [14]. Through this method, instructions delivered by the customer activate the replenishment of the "supermarket" by replacing the material consumed [15]. Kanban can also be implemented to manage raw material levels [14].

Concepts such as Heijunka and standardized processes are essential for the successful application of the remaining techniques. Heijunka means leveling and, when properly applied, Heijunka prepares industries to face the demand about to be generated in the near future, having substantial positive results in terms of improvements in quality, productivity, and customer satisfaction [16]. Balancing the workload is also essential to determine the inventory level of "supermarkets", preventing the existence of process stops due to a lack of material. On the other hand, non-standardized processes will avoid attaining positive results when applying the just-in-time concept [13].

Assembly line balancing (ALB) consists of the decision process of assigning tasks to jobs in a balanced way, from the supply of raw materials to the manufacture of the final product. The main objective is to level the workload throughout the processes in a cell or value stream, to remove bottlenecks or excess capacity, and to obtain the most efficient balance of the capacities and flows of production processes [17]. For this technique, it is important to consider the connection between two main variables, the cycle time (CT) and the takt time (TT). While balancing the line, one must ensure the following conditions:

- The CT cannot be superior to the TT, since this means that, in the present work configuration, it is impossible to match the customer's demand;
- The CT should not be vastly inferior to the TT, since this represents time gaps and low resource occupation, causing waste for the organization [18].

Another relevant Lean tool, focused on a CI culture, is 6S (an evolved version of the 5S methodology), described as follows: Seiri (Sorting), Seiton (Set in Order), Seiso (Shine), Seiketsu (Standardize), Shitsuke (Sustain), and Safety [19,20].

Besides Kanban, there is also the implementation of another stock control system called Constant Work-In-Progress (CONWIP) [21]. Characterized by its flexibility, superior efficiency, and adaptability to scenarios with greater variability and differences between products, its purpose is to control or manage the total amount of work (WIP—Work-In-Progress) in a productive environment, keeping it constant. At the end of the line, the process releases the respective card, and it then becomes available for a new order [22].

Also, it is important to refer to one of the main metrics considered in mass production environments, the overall equipment effectiveness (OEE). The OEE can be obtained through Equation (1) [23].

$$\text{OEE}\ (\%) = \text{A}\ (\%) \times \text{E}\ (\%) \times \text{Q}\ (\%) \tag{1}$$

This indicator is represented by three different indexes: availability (A), efficiency (E), and quality (Q), accounted to consider breakdowns and setup pauses, short or long-term breakdowns, and scrap or rework-related breakdowns [24].

Based on the same production lines for tubes for vehicle air conditioning, Dias et al. [25] considered the weighted work content of four workstations and, applying line balancing and eliminating waste, managed to increase the OEE of the production line by 21%. Still taking into account the same product, Lopes et al. [26] essentially used Pareto's diagrams and Ishikawa's tool to identify existing quality problems in production lines, reducing the number of defective parts produced by around 12% and increasing productivity by around 11%. Reda and Dvivedi [27] used value stream mapping and plant layout in the first phase for waste identification, then applied Fuzzy QFD (quality function deployment) and FMEA (failure modes and effects analysis) to prioritize waste mitigation and determine the risk associated with the use of these Lean tools. Kumar et al. [28] successfully used the Laen Poka-Yoke tool to reduce quality problems in a ball dispenser. There have been other case studies on the application of Lean tools to improve quality and reduce the production/assembly time of components in the automotive industry, but none successfully used the tools intended to be used in this work, so the methodology used represents an innovative step in relation to the literature published to date.

3. Methodology

As mentioned, the objective of this work was to improve an air conditioning pipe production line for the automotive industry; hence, the research question is "How to improve the air conditioning pipe production line's OEE?". The used methodology was Action Research [29] and the methods applied were from Lean (Heijunka, Standardized Work, 5S) and CONWIP [5,7]. This study's methodology is explained in Figure 1.

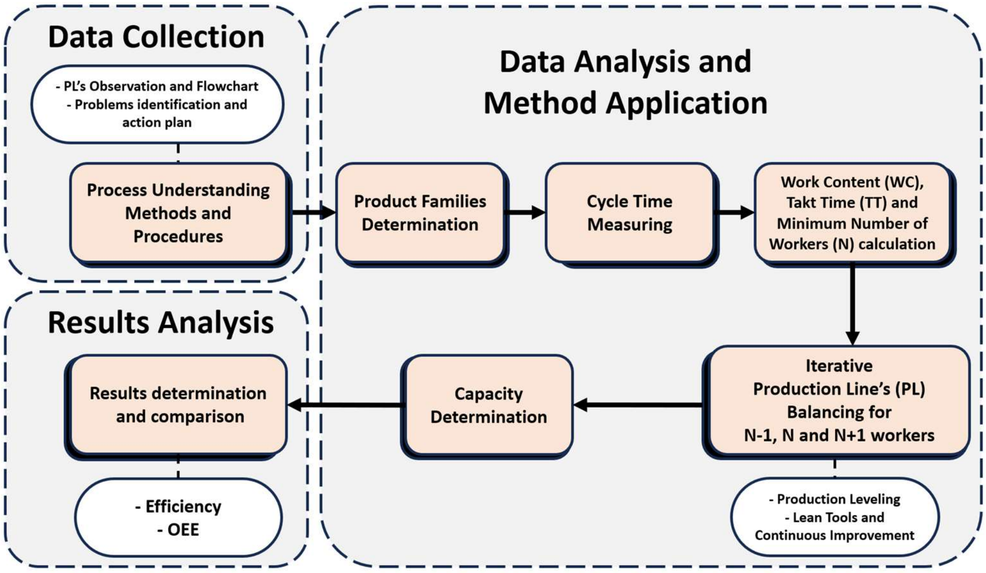


Figure 1. Research methodology.

Through Figure 1, it is possible to assume that this study's methodology consists of three main parts:

- Data collection, with deep observation of the manufacturing environment, accompanied by the mapping of the processes and material flows associated with the production line to better understand it and how it operates;
- Data analysis and method application, with the initiation of the variability study regarding this work's target, by analyzing the production line and determining the main problems and respective opportunities for improvement. The process started by measuring times, forming product families, and determining the processes' bottlenecks. The previously found opportunities were explored to balance and improve the efficiency of the line, along with its capacity. The PL's balancing was conducted. Later, layout improvements were implemented, along with CONWIP methodology, to ease the components' stage management. A second balancing stage was then undertaken, and the production capacity was determined;

- Results analysis, where the OEE was determined and evaluated throughout the study's course. It was also assessed whether the efficiency of the line had improved, along with its capacity, so that the production objectives could be achieved and the waste levels could be reduced.

The targeted production line used as a case study in this work had little and outdated information regarding its capacity and its production objectives. For this reason, the line worked with an undefined number of workers and shifts, according to the client's needs. On the other hand, the only data that were provided were that the global production objective defined for the line was 28 parts/h. This objective was allegedly defined according to the bottleneck of the line in the past.

Regarding the productive process itself, the production line was supported by several preparation areas, where the components are submitted to several operations until they are ready to enter the line. Passing that, these components are assembled and submitted to a different set of operations in the production line, until a completed part or reference is obtained. The running production system depends on the clients' orders, as a reference is only produced if a customer places an order for that product. This management is executed by internal software used by the company.

3.1. The Company's Approach: PL's Analysis

This work is in line with others previously performed based on production lines devoted to the production of air conditioning pipes for the automotive industry, using the same company to develop the case study [5,25,26]. In the initial stage, it was necessary to analyze the operations within the preparation areas and the assembly line.

In the preparation stage, the referenced process starts with two distinct operations. On one hand, the raw material warehouse receives the hose/pipe, which is subsequently cut at the pipe-cutting station, and then transported by logistic train to the lines. On the other hand, the aluminum tubes come directly from the supplier with the desired dimensions, and the lines are supplied through a Kanban system. The pipes will then be subjected to embedding and washing operations. Welding operations will be divided into flame and induction welding. The tubes can then be bent. Certain references will require the placement of foams, in which case the tubes will be transported to external suppliers. Some parts will also require hand soldering. Subsequently, a clogging test will also be performed. To detect larger leaks at an earlier stage of the process, some parts will also be tested in water cabins. Finally, the screwing operation starts, namely for the placement of the bolt and other similar components (the objective of which will be to facilitate the assembly of the parts in the vehicles). In the end, the products are transported to the finished products warehouse and shipped to the final consumer according to the orders.

In Figure 2, it is possible to observe the flowchart of the line's production process.

In the assembly line, according to Figure 2, it is possible to observe a different set of operations and component flows. Normally, there is a production of two references at the same time, depending on the occupation of the workstations.

3.2. Critical Approach: Opportunities for Improvement

After analyzing the production flow described in Figure 2, it was necessary to perform an up-close observation of the line functioning. Interviews with the workers were also conducted to more accurately understand the real problems that the line faced. Through the interactions with the workers and the team's involvement, with the practice of values such as improvement management, respect for people, and problem resolution, it was possible to identify a series of problems within the PL (production line). Significant results have been achieved before regarding the use of these types of practices, encouraging researchers to acknowledge the influence of Lean behavioral competencies during Lean adoption and their connection to organizational performance, since positive emerging human relationships are beneficial to process improvement and competencies development [30].

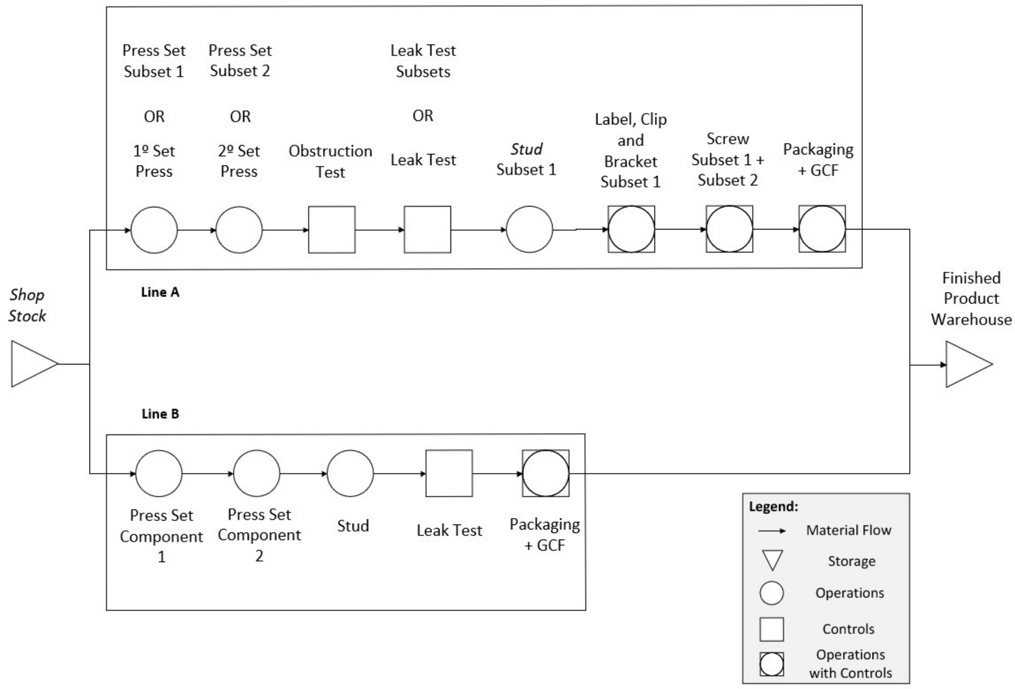


Figure 2. Flowchart of the line's production process.

Via a first-hand survey, it was possible to summarize the main problems identified in Table 1.

Table 1. Description of problems identified.

Problems	Description
Unbalanced line	Workstations were not balanced due to the large variability in the conceived products and the different production times between products.
Low efficiency	Low efficiency, since the line's efficiency is very low when compared with the remaining assembly lines in the company.
Unattainable demand	Failure to match the established objective with customer demand for some references.
Displacements	Long and unnecessary distances are covered between workstations.
Negligence before non-cyclical operations	Non-cyclical activities, such as line output, supply to the workstation, and displacements between stations were not considered when defining the initial objective.
Difficult management of the component's preparation stage	Difficulty in supervising the components' preparation stage before they enter the assembly line leads to increased difficulty in managing the assembly line.
Long bottleneck workstations	Excessively long bottleneck times in some workstations to produce several references.

After determining the main issues, we proceeded with the description of the main opportunities for improvement according to the enumerated issues described in the previous table. These opportunities are provided in Table 2.

Table 2. Problems and opportunities for improvement.

Problems	Opportunities for Improvement
Unbalanced line Low efficiency Unattainable demand Displacements Long bottleneck workstations	Variability study with the balancing of the production line. Processes improvement, favored by mechanical and documental improvements.
Negligence before non-cyclical operations	Layout changes to improve the production flows and efficiency of the line.
Difficult management of the component's preparation stage	Implementation of a CONWIP methodology to ease the component's preparation stage management.

Regarding the customer orders, it was possible to conclude that the production objective was around 862 parts per day. The variability study was then initiated to evaluate the true capacity of the line when compared with the initial situation. Following this, it would be possible to apply several improvements to eliminate all the wasteful activities and improve the line's condition.

3.3. Method Implementation: PL Improvement

The process started with the formation of reference families, considering the similarity of the processes and characteristics of each reference. As this line is associated with the production of many distinct references, it was necessary to prioritize which references to consider so that the process could take place with maximum efficiency. As such, a selection was performed to look for the set of references for which there were production orders scheduled for the upcoming months. Thus, nineteen basic references were selected.

The first step consisted of the analysis of some given information, that is, by understanding the production processes of the product references under study, using the analysis of the technical sheets and respective plans. Next, all the product references were analyzed and grouped into families. Thus, references with similar production processes and flows were joined in the same family. A description was also provided for each family, distinguishing each product family. Then, the proportion of production per family was determined according to the quantities of references that needed to be produced from each family. According to the weekly customer requests, it was possible to produce an average monthly production estimate, obtaining the results presented in Table 3.

It was then possible to highlight the three most produced references in the PL. The reference T.3 (Family 2) constituted the high runner of the line, making up approximately 40% of the line production. The reference T.15 (Family 10) corresponded to about 20% of the line production, and the references related to Family 3 were associated with about 10% of it. In a regular case, the line produces two parts at the same time, which results in the need to establish family combinations. However, this production is essentially managed according to the client's requests, and there is no optimal combination of families. Thus, according to the operations listed per product family, the incompatibility matrix presented in Figure 3 was developed.

A color scheme was used to differentiate the multiple combinations obtained, following the below-described pattern:

- Combinations highlighted in red correspond to the combinations considered impossible, since they require the overlapping of jobs between the references. For these cases, the calculation of the number of operators required was not considered;
- Combinations marked with green are related to possible combinations among the presented product families;
- Yellow combinations are associated with possible combinations. However, they are not ideal, so they are highlighted with a distinct color.

Table 3. PL's average monthly production.

Reference	Family	Monthly Medium Production (Parts)	Monthly Production Proportion (%)	Monthly Family Production Proportion (%)
T.1	1	580	4.65%	**6.99%**
T.2	1	293	2.35%	
T.3	2	4842	38.81%	**38.81%**
T.4	3	583	4.67%	**9.27%**
T.5	3	350	2.81%	
T.6	3	150	1.20%	
T.7	3	74	0.59%	
T.8	5	247	1.98%	**1.98%**
T.9	6	662	5.30%	**5.30%**
T.10	7	280	2.24%	**2.32%**
T.11	7	10	0.08%	
T.12	8	354	2.83%	**2.83%**
T.13	9	312	2.50%	**5.10%**
T.14	9	325	2.60%	
T.15	10	2451	19.65%	**19.65%**
T.16	11	342	2.74%	**2.74%**
T.17	12	20	0.16%	**0.16%**
T.18	13	319	2.56%	**2.56%**
T.19	14	285	2.28%	**2.28%**
Total		12,475	100.00%	

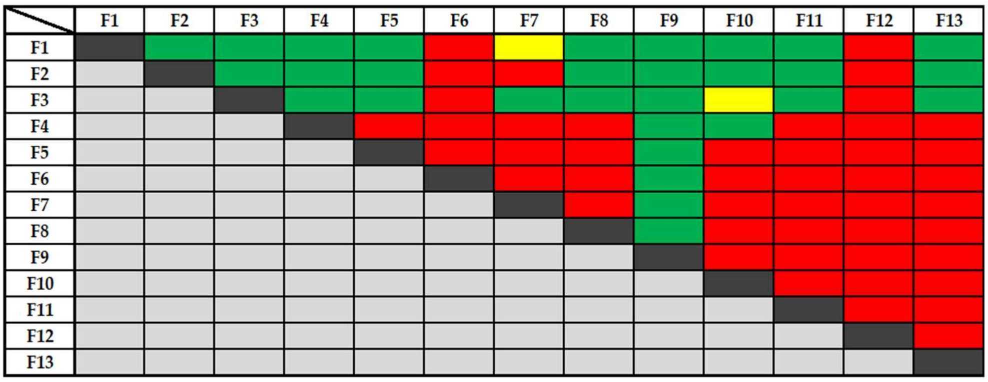


Figure 3. Incompatibilities matrix between families.

For the green and yellow combinations, the number of operators was calculated based on the minimum number of operators required to produce each reference, determined in advance. Some exceptions were considered according to the processes inherent to the production of each reference. Only workers assigned to the production line and not the preparation areas were considered to form family combinations. The main preparation area should be continuously working, with two permanent workers at their respective workstations. The remaining preparation areas also supply other lines, and the jobs are already defined, which is why they have not been included in this pre-analysis.

For the study carried out, the equipment availability required for each family was established and the combinations are presented in Table 4.

Table 4. Family combinations.

Combination	Family
A	F1 + F9
B	F2 + F8
C	F3
D	F10 + F4
E	F5
F	F6
G	F7
H	F11
I	F12
J	F13

Along with this, the monthly produced parts per combination were considered. According to the orders, approximately 680 parts should be produced daily. However, in this case, this production line's actual production levels were planned for around 900 parts/day to cover shortages and stock and support factory shutdowns during break periods (holidays). Therefore, an increase in orders of 45% was considered proportionally by reference, reaching an average production of around 862 parts/day, to represent the PL's operation more realistically and to correspond to the real production levels that the production unit was required to reach.

It is relevant to mention that, as other methods could have been used to determine the near-optimal family combinations, such as the use of metaheuristic algorithms, they were not applied in this study. The reason for this resides in the existence of multiple conditioning variables and specific cases within the family combinations that could hardly be formulated to fit a metaheuristics algorithm within the existing time frame. The study was limited to the 5 month internship and the data collection stage, due to the large volume of information, had already unexpectedly postponed the established target dates. The risk of causing further potential delays and holding up the data analysis and method application stage, ultimately harming the achievement of reliable results and their analysis over time, was real. Additionally, the application of the incompatibility matrix was favored by the company experts as an adequate tool to apply in a complex production line, such as the one presented in this work.

4. Results Analysis

4.1. Initial Case

In the initial situation, the existing production times were equivalent for all the references. They allegedly corresponded to the line's bottleneck (BN), with a production of 28 parts/h. All references assumed the same line BN. However, there were no reliable data to prove that this time was correct. Additionally, based on the operational flow attached to each reference, the differences between each of the products produced were noticeable, which is normally associated with very different work contents (WCs) between references. In this sense, it was imperative to measure times and balance the line to obtain reliable data regarding the PL's real capacity.

4.2. Improvement: Iteration 1

Considering family combinations and the monthly required production, it was possible to measure the CT and ultimately obtain the WC and the monthly production ratios presented in Table 5.

Table 5. Weighted Work Content calculation (Iteration 1).

Combination	Family	WC (s)	Ratio (%)
A	F1 + F9	173.30	26.63%
B	F2 + F8	177.05	43.90%
C	F3	545.88	9.27%
D	F10 + F4	260.60	4.72%
E	F5	467.70	5.30%
F	F6	607.40	2.33%
G	F7	398.40	2.84%
H	F11	338.80	0.16%
I	F12	558.36	2.56%
J	F13	383.00	2.29%

The weighted WC can be obtained through Equation (2):

$$\text{Weight WC} = \sum \text{WC}_{\text{i}} \times \text{Proportion}_{\text{i}} \quad (2)$$

The weighted WC obtained was 260.6 s.

Additionally, the TT was also determined considering the production of two references simultaneously and so there was twice the availability for calculation purposes. The number of shifts adopted was two, corresponding to an availability of 77.50 h of work per week, with a demand for 862 parts/day. Taking into account the data provided, it was possible to calculate the TT using Equation (3):

$$\text{TT} = \frac{\text{Week Availability} \times 3600 \times 2}{\text{Daily Demand} \times 5} \quad (3)$$

The TT obtained was 129.5 s.

N corresponds to the minimum number of stations necessary for the line's CT to be lower than TT. The value of N was obtained through Equation (4):

$$\text{N} = \frac{\text{Weighted WC}}{\text{TT}} \quad (4)$$

The value obtained for N was two operators. It is important to note that the minimum number of stations does not guarantee the greatest balancing efficiency. In this sense, based on the operations that constituted each combination, this number of operators was low enough to be able to satisfy the average demand for any reference with just two operators. It was therefore decided to design the production flow of each part between the various workstations and to determine the apparent number of operators necessary to carry out each reference. To determine the number of operators needed to produce each reference, a record of the operations required for each process was established, counting the number of operators needed to work at each station.

For each family, the occupation of each of the associated workstations by each operator was analyzed. Ultimately, the number of operators needed to manufacture each of the products was calculated, constituting the maximum number of individual positions that they could perform. Then, the incompatibilities matrix was used for family combinations. This matrix is presented in Figure 4.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1		3	4	4	4		5	4	2.5	2	4		4
F2	3		4	4	4			4	2.5	2.5	4		4
F3	4	4		5	5		6	5	3.5	3.5	5		5
F4	4	4	5						3.5	3.5			
F5	4	4	5	0					3.5				
F6	0	0	0	0	0				5				
F7	0	0	6	0	0	0			4.5				
F8	2.5	4	5	0	0	0	0		3.5				
F9	2.5	2.5	3.5	3.5	3.5	5	4.5	3.5					
F10	2	2.5	3.5	0	0	0	0	0	0				
F11	2.5	4	5	0	0	0	0	0	0	0			
F12	0	0	0	0	0	0	0	0	0	0	0		
F13	4	4	5	0	0	0	0	0	0	0	0	0	

Figure 4. Incompatibility matrix considering the workers required per family combination.

As can be seen from Figure 4, the maximum number of stations was considered to minimize transport and bottlenecks. For combinations of two families, namely the combination of A, B, and D, it was decided to follow the value N + 1 based on Figure 4, which was obtained for each family combination when carrying out the balancing, as described below:

- Combination A (F1 + F9) − N + 1 is equivalent to approximately 3, so balancing for N − 1, N, and N + 1 is equal to one, two, and three operators.
- Combination B (F2 + F8) − N + 1 is equivalent to 4, so balancing for N − 1, N, and N + 1 is equal to two, three, and four operators.
- Combination D (F4 + F10) − N + 1 is equivalent to approximately 4, so balancing for N − 1, N, and N + 1 is equal to two, three, and four operators.

The number of operators varied between two, three, four, and five for most of the workstations. Therefore, a balance for N − 1, N, and N + 1, with two, three, and four operators, respectively, was initially assumed to assess whether the presence of the fifth operator would be necessary. Subsequently, the measurement of the CT was performed according to the company's procedure, being the line balanced according to the minimum number of operators (N) and for N, N − 1, and N + 1 operators.

In Iteration 1, the CTs were analyzed for the work defined for two shifts, respectively, associated with 77.5 h of weekly work. From these data, a TT of 186.3 s was obtained, that is, a production rate corresponding to the manufacture of two parts every 129.5 s. Considering that the bottleneck for a large number of family combinations exceeded the value of the TT, it was possible to consider that the customer's needs could not be satisfied in this situation, not even with an N + 1 operator formation. In this sense, it was necessary to reduce the sources of wasted time and explore relevant opportunities for improvement. The assessment of the need to produce during three shifts instead of two shifts, to be able to produce the desired quantities, was also considered since adding the fifth operator was not plausible in some cases (as the number of operators would be greater than the number of posts).

4.3. Improvement: Iteration 2

In the second iteration, as mentioned, the line would operate in three shifts. As the workers allocated at each station were all experienced and already carried out operations in a standardized way, it was essential to implement improvements at workstations with more relevant waiting times or with an opportunity to be upgraded. These were both applied at the documental level, to simplify and improve the processes for the operators and other stakeholders involved in the production, and at the mechanical level, to contribute to better functioning of machines and equipment onsite. One of these changes consisted of the intervention of a bracket-closing machine used in Family Combination E. This is an assembly workstation where the tags are placed, and the brackets are closed within the aluminum pipes. The CT was 249.4 s to produce two parts. However, this workstation resulted in waiting times (wastes), and some major changes were applied and described in Table 6.

Table 6. Bracket-closing machine improvement.

Before Improvement	Improvement Action	After Improvement
The machine has automatic safety barriers that activate when it is working and deactivate in the activity moments of the operator	Place the tag printer in the exterior structure of the machine.	The worker can assemble the tags while the machine is working, without any interruption of the safety barriers.
Sequential process. The machine cycle starts with the tag printer, with the operator assembling the tags and the brackets, and verifying the part in the control gauge. The machine then starts the automatic closing of the pre-positioned brackets.	Divide the working process into two independent cycles for the tag assembly stage and the bracket closing stage. Implement a one-second waiting time between readings.	The tag assembly stage for the next two parts occurs simultaneously with the bracket closing stage, performed automatically by the machine. The demand of a one-second wait between readings allows the detection of the first and second tags (one per part).

These effective changes are presented in Figure 5.

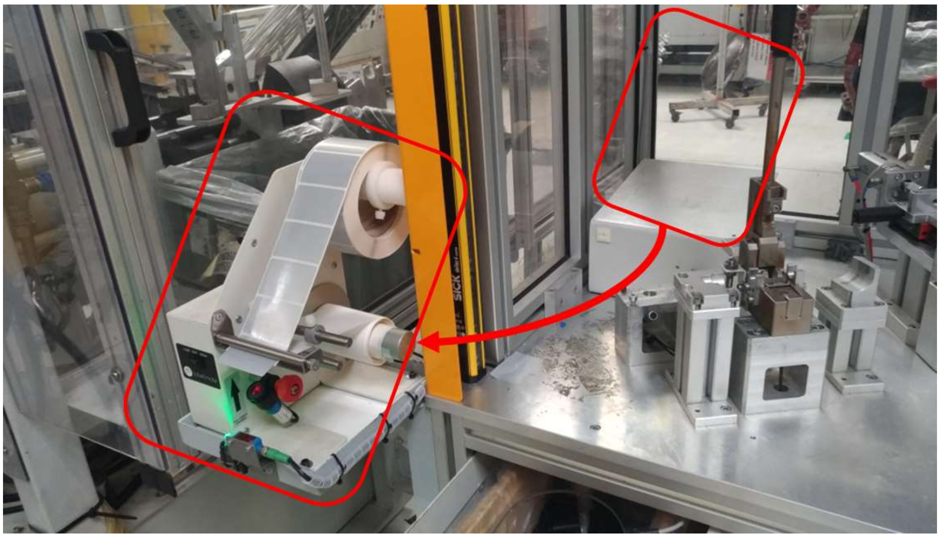


Figure 5. Bracket-closing machine improvement (before/after).

The outcome of this improvement reflected a 7% CT reduction from 249.4 s to 232.8 s, so it was possible to increase the process efficiency. On the other hand, regarding reference T.8 of Combination E, high scrap levels on the welding and bending stations (preparation stages) were noticeable, which represented high costs for the organization. The preparation process for T.8 is described as follows:

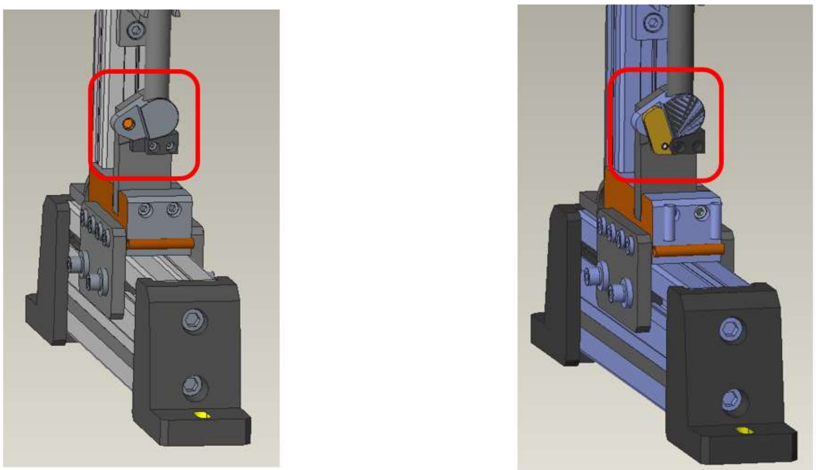
1. Embedding connection component on one end of the pipe;
2. Welding connection component on the other end of the pipe;
3. Crimping metallic sleeve loose on the pipe;
4. Bending pipe and pipe verification in the control gauge.

To reduce the scrap levels, the preparation process was deeply analyzed, and the main conclusions were compiled in Table 7:

Table 7. Main problems and improvement actions for T.8 preparation areas.

Problem	Improvement Action	Process	Action Type
Incorrectly bent parts	Readjustment of the pipe-holding system	Bending	Standard Restitution
Incorrect orientation of the connection component	Implementation of a holding system on the welding placer	Welding	Improvement
	Implementation of a control guidance pin on the crimping orientation tool	Crimping	Improvement

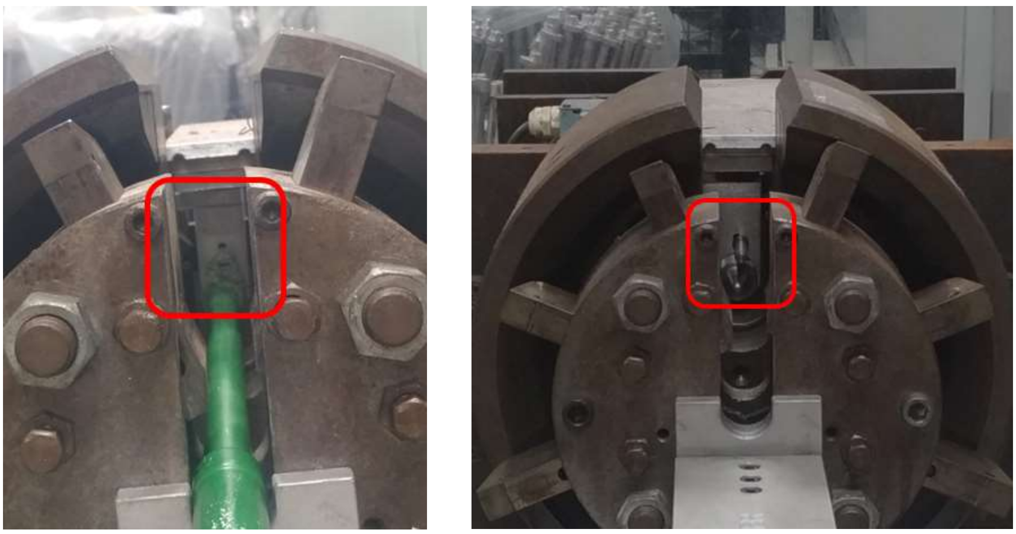
The addition of the holding system to the welding station is shown in Figure 6.



(**a**) (**b**)

Figure 6. Welding station improvement action with holding system implementation: (**a**) Welding tool before improvement action; (**b**) Welding tool after improvement action.

The guidance pin applied to ensure the orientation of the metal sleeve is shown in Figure 7.



(**a**) (**b**)

Figure 7. Crimping station improvement action with orientation pin implementation: (**a**) Crimping tool before improvement action; (**b**) Crimping tool after improvement action.

With these actions, it was possible to reduce the scrap levels and quality defects of poorly oriented aluminum sleeves, which stabilized at a regular level (referred to as welding and bending adjustment parts). Besides these, a large number of other improvements were applied, both concerning the assembly stage workstations and the preparation workstations. All these improvements are presented in Table 8.

Table 8. Comparison before and after additional improvement actions (PLs and preparation areas).

Before Improvement	Improvement Action	After Improvement
Leak test appliance openings were too tight, generating additional scrap and wasted time (with the difficult assembly process of the parts in the connectors).	Increase in leak test appliance openings.	Reduction in damaged parts and elimination of wasted time in a critical workstation.
Damaged control gauges and preparation workstations (welding tools and screwing machines, amongst others).	Readjustment and maintenance of damaged control gauges and other preparation tools.	Reduction in risks such as the verification of NOK parts and scrap production. Reduction in productive flow interruptions due to malfunctioning.
Difficult movement of heavy equipment.	Providing adapted equipment for transportation car and wheel assembly in selected machines.	Prevention of safety accidents or incidents. Improvement in the ergonomic condition of the workstations. Improvement in the production flow.
Misuse and incorrect setting of production tools, generating scrap, and time wasted in adjustments.	Elaboration and update of technical sheets, visual aids, and work instructions.	Easier setting process and reduction in defects and scrap.

After the improvement actions' application, the PL's balancing was re-performed. Considering family combos and the monthly required production, it was possible to measure the CT and ultimately obtain the work content (WC) and the monthly production ratio. These variables are presented in Table 9.

Table 9. Weighted work content calculation (Iteration 2).

Combination	Family	WC (s)	Ratio (%)
A	F1 + F9	173.30	26.63%
B	F2 + F8	177.05	43.90%
C	F3	545.88	9.27%
D	F10 + F4	260.60	4.72%
E	F5	451.10	5.30%
F	F6	607.40	2.33%
G	F7	398.40	2.84%
H	F11	338.80	0.16%
I	F12	558.36	2.56%
J	F13	383.00	2.29%

The weighed WC can be obtained using Equation (2), and the weighted WC obtained was equivalent to 259.8 s. On the other hand, the TT was also determined considering the production of two references simultaneously, with twice the availability for calculation purposes. The number of shifts adopted was two, corresponding to an availability of 77.50 h of work per week, with a demand for 862 parts/day. Taking into account the data provided, it is possible to once again calculate the TT using Equation (3). The TT obtained was equivalent to 186.3 s. N corresponds to the minimum number of stations necessary for the line's CT to be lower than the TT. The value of N was obtained through Equation (4). The value obtained for N was two operators. However, as mentioned during Iteration 1, the minimum number of stations does not guarantee greater balancing efficiency. Therefore, balancing will be carried out, keeping in line with what was previously mentioned.

After the improvements were applied, in Iteration 2, the line was rebalanced and the line's operation was also tested for three shifts, with 111.5 h of work per month, thus resulting in a TT of 186.3 s. It was found that the bottleneck was lower than the TT for at least one of the balances carried out for each combination of families, except for Combination F, where it was necessary to consider that the balancing for N + 1 would be equivalent to five workers. This indicates that the line would have to work three shifts to fulfill customer orders.

After performing the balancing of the line, it was concluded that there was a need to determine the actual capacity of the line, because TT was calculated based on the available working time and according to the number of daily parts to be reached. Since each combination of families was subjected to a different set of processes, with production times that also varies greatly among themselves, the comparison between CTs and a general production pace may prove unfounded. Thus, it was decided to analyze the capacity of the line, considering the CTs and the production of parts required by a combination of families, to the detriment of the response against a fixed number of 862 parts/day.

4.4. PL's Capacity

After carrying out balancing, the first analysis was performed for the line's capacity through a comparison between the monthly working time available to produce and the monthly working time spent producing orders. When analyzing the line's capacity, some considerations must also be taken into account, namely 90%, to obtain more plausible results taking into account the real factory environment. For comparative terms between the various iterations, the calculation of the results to produce one part per cycle will be considered. Capacity analysis begins by calculating the monthly working capacity of the line. It is therefore understood that they would work an average of 21 days per month and that, per day, after removing all breaks (time for breakfast, lunch, and cleaning the station), they would effectively work for 14.9 h in three shifts and 22.9 h in three shifts, which represents effective working times of 312.9 h per month and 480.9 h per month, respectively. The capacity of the PL operated at 90% efficiency, regarding the initial data, is presented in Table 10.

Table 10. Total production time consumed at 90% efficiency (Initial Case).

Efficiency		90%
Monthly Requests (Parts)	**Cycle Time (Seconds)**	**Production Time (Hours)**
18,102	257.2	1422.6
Total roduction time sum (hours)—2 parts per cycle		1422.6
Total production time sum (hours)—1 part per cycle		711.3

Based on this, it was determined that, if the line operated at 90% under the described circumstances, it would be unable to meet customers' orders, since it would take 711.3 h to produce all the required parts. In this sense, a comparison of the capacity of the production line between Iteration 1 and Iteration 2 was performed considering the operation of the line at an efficiency of 90%. For Iteration 1, according to the previously mentioned assumptions, for the combinations of two families, namely combinations A (F1 + F9), B (F2 + F8), and

D (F10 + F4), the value of N + 1 used was based on Table 9, and the same terms were used for comparative purposes. For Combination A (F1 + F9), N + 1 was equivalent to approximately three, so the capacity was calculated considering the balancing for N − 1, N, and N + 1 being equal to one, two, and three operators. The results are presented in Table 11.

Table 11. Production time consumed at 90% efficiency—Combination A (Iteration 1).

Combination	Family	References	Monthly Requests (Parts)	Cycle Time (Seconds)			Production Time (Hours)		
	Balancing for N − 1, N e N + 1 Workers			1	2	3	1	2	3
A	1	T.1	841.0	207.7	106.4	106.4	48.5	24.9	24.9
A	1	T.2	425.0	207.7	106.4	106.4	24.5	12.6	12.6
A	9	T.3	3554.0	207.7	106.4	106.4	205.0	105.0	105.0
Production time sum (hours)—2 parts per cycle							278.1	142.5	142.5
Production time sum (hours)—1 part per cycle							139.0	71.2	71.2

Regarding Combination B (F2 + F8), N + 1 was equal to four, so the balancing for N − 1, N, and N + 1 corresponded to two, three, and four operators. The same was the case for Combination D (F4 + F10), in which N + 1 was also equivalent to approximately four, meaning that the same balancing applied. For the remaining combinations, the number of operators varied between two, three, four, and five for most stations. In this sense, capacity analysis was carried out, assuming the balance for N − 1, N, and N + 1, for two, three, and four operators, respectively. The results are presented in Table 12.

Table 12. Production time consumed at 90% efficiency- Combinations B to J (Iteration 1).

Combination	Family	References	Monthly Requests (Parts)	Cycle Time (Seconds)			Production Time (Hours)		
	Balancing for N − 1, N e N + 1 workers			2	3	4	2	3	4
B	2	T.4	7021.0	114	88.6	73	222.3	172.8	142.4
B	8	T.5	453.0	114	88.6	73	14.3	11.1	9.2
B	8	T.6	472.0	114	88.6	73	14.9	11.6	9.6
D	4	T.7	359.0	155.3	102.2	102.2	15.5	10.2	10.2
D	10	T.8	496.0	155.3	102.2	102.2	21.4	14.1	14.1
E	5	T.9	960.0	277.6	277.6	277.6	74.0	74.0	74.0
F	6	T.10	406.0	419.1	304	210.5	47.3	34.3	23.7
F	6	T.11	15.0	419.1	304	210.5	1.7	1.3	0.9
G	7	T.12	514.0	249.7	223.7	141.9	35.7	31.9	20.3
C	3	T.13	846.0	317.8	269.9	177.6	74.7	63.4	41.7
C	3	T.14	508.0	317.8	269.9	177.6	44.8	38.1	25.1
C	3	T.15	218.0	317.8	269.9	177.6	19.2	16.3	10.8
C	3	T.16	108.0	317.8	269.9	177.6	9.5	8.1	5.3
H	11	T.17	29.0	249.7	172.7	158.2	2.0	1.4	1.3
I	12	T.18	463.0	406.1	263.1	197.6	52.2	33.8	25.4
J	13	T.19	414.0	243.1	199.1	148.1	28.0	22.9	17.0
Production time sum (hours)—2 parts per cycle							677.7	545.4	430.9
Production time sum (hours)—1 part per cycle							338.9	272.7	215.5

From Tables 11 and 12, it is possible to obtain the total production time consumed with the production of one part per cycle. The results are presented in Table 13.

Table 13. Total production time consumed at 90% efficiency (Iteration 1).

Production Time (Hours)			
Balancing for N − 1, N e N + 1 Workers	**N − 1**	**N**	**N + 1**
Production time sum (hours)—1 part per cycle	139.0	71.2	71.2
Production time sum (hours)—1 part per cycle	338.9	272.7	215.5
Total production time (hours)—1 part per cycle	477.9	343.9	286.7

For Iteration 2, after implementing several improvement actions, it was found that the bottleneck was inferior to the TT for at least one of the balances carried out for each combination of families for all combinations, except for Combination F. Hence, when determining the PL's capacity, for all the remaining combinations, the pre-mentioned balances would be maintained. Thus, for Combination A, the capacity continued to be calculated considering the balancing for N − 1, N, and N + 1 being equal to one, two, and three operators. The results are equivalent to the ones presented in Table 11.

For Combination B and Combination D, the capacity was calculated considering the balance for N − 1, N, and N + 1, for two, three, and four operators, respectively. The results are presented in Table 14 (now excluding Combination F from the results).

Table 14. Production time consumed at 90% efficiency—Combinations B to J excluding F (Iteration 2).

Combination	Family	References	Monthly Requests (Parts)	Cycle Time (Seconds)			Production Time (Hours)		
	Balancing for N − 1, N e N + 1 Workers			2	3	4	2	3	4
B	2	T.4	7021	114	88.6	73	222.3	172.8	142.4
B	8	T.5	453	114	88.6	73	14.3	11.1	9.2
B	8	T.6	472	114	88.6	73	14.9	11.6	9.6
D	4	T.7	359	155.3	102.2	102.2	15.5	10.2	10.2
D	10	T.8	496	155.3	102.2	102.2	21.4	14.1	14.1
E	5	T.9	960	277.6	277.6	277.6	71.8	69.2	48.2
G	7	T.12	514	249.7	223.7	141.9	35.7	31.9	20.3
C	3	T.13	846	317.8	269.9	177.6	74.7	63.4	41.7
C	3	T.14	508	317.8	269.9	177.6	44.8	38.1	25.1
C	3	T.15	218	317.8	269.9	177.6	19.2	16.3	10.8
C	3	T.16	108	317.8	269.9	177.6	9.5	8.1	5.3
H	11	T.17	29	249.7	172.7	158.2	2	1.4	1.3
I	12	T.18	463	406.1	263.1	197.6	52.2	33.8	25.4
J	13	T.19	414	243.1	199.1	148.1	28	22.9	17
Production time sum (hours)—2 parts per cycle							626.4	505	380.5
Production time sum (hours)—1 part per cycle							313.2	252.5	190.2

As mentioned, for Combination F, the balancing for N + 1 would now be equivalent to five workers, so the capacity was obtained considering that same condition. The results are shown in Table 15.

Table 15. Production time consumed at 90% efficiency—Combinations F (Iteration 2).

Combination	Family	References	Monthly Requests (Parts)	Cycle Time (Seconds)			Production Time (Hours)		
	Balancing for N − 1, N e N + 1 Workers			3	4	5	3	4	5
F	6	T.10	406.0	419.1	304	210.5	34.3	23.7	20.4
F	6	T.11	15.0	419.1	304	210.5	1.3	0.9	0.8
Production time sum (hours)—2 parts per cycle							35.6	24.6	21.2
Production time sum (hours)—1 part per cycle							17.8	12.3	10.6

Through Tables 11, 14 and 15, it was possible to obtain the total production time consumed with the production of one part per cycle. The results are presented in Table 16.

Table 16. Total production time consumed at 90% efficiency (Iteration 2).

Production Time (Hours)			
Balancing for N − 1, N e N + 1 Workers	N − 1	N	N + 1
Production time sum (hours)—1 part per cycle	139.0	71.2	71.2
Production time sum (hours)—1 part per cycle	313.2	252.5	190.2
Production time sum (hours)—1 part per cycle	17.8	12.3	10.6
Total production time (hours)—1 part per cycle	470.0	336.0	272.1

Taking into account the actual results presented in Tables 13 and 16, it was concluded that, with two working shifts, N + 1 operators would still be needed to fulfill customer requests, as usual. It also became possible to work in three shifts with N − 1 operators to satisfy demand. As was indicated at the beginning of this work and further validated throughout the variability study, it was confirmed that there were two significant causes for the PL's low efficiency, namely:

- Inadequate distribution of workstations or poor organization of the line's layout;
- Inefficient organization of work in the preparation phase before entering the PL.

These problems are addressed in detail within the next two topics.

CONWIP

As has been described throughout this work, the large number of products on the line and the variety of processes to which each of the references is submitted has jeopardized the efficiency of the line and, essentially, of the preparation stage. The preparation phase until the products can enter the line is extremely complex and variable, which causes stops on the line and the production of several references simultaneously, without any kind of balancing, to satisfy customer orders [31]. For this reason, it was decided to apply the CONWIP methodology to the preparation phase in order to control and know exactly at which stage of the preparation process the produced components are and when they will be available to enter the line. Likewise, a correlation was created between the preparation stage and the line, contributing to the mechanization of the production management process. For this purpose, a CONWIP board was developed, as presented in Figure 8.

Through Figure 8, the PL identification (Line A and Line B) was immediately established, along with the line references' identification. It is also possible to observe that some specific spaces were destined to contain the following items:

- Operations regarding the preparation stages (A);
- Informative document with production tracking (B);
- Informative document with the families of references divided by color, with a general description of each family (C):
- Informative document with a bill of materials (BOM) per reference for Line A (D) and Line B (E);

- Informative document with all components used for each reference (F).

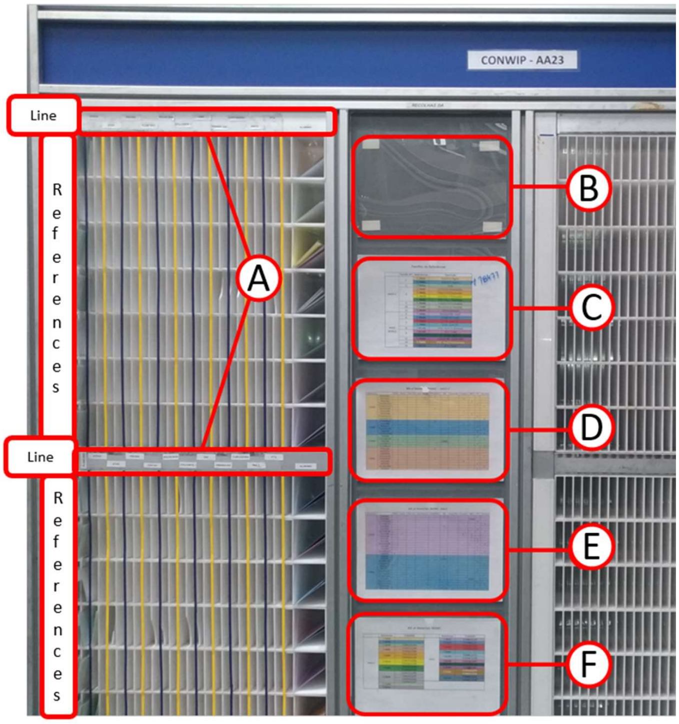


Figure 8. CONWIP board description.

Specific cards were also developed to determine which and how many components were produced at each preparation stage.

Main Preparation Area's Layout Improvement

The arrangement of workstations initially presented was considered one of the main sources of waste on the studied line, negatively contributing to the adequate production flow. In Figure A1, it is possible to observe the initial layout of the line with the preparation area and the assembly line. As noticed, in a regular situation, there was an accumulation of WIP in the center of the preparation area and assembly line, obstructing the passageway for materials or workers to the other end of the line (highlighted in red in Figure A1). The red arrows indicate the material input and finished product output areas at the end of the line. For that reason, a great waste of time was associated with the movement of material along the corridor outside the line due to the accumulation of material in the central corridor, as well as additional waiting times related to the stoppage of the stations for the packaging of material to release the material. In an attempt to ease the material flow within the line and minimize these issues, several layout and space management improvements were applied and are described in Table 17. The final layout is shown in Figure A2.

Table 17. Comparison before and after improvement actions for the PLs and preparation area layout.

Before Improvement	Improvement Action	After Improvement
Production flow improvement and WIP area liberation.	Removal of the gauge shelf of the preparation area and place it closer to the end of the assembly line.	Improvement in the production flow Reduction in the control gauges transport distance from the shelf to the final process workstations (A in Figure A2).
Low efficiency and organization of the preparation area.	Optimization of the preparation area's workstations by forming two independent production cells.	Improvement in the production flow Efficiency increases due to excellent worker usage and process optimization (B in Figure A2).

5. Discussion

As previously stated, the only data that were initially provided were the line's bottleneck, which was about 28 parts per hour, with the production of one part per cycle. Taking into account the information presented in Tables 13 and 16, and considering a monthly production of 18,102 parts, the results for the current situation, iteration 1, and iteration 2 (with the production of one part per cycle) were determined. They are presented in Figure 9.

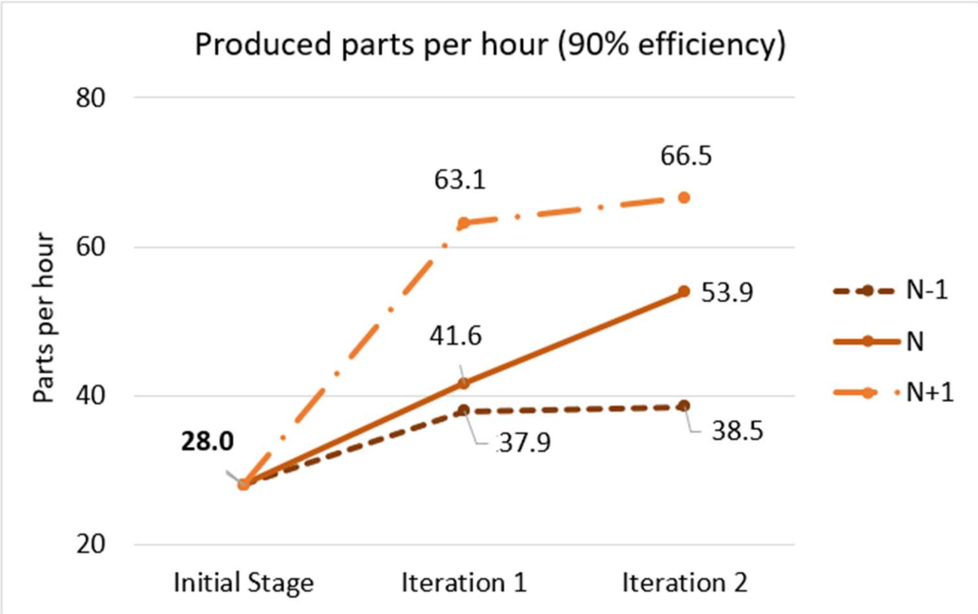


Figure 9. Produced parts per hour (90% efficiency).

Observing Figure 9, some essential findings can be settled:

- Considering that the line is working in two shifts, the objective production rate is 37.9 parts/h with N − 1 workers, 41.6 parts/h with N workers, and 63.1 parts/h with N + 1 workers;
- Considering that the line is working in three shifts, the objective production rate is 38.5 parts/h with N − 1 workers, 53.9 parts/h with N workers, and 66.5 parts/h with N + 1 workers.

The OEE was calculated in Table 18. The production line's OEE considered the availability, efficiency, and quality indexes provided and measured by the company's internal management system.

Table 18. PL's OEE calculation.

Months	Availability (%)	Efficiency (%)	Quality (%)	OEE (%)
February	98.5	28.8	99.5	28.2
March	99.6	38.8	99.8	38.6
April	99.2	44.2	99.9	43.8
May	98.8	44.5	99.5	43.8
June	98.0	47.2	99.8	46.2

From Table 18, it can be noticed that the efficiency index suffered the biggest variation in comparison with the availability and quality indexes, which remained relatively stable throughout the study. By February 2023, the OEE was approximately 28%. However, in June, before the industrialization actions on the production line (which contributed to additional stoppages, damaging the line's OEE), this indicator reached a value of 46%.

By interpreting the global results, it was possible to state that the best-case scenario was obtained in Iteration 2, considering the line working three shifts with N − 1 workers (objective production rate of 38.5 parts/h) or two shifts with N + 1 workers (objective production rate of 63.1 parts/h). The significant increase in the line's efficiency from 28.8% in February to 47.2% in June was also meaningful and directly contributed to an increase of approximately 18% in the OEE during the same period. Thus, it was possible to conclude that the actions implemented were beneficial and contributed to the optimization of the line.

The actions described in this work were directly related to the Lean tools applied and resulted in a significant improvement in the production flow in these production cells for tubes for car air conditioning systems. The improvement in the production flow was also in line with the current requirements to adapt production lines to Industry 4.0 concepts [32]. Usually, this approach to Industry 4.0 concepts is performed through small improvements in production lines or processes [33], allowing a gradual introduction of these concepts, but almost always supported by a simplification and linearization of processes, for which Lean tools are crucial [34]. Automation usually plays an important role in reducing production time and performing repetitive tasks that would be tedious for humans to perform countless times throughout their working journey [32]. The simplification of processes and their automation allow the introduction of sensors along production lines, which can send data to central information collection and decision-making systems, thus allowing an accurate notion of the production state at every moment, providing the possibility of acting more quickly if any unforeseen event arises [35]. Indeed, the collection of information is crucial for the implementation of Industry 4.0 concepts, as it is this information that allows rapid decision-making that can be extremely important for production management. The simplification of processes developed with the aid of Lean tools in this work is intended to be a first step so that the line can be completely automated in the near future and Industry 4.0 principles can be applied.

6. Conclusions

The work carried out consisted of applying CI and Lean tools to reduce waste and process variability within a selected PL subjected to the high diversity of products to be produced in order to determine the line's capacity and achieve the desired productivity levels. For this purpose, an analysis of the production line processes of a company manufacturing flexible tubes for air conditioning systems and the integrated application of continuous and Lean improvement tools was performed to determine and optimize its production capacity. This study started by carrying out the line variability study, beginning with the balancing of the line. Considering the afore-mentioned balances, the best results were obtained after Iteration 2. At the production/hour level, there was proportionally an overall increase in the objectives of the line from 28 parts/h to 63.1, 41.6, and 37.9 parts/h (for N + 1, N, and N − 1 workers), for Iteration 1 of the balancing, and later, for 66.5, 53.9, and 38.5 parts/h (for N + 1, N, and N − 1 operators), after balancing and applying improvements in Iteration 2. It was concluded that, for the operation of the line in three shifts with N − 1 operators or two shifts with N + 1 operators, the production objective would be 38.5 parts/h or 63.1 parts/h, respectively. Under these conditions, it was possible to achieve one of the initially considered objectives, as the line's capacity was determined, making it possible to ensure that the customer's requests would be attended to.

After carrying out the balance, multiple interventions were performed, namely in terms of layout and the ease of organizing the components before moving to the production line. For the layout, several changes were made to increase efficiency and process flow. Likewise, the implementation of the CONWIP methodology on the line made it easier to manage the production phases for the components before coming online. In addition, many other improvements were also performed, ranging from mechanical modifications to the equipment to the updating and implementation of technical documentation to support operators, namely through visual aids and work instructions. In this case, the proposed objectives were accomplished once again, since the multiple bottlenecks noticed during the study were analyzed and the main sources of waste were reduced by implementing a mix of CI and Lean tools. These improvements contributed beneficially to the increase in production, quality, and safety of the processes. In a general sense, the positive outcome resulting from the implemented improvements was notorious. The efficiency of the line increased from 28.81% to 47.21% in five months. This increase was also reflected in the OEE. With this, the final goal was achieved, allowing for the comparison of the OEE at the beginning and the end of the study, rising from 28% to 46% from February to June. Further into the projects and closing in on this study's conclusion, some additional data were provided regarding the subject at hand.

As a limitation to the development of this work, it needs to be mentioned that several process complications occurred during the industrialization stage. This led to further delays in the projects' planning and, to fulfill the client's requests, some of the PL's problems were not fully solved at the beginning of the project.

At a global level, it is possible to conclude that the initially established objectives were fulfilled, since it was possible to determine and increase the production line capacity through the application of several CI and Lean techniques, such as line balancing, 6S, CONWIP, and OEE, amongst others. Simultaneously, there was a gradual increase in the line's efficiency, as well as in the OEE, which indicates that the improvements had a positive effect. Even though it was possible to observe an OEE increase during the considered period, the PL's efficiency is still very low when compared to other lines. To further improve this line, it was necessary to continue to collect data on the production floor and apply several value iterations until a satisfactory result was found regarding this subject.

As a scientific contribution of this work, it is possible to observe that the implementation of just one Lean or improvement tool was not enough to achieve significant performance increases in production lines. Moreover, just one iteration could hide eventual better solutions toward the optimal solution. The problem here considered with production lines manufacturing several references of a given product and including different manufacturing processes is very common in many companies, mainly in the automotive and metalworking industries. Thus, it is expected that the approach described in this work can be of great importance to trigger similar works in other companies, reducing the resources allocated to the processes and contributing to more sustainable manufacturing processes.

During the development of this study, several limitations were considered regarding the adopted methodology and its further implementation. These were mainly noticed during the data collection and data analysis stages, since it was difficult to find the right method to analyze and display the mapping of the processes and material flows due to the high complexity of the line. Furthermore, the organization and exploratory analysis of the collected raw data were also demanding due to the time consumed during the gathering and analysis of the high volume of information gathered and the delays caused. These difficulties were ultimately surpassed owing to the support of the production team and growing knowledge of the production environment, which directly influenced the techniques applied throughout this work.

In future work, one of the possible improvements that could be carried out is to attempt to use a metaheuristic algorithm to identify the best combinations between families, which was not possible under the described circumstances. Another possible improvement concerning the OEE, as the company possesses the system required to support this activity, would be to apply Artificial Intelligence (AI) techniques to improve this metric. Several works are supportive of this concept's implementation success. By applying machine learning, for instance, it was possible to improve assembly performance by analyzing OEE indicator samples, patterns, and prediction functions and organizing and storing them in one structure named the assembly pattern catalogue (APC). By using this model, it became possible to predict assembly efficiency so that a more accurate and faster production and capacity planning could be achieved. Besides that, several charts and metrics were tested to demonstrate the practical usability of this system at an automotive company.

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Appendix A

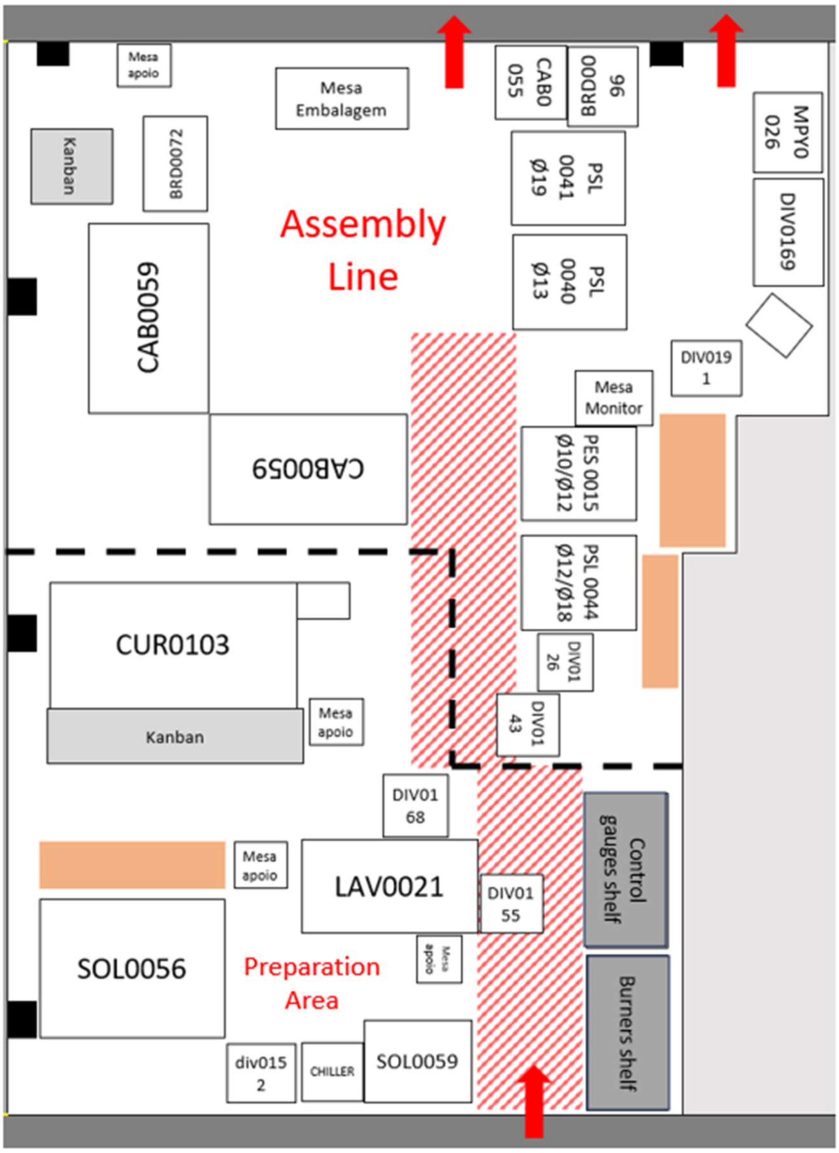

Figure A1. PL and main preparation area's layout before improvement.

Appendix B

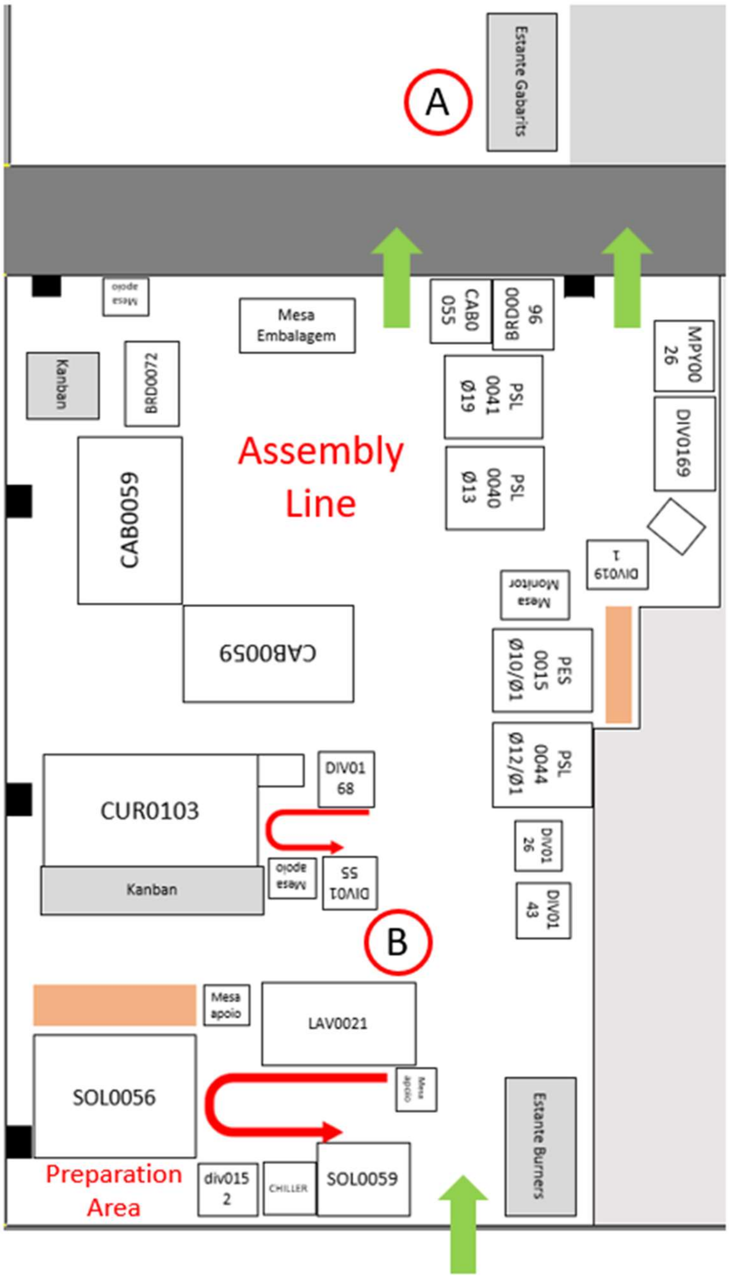

Figure A2. PL and main preparation area's layout after improvement.

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