



DMAIC implementation on catalytic converter production line: a case study

Maria Isabel da Silva

Thesis Submitted to the School of Technology and Management of the Polytechnic Institute of Bragança (Portugal) with the Technological Federal University of Paraná (Brazil) to Fulfil the Requirements for the Double Degree program to obtain the degree of
of
Master of Science in Industrial Engineering - Mechanical Engineering branch.

Supervised by:

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*"Nature never appeals to intelligence
until habit and instinct are useless.
There is no intelligence where there
is no need of change."*

*H.G. Wells, **The Time
Machine***

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Abstract

This thesis presents the application of the DMAIC methodology to improve the production process of a production line of catalytic converters in an automotive components company. This production line has been reporting non-compliance with customer demands within the normal working hours. The study was based on the five phases of the DMAIC methodology: Define, Measure, Analyze, Improve and Control. In the Define phase, the problem was identified and the characterization of the project specifications and its objectives was carried out. The Measure phase focused on representing the problem in a quantifiable way through measurements of the initial conditions of the line. The third phase involved analyzing the measured data in order to identify the main problem and assign its root causes. For the Improve phase, appropriate solutions were selected for each identified root cause. In the Control stage, a Gantt Chart was developed for the planning and implementation of improvements, documentation, training and monitoring and to validate the improvements that had already been implemented in terms of eliminating or reducing the problem.

The results of the project involve each tool applied at each stage of the DMAIC, but it is important to emphasize that it will support the company with the application of simple, fast and inexpensive solutions that acted on the elimination root causes of the problem.

Keywords: DMAIC; Production Improvement; Catalytic Converters.

Resumo

Título: Implementação do DMAIC em uma linha de produção de conversores catalíticos: um estudo de caso

Esta tese apresenta a aplicação da metodologia DMAIC para melhorar o processo produtivo de uma linha de produção de conversores catalíticos em uma companhia de componentes automotivos, que vem relatando não cumprimento das demandas do cliente dentro das horas normais de trabalho. O estudo foi baseado nas cinco fases da metodologia DMAIC: Definir, Medir, Analisar, Melhorar e Controlar. Na fase Definir, o problema foi identificado e a caracterização das especificações do projeto e seus objetivos foi realizado. A fase Medir, focou na representação do problema de maneira quantificável por meio de medições das condições iniciais da linha. A terceira fase envolveu a análise dos dados medidos de forma a identificar o problema principal e atribuir as suas causas raízes. Para a fase Melhorar, houve a seleção de soluções adequadas à cada causa raiz identificada. No estágio de Controle, foi desenvolvido um Gráfico de Gantt para o planejamento e implementação de melhorias, documentações, treinamentos e monitoramentos e as validar as melhorias que já haviam sido implemetadas em termos the eliminação ou redução do problema.

Os resultados do projeto envolvem cada ferramenta aplicada em cada estágio do DMAIC, mas é importante ressaltar que irá auxiliar positivamente a empresa com a aplicação de soluções simples, rápidas e pouco custosas que atuaram na eliminação das causas raíz do problema.

Palavras-chave DMAIC; Melhoria de Processos; Conversores Catalíticos.

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Acronyms

AGV Automated Guided Vehicles. 6, 7

CTQ Critical to Quality. 19

DMAIC Define - Measure - Analyze -Improve - Control. 2–4, 10, 11, 17, 19, 20, 22–25, 32, 34, 35, 37, 50, 71, 73, 75

FMEA Failure Mode and Effect Analysis. 20

HR Human Resources. 5

IT Information Technology. 5

SIPOC Supplier - Input - Process - Output - Customer. 23–25, 34, 35

TT Takt Time. 10, 21, 28, 29, 52, 53, 55, 70, 71, 74

VOC Voice of the Customer. 19

VSM Value Stream Mapping. 20

Chapter 1

Introduction

In this section, it is outlined the current situation of Catalytic Converters market, presenting its importance in terms of environment, production and economics. The objectives of the present thesis are also highlighted.

1.1 Catalytic Converter Market

The automotive industry has changed significantly due to the introduction of regulations that aimed reducing CO₂ emissions. The implementation of Regulation 2019/631 by European Parliament and by the Council of 17 April 2019, [1], has set new standards for CO₂ emission performance in new cars and vans. Consequently, this regulation, which came into effect in January 2020, resulted in a significant reduction of 12 % in the emissions when compared to the previous year. It also imposes penalties on manufacturers that exceed the permitted emission limits, encouraging compliance with the standards.

One of the benefits generated by this regulation is the increase of competitiveness in the automotive industry. The mobility and transportation sectors in Europe are completely committed to achieving climate neutrality and reducing the negative effects of industry on air pollution by producing the appropriate cars [2].

Catalytic converters play a crucial role in reducing emissions of carbon monoxide,

hydrocarbons, nitrogen oxides (NO_x), and particulate matter generated by internal combustion engines. These devices enable compliance with the emission requirements set by the regulations. Consequently, the demand for catalytic converters is expected to rise significantly in the coming years. By 2030, the global catalytic converter market is projected to reach a revenue of 76,7 billion USD, compared to approximately 49,25 billion USD in 2021 [3].

The catalytic converter industry is characterized by intense competition, with key players such as BASF SE, Tenneco Inc., Continental, Faurecia, Bosal, and Eberspächer. The increasing competitiveness and demand result in the need for improvement in production processes [4]. Consequently, a systematic approach, focused thinking, and active participation from all stakeholders within the company is essential. Implementing proper methodologies and tools can simplify the task of improvement, enabling companies to meet high-quality standards and deliver products on time.

One of the existing methodologies that has been widely utilized in the industry is Six Sigma. Acting as a performance improvement approach, it aims to identify and eliminate causes of defects, reduce cycle times and operational costs, enhance productivity, meet customer expectations, and improve the production process. At the core of Six Sigma lies the Define - Measure - Analyze -Improve - Control (DMAIC) (Define- Measure- Analyze- Improve- Control) problem-solving methodology, which integrates a range of tools, [4]. DMAIC provides a structured framework for performance improvement, helping organizations achieve their productivity, cost, and profitability goals, [4]–[6]. By implementing the DMAIC methodology in the production line of catalytic converters, manufacturers could achieve substantial improvements in quality, cost, and delivery performance. This, in turn, contributes to the overall growth and sustainability of the catalytic converter market.

1.1.1 Problem Definition

The production process of a catalytic converter is complex and involves several operators, components, tools and machines. Companies must be on schedule, uphold high standards of quality, and ensure operational effectiveness in order to succeed in this highly competitive market. To accomplish all of this, continuous improvement methodologies are highly recommended.

The present work is the result of an internship at a Portuguese automotive component manufacturer, from May 2022 to February 2023. The internship took place in the Productivity department, which is in charge of continuous improvement initiatives across all production lines. However, for this work, one of the most critical catalytic converter production lines at the company was approached.

The production line is currently facing difficulties in meeting customer demand, leading to the necessity of overtime shifts and weekend work. This problem presented itself as an opportunity to approach DMAIC methodology to enhance the production process. A systematic investigation of the root causes behind the failure to meet customer demand could be done, facilitating the development of effective solutions.

1.2 Objectives

1.2.1 General Objectives

The main goal of the present work is using the DMAIC methodology to improve a catalytic converters production line that is not reaching customer demand within normal working hours. This is going to be done by mainly measuring the times, and analyzing the work methods in order to identify problems, find the corresponding root causes, and address the best solutions.

1.2.2 Specific Objectives

In order to achieve the general objective, the specific ones must also be defined, which are the following:

- ▶ Defining specifically the process that is going to be studied through a Project Charter and SIPOC (Supplier, Input, Process, Output, Customer);
- ▶ Measuring the initial conditions of the line, throughout time studies and Work Methods Analysis;
- ▶ Analysing the measurement and defining the root causes of the problems found in the initial state;
- ▶ Suggesting adequate improvements to the addressed root causes;
- ▶ Create a Control Chart to schedule improvements;

1.3 Thesis Structure

The present thesis is divided into 6 chapters: Chapter 2 presented an overview of the company and the catalytic converter production line under study, in order to give the necessary information to the understanding of the case study; In Chapter 3, the review of the literature concerning the main topics approached on the present work was made; In Chapter 4, the DMAIC methodology adopted to perform the improvement of the production line was exposed; Chapter 5 described the results that the application of the previous-explained methodology generated; Chapter 6 described the conclusions and suggestions for future work.

Chapter 2

Case study

This chapter exposes a brief description of the company and the characterization of the production line under study in its initial state.

2.1 The company

The case study involves an automotive part manufacturing company that produces catalytic converters and other components, such as bent pipes, and mufflers. It contains 8 departments: Logistics, Productivity, Quality, Supplier Quality, Human Resources (HR), Engineering, Security, and Information Technology (IT). This company houses approximately 50 production lines. Each production line can be classified according to the type of product, such as:

- ▶ **Final assembly lines:** Catalytic converters or mufflers that are prepared to be shipped to the final customer are the final parts of those production lines. Those are characterized by having many tasks being performed by multiple machines and by several operators;
- ▶ **Semi-finished goods' production lines:** Small production lines of one or two operators, in charge of the task in a single machine, typically a press or a bender. These lines produce semi-finished goods. Those, are the components for the final

assembly line. For instance, the production of catalytic converter - final part - requires a bent pipe - semi-finished good.

In Figure 2.1, it is represented as 2 Semi-finished goods production lines. The semi-finished goods produced are taken by a forklift and an Automated Guided Vehicles (AGV) to a Final Assembly production line. In which, those semi-finished goods compose the final part. Then, the final parts are put in containers by an operator, and in turn, they are taken to a Truck Area by an AGV. Finally, those trucks are supplied with these final parts and sent to the final customer.

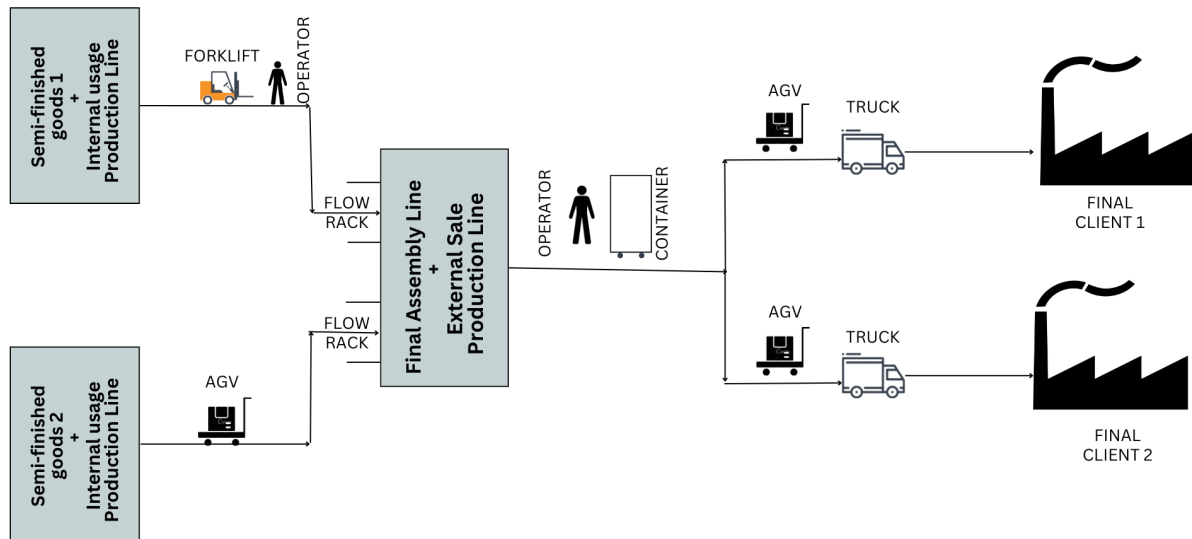


Figure 2.1: Scheme with Semi-finished goods and Final assembly lines

Furthermore, another important topic to highlight is that the company uses a pull system, which means the customer request triggers the production activity. As the logistical flow is increased in relation to the flow of information and materials, the needless stock is decreased. So the products are produced in a planned way according to the customer demands. Figure 2.2, built using Microsoft Visio[®], summarizes the functioning of the pull system. It can be seen by this figure that, the customer demand triggers the flow

of material for the semi-finished good production line, consequently triggering the final assembly production line. The product is then sent to the final customer, which creates a new demand, which is made every 6 weeks.

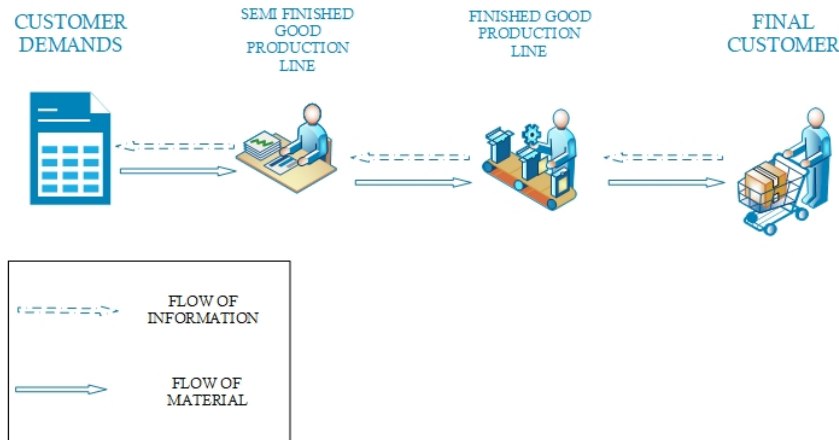


Figure 2.2: Scheme summarizing the pull system

2.2 Catalytic converter production line

This section will present an overview of the catalytic converter production process.

2.2.1 General Information

The production line under study is a Final Assembly, in which catalyst converters are produced and taken to the final external customer. It contains several components, some of which are produced in the company itself in the Semi-finished goods production lines, while the others come from external suppliers. In both cases, the Logistics department supplies those components to the production lines throughout AGVs or through operators' driven forklifts. When the components arrive in the production line, they are placed in supply ramps inside or outside the machines. Figure 2.3 represents an example of a supply ramp outside the machine, which contains boxes of components.

The final part of this Final Assembly line is a catalytic converter, which is responsible for the transformation of hazardous engine exhaust particles such as carbon monoxide and



Figure 2.3: Supply ramp containing box of components

nitrogen into less hazardous ones such as vapor and carbon dioxide, through a chemical reaction. After understanding the general context of the production line, it is important to know a description of the production process.

2.2.2 Detailed description of the actual process

The catalytic converter production line has 5 operators that are distributed along the line. Figure 2.4 represents a scheme of the machine distribution and the simplified production flow of the line. Each of the machine has a different function that altogether composes the catalytic converter's final assembly.

There are 6 Welding machines, responsible for the assembling of the smaller components through weld beads. The assembly process through welding starts on Welding Machine 1 and ends on Welding Machine 6. It results in a larger part that takes shape throughout the production process. Afterwards, the assembled part undergoes the Leak Test 1, which verifies the existence of any pores or cracks in the weld beads. In the patch

positioning table, the patches are fitted and later fixed to the part by the Crimping Machine, which also fixes the upper and lower thermal plates. These plates enable to avoid constant heat exchanges when the exhaust system is in operation in a vehicle. Afterwards, as soon as the part leaves the Crimping Machine it is taken to the Pressure Pipes table, where they are attached to the part.

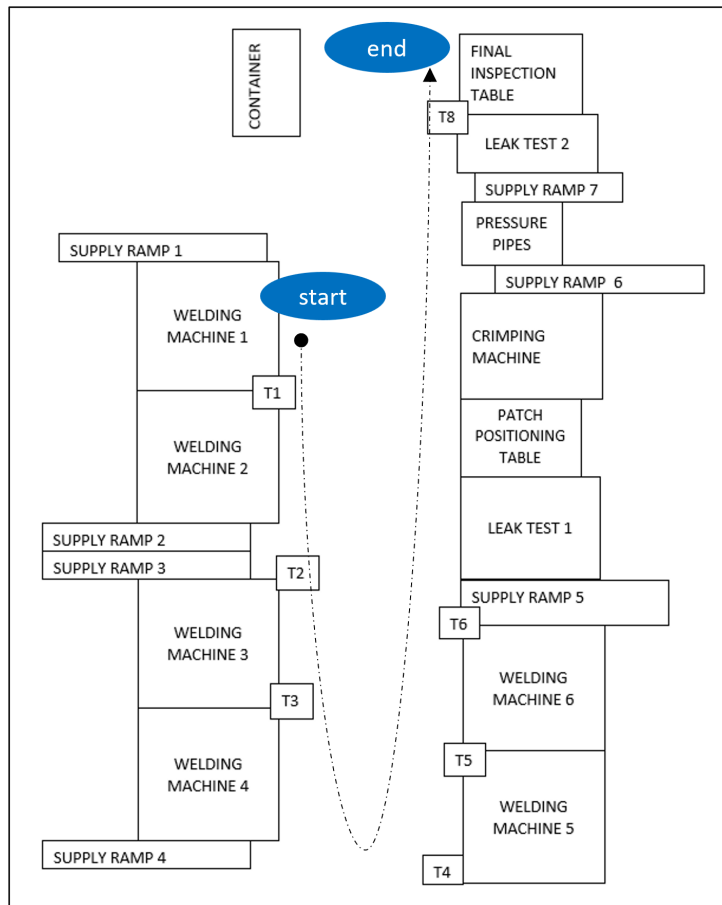


Figure 2.4: Simplified scheme representing the machine distribution and flow of production of the catalytic converter production line

After attaching the thermal plates, patches, and pressure pipes, the Leak Test 2 is carried out, in order to check the integrity of the components. This process completes the assembling and testing of the part. Thus, it goes to the Final Inspection Table. There, there is a quality check of the control points that are specified according to the customer's demand, which is circled with a pen so that there is proof that those points

were indeed checked. The part can now be placed in a container that receives 36 parts and subsequently is changed to an empty one by the logistics department.

Furthermore, the main goal of the catalytic converter production line is to meet customer demand on time, producing quality final parts, not exceeding Takt Time (TT), and in accordance with the work standards.

The company uses two main documents for the definition of Work Standards, which are the following:

- ▶ **Cycle time measurement sheets:** which expose the time each operator takes to perform his task.
- ▶ **Operator flow diagram:** This document shows the task performed by each operator represented by a set of arrows that show from the first to the last step and which machines they pass through.

Currently, the production line does not have updated work standards. This could lead to inefficiencies in the production process and consequently have a negative impact on customer satisfaction. It could also contribute to operator confusion and errors, leading to further delays and disruptions in the production line. In addition to that, the production line under study is unable to meet customer demand within regular working hours, resulting in the need for overtime shifts and weekend work. To solve these problems, the DMAIC methodology was approached. This methodology, in the present work, aimed to analyze the root causes contributing to the problem-solving, identify areas of improvement, and implement effective solutions.

Chapter 3

State of Art

This chapter aims to provide an overview of the work standards and the DMAIC methodology. First, the Work Methods Analysis and the Work Measurement concepts were introduced, as well as some methods to define them. Afterward, DMAIC was explained by the presentation of concepts and tools involved in each one of its stages.

3.1 Work Standards

Work Standards have the purpose of capturing the maximum result of human effort in industrial environments, avoiding uncertainty and waste [7]. The definition of work standards provides crucial information for the proper functioning of the production process in organizations [8]. From them, it is possible to establish achievable and objective goals and to identify possible problems in the production process. Once they are known, any obstacle impeding the process becomes more apparent.

The work standards must be developed from the best examples of the task to be standardized and cannot include extra movements or allow for deviations. According to [9], those deviations can cause serious productivity problems and long production cycles. Thus, the development of work standards must be based on a trained worker performing his task at a regular speed and under normal circumstances. Additionally, it is crucial to visually represent the work standards to facilitate task execution for operators. By

providing clear visual guidelines, operators can effectively perform one or more tasks within the production lines [10].

Furthermore, the creation of work standards based on best practices enables operators to absorb knowledge and continuously improve their work. On the other hand, if operators develop their own working methods without standardized guidelines, valuable knowledge remains isolated and may be lost if they change roles or leave the company [8], [11]. Thus, implementing work standards not only ensures consistency and efficiency but also facilitates knowledge transfer and long-term organizational development.

Work standards also give valuable information for analyzing and measure data of a production line, as it answers some important questions, [8]: what is being produced? What methods are used to guarantee quality, efficiency, and safety? How many operators are needed? How long it takes to perform each task for each operator?

Work methods analysis, within work standards, [12], focus on how a task should be performed. This part is important since, by understanding how a task is done, security, quality, and performance issues are avoided. Hence, accidents could be prevented, as they configure settings in the workplace and describe the necessary tools for the successful performance of a given task [13]. Additionally, complementing the information inside work standards, there are the work measurements. They indicate how much time it should take to complete a task, [14]. This part is important since time is an input for capacity planning, estimating labor costs, and budgeting.

3.1.1 Work Methods Analysis

Work Methods Analysis focuses on determining *how* a production process is carried out, [8], [12], [14], [15]. The work methods must be analyzed when, [8], new practices are adopted or certain tools, products, or equipment in a production process are modified, [12]. If there are any problems with quality and safety, this analysis could be essential to understand what should be changed in the method currently adopted.

There are several tools used to perform the work methods analysis, [12], [14]. One or

more of those tools could be used according to the production process under study, [12], [15]. Table 3.1 represents a summary of those tools. The flow diagram and process chart are mainly used to represent the operator's motion. They are visual representations used to analyze the movement of people or materials [12].

Activity and Operations charts are used for the identification of inefficiencies in the production process. Activity charts focus on studying the use of operators and machines while recording the method through direct observation. On the other hand, operations charts analyze body movement and aim to show the economy of motion by identifying wasted motion and idle time [12].

In [15], a combination of process chart, flow chart and activity chart is made, each one with a specific goal within the work method analysis. A Value Stream Mapping to analyze a pull system company is used in [16], and a Spaghetti Diagram to understand the movements in the sector of raw material storage is used by [17]. In [18], an operations chart was used with the aim of identifying each movement in more detail in order to eliminate waste.

Tool	Main Function
Flow diagram	People and Material Movement [12], [14], [15]
Process chart	Sequence of steps for a process, [14], [15]
Activity chart	Representation of a combination of the machine - operator [14], [18]
Operations chart	Representation of specific body motion [12]
Worker-machine chart	Portions of a work when an operator is idle or busy [14]
Value Stream Mapping	Specifics in the production process, such as the movement of materials and information up to the customer [16]
Spaghetti Diagram	Routes, timing, and plant floor movement flows [17]

Table 3.1: Summary of Tools in Work Methods Analysis

3.1.2 Work Measurements

Work measurements involve the estimation of *how long* it should take to complete a task, [8], [12], [14], [19]. It also involves the calculation of standard time performed by operators,

working under typical conditions.

The standard time can be set in four ways. One of the most simple and affordable ways is based on historical data and prior experience. It can also be set through time studies, requiring measuring and observing the times of the operators continuously performing their tasks [12]. Additionally, the standard time could also be set by predetermined time standards, by specifying a sequence of human motions that represent a task, an estimate of the standard time for performance can be determined [14]. Work Sampling is also a way of setting standard time by making brief observations of the operator or machine at random intervals and observing the task's nature [14].

The most used method to obtain the standard time is through Time Studies [8], by using a sequence of the following 8 steps:

1. Definition of the task that will be studied;
2. Division of the task into precise elements, called Measurement Points (MP), to facilitate their visualization for each operator;
3. Definition of sample size, the number of time observations (n) to measure the task;
4. Recording the time between the start and end point for each MP meanwhile observing the performance rating of each operator
5. Calculation of the average observed time for each MP.
6. Determination of the Performance rating (r) based on what was observed on step 4. Calculation of Normal Time (NT) by multiplying the performance rating with the average observed time.
7. Calculation of the sum of NT for each operator.
8. Calculation of standard time considering the Allowance Factor (a), which provides an adjustment to the total normal time for personal needs, unavoidable work delays, and worker fatigue.

In the 8-step sequence of standard time obtaining, sample size definition is a crucial step, once it ensures reliable data measurement [12], [20], [21]. Reliability is related to the consistency, reproducibility, and repeatability of the data measured. Reproducibility refers to obtaining similar results when different individuals use the same methods for measurement. On the other hand, Repeatability refers to obtaining similar results when the same measurement is repeated by the same individuals under the same conditions.

Thus, it was found two different ways of defining the sample size: conventional guides and statistical methods. According to [8], [20], [22], the conventional guide is normally used by some companies to estimate the sample size, and it is based on the total number of minutes per cycle to perform the task for which the time is being measured. The Table 3.2 summarizes this relationship [8].

Minutes per cycle (min)	0,10	0,25	0,50	0,75	1,0	2,0	5,0	10,0	20,0	40,0
Number of cycles recommended	200	100	60	40	30	20	10	8	5	3

Source: adapted from Kanawaty (1992)

Table 3.2: Number of recommended cycles for time study

In addition, there is the statistical method, which is one of the most reliable ways to define the sample size [8], [12]. This method starts by taking into consideration a preliminary sample size k , the mean and the standard deviation of the k time observations collected on the production line, the accuracy, and the level of confidence [23]. Next, it will calculate a new sample size of n . If n is bigger than k , another iteration is needed. On the other hand, if n is smaller or equal to k , the stoppage condition is reached, and the sample size k can be used. Another important point that needs to be taken into consideration, using the statistical method to define the sample size, is the variation between the elements of the tasks, once it will be required a larger sample if there is a significant variation [12], [14].

One of the key drawbacks of the statistical method is the sensitivity to subjectivity in the time observations collected since it depends on the operator speed, the observer who is timing the task, and the state of the workstation during the collection of time observations. A significant action in order to avoid this drawback is to take observations

of the task continuously [8], [24].

Furthermore, another step to highlight, regarding the standard time calculation are step 4 and 6, involving performance rating. This concept can be used to identify areas where workers may be struggling with their performance. It refers to the measurement of how efficiently the operators complete their tasks, and it can be defined by the operator's pace [22], [25].

Typically, the performance rating is expressed as a percentage of the standard time allowed for the task. With the expected or standard level of performance being 100%, the values could be bigger than it, meaning that the qualified operator is performing the task at a higher-than-the-standard pace. For an unqualified operator, however, the performance rating may be lower than 100% because they may take longer to complete the task due to their lack of experience or skill [12]. It is also important to highlight that the cooperation of the operators and their motivation inside the company may also influence in the performance rating values [25].

Another step to highlight in the standard time obtaining is the eighth step, which involves the allowance factor evaluation. This factor represents an adjustment that incorporates personal, fatigue, and unavoidable delays allowances into the total normal time, calculated in the seventh step, [8], [12]. Those allowances can be described as:

- ▶ **Personal Allowances:** Time allocated to an operator for rest and other requirements, like using the restroom and taking morning and afternoon breaks.
- ▶ **Fatigue Allowances:** Time that an operator needs to recover after engaging in a demanding activity. A break is needed after doing the work for a while in order to recover from fatigue before restarting.
- ▶ **Unavoidable delay allowances:** Time in which the production line is not working because of an external cause, not controlled by the operators. This could be, for instance, equipment breakdowns, supervisory discussions, and a lack of tools or resources.

Some fixed values most commonly used while considering the allowance factor are presented in Table 3.3 [22]. In this table, there are only values for personal and fatigue allowances, because the others are unavoidable and can not be foreseen.

Allowance Factor Category	Base Value
Personal Allowances	5 to 7 percent
Fatigue Allowances	4 per cent

Table 3.3: Summary of the commonly adopted values for each category of Allowance Factor

3.2 DMAIC methodology

DMAIC is a simple problem-solving methodology that works as the foundation for Six Sigma. The term Six Sigma stands for a performance improvement approach focused on quality, productivity, profitability, and cost of operations [4]. In that matter, the structured methodology DMAIC is used by Six-Sigma teams to improve and control processes.

This methodology has been used in several areas and with several purposes. It could be used for reducing the cost of poor quality in a helicopter component company [26] in the improvement of an aluminum casting operation [27]. It could also be used to reduce defects of a glove manufacturer [5], and even, to reduce lead time in public universities [28].

It is important to emphasize that the scientific studies of this methodology have been growing in recent years. This may reflect in a bigger implementation in industrial environments. Figure 3.1 was made based on data from the SCOPUS platform when searching the combined words "DMAIC" and "Improvement", in which it is possible to see the increasing evolution of works published in journals according to the year. Bearing in mind the growing relevance of this methodology, it is necessary to understand each one of its stages. Thus, the stages of DMAIC can be explained as follows, [29], [30]:

- **Define:** In this stage, the problem faced by the production line, as well as the project goals are identified. The related processes, inputs, outputs, people involved,

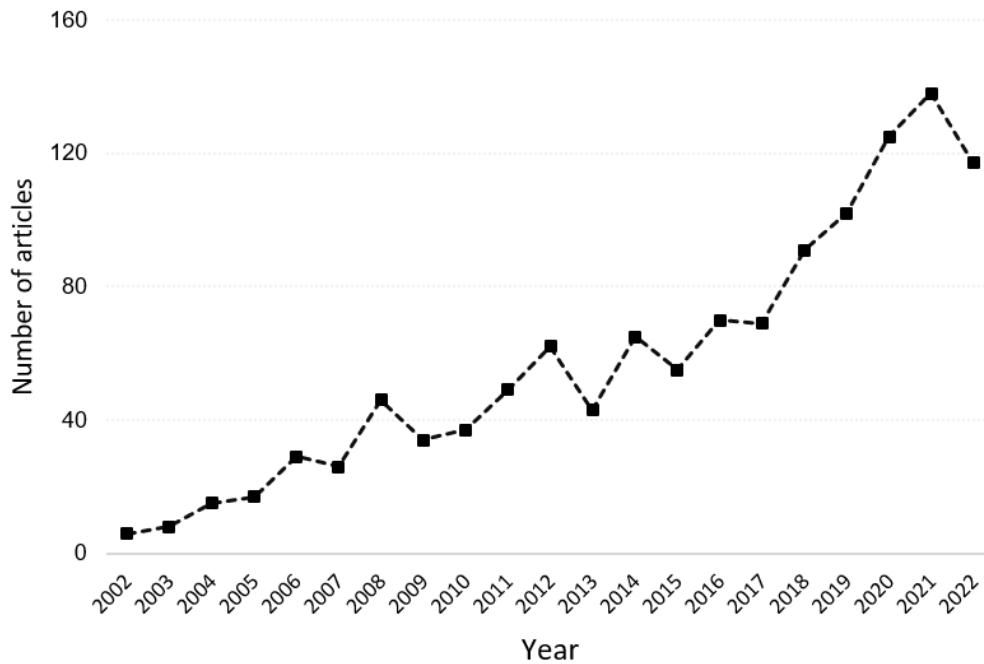


Figure 3.1: Evolution of the number of published works by year (Scopus)

customer needs, and requirements, can also be specified;

- ▶ **Measure:** In this stage, information about the initial state is gathered. This information is essential as it can provide the performance of the process in a quantifiable way. This facilitates the visualization of the problems;
- ▶ **Analyze:** This stage aims to identify potential factors that can be the root cause of problems using graphical or statistical analysis tools;
- ▶ **Improve:** The objective of this stage is to develop and put into action process modifications and solutions that address the problems identified during the previous stage in order to enhance performance;
- ▶ **Control:** In order to ensure that the solutions and improvements, suggested in the previous stage, are maintained and implemented. The Control stage aims to monitor the reduction or elimination of the problem referred at the beginning of the project, with the Define stage, as well as the root causes found in the Analyze stage.

CHAPTER 3. STATE OF ART

Figure 3.2 summarizes some of the tools used in each of the 5 stages of DMAIC methodology:

AUTHOR	DMAIC METHODOLOGY TOOLS				
	DEFINE	MEASURE	ANALYZE	IMPROVE	CONTROL
(Alqahtani, 2020)	Voice of Customer, Defect Definition, Project Charter, SIPOC	Performance Measurements, Value Stream Mapping (VSM)	VSM, Simulation Analysis, Cause Investigation	Pilot Study, VSM	Monitoring systems
(Prashar, 2014)	Project Charter, CTQ Tree, SIPOC	Process Map, Measurement system Analysis, Data Collection Plane, Baseline Sigma, Process Capability Analysis	Brainstorming, Cause and Effect Diagram, Pareto Analysis	Counter Measure Matrix, Impact/Effort Matrix, Solution Prioritization Matrix, Process Failure Mode Effect Analysis, Impementation Plan, Cost & Benefit	Control Plan, Control Chart
(Mishra & Sharma, 2014)	SIPOC, Data Table of Defects	Counting of Data, Pareto Diagram, Histogram	Brainstorming, Cause and Effect Diagram, Control Charts, Other graphs	Brainstorming sessions, Table of Number of Improvement actions	PDCA to monitor activities, Control Plan
(Srinivasan et al., 2014)	Project Charter, Pareto Diagram	Measurement of data, Process Capability Analysis	Cause and Effect Diagram, Likert Scale Analysis	Brainstorming, specific tests, ANOVA, Histogram	Tests to check the results, Sigma Levels Analysis, Control Plan
(Gupta et al., 2016)	Production Mapping, Project statement	Data Collection, Pareto Diagram, Control Charts	Cause and Effect Diagrams	Implementation of improvements, Check Sheet	Pareto Diagram
(Li et al., 2008)	Mapping of the process	Control Charts, Process Capability Analysis	Cause and Effect Diagram	Reducing of variations	Control charts
(Marques & Matthé, 2017)	Project Charter, SIPOC, CTQ	Tests to assess baseline performance, Pareto chart	Cause and Effect Diagram, Pareto Chart, ANOVA	Brainstorming, Implementation of improvement ideas	Control Plan, Standardization
(Junior et al., 2021)	Pareto Diagram	Quality analysis of the parts, Statistical Study, Process Capability Analysis	Defects Identification	Brainstorming, Bottleneck reduction	Control Charts

Figure 3.2: Summary of the tools used in each of the 5 stages of DMAIC per Author per year

The define stage works as a foundation to carry out the rest of the project, once it aims to identify the problem to be approached from several angles, and to define the project scope, budget, requirements, and goals, as well as the team that is going to deploy the project [28], [31]. Some tools commonly used in this stage aim to organize all the information needed to start the project [26]–[28], [31].

Regarding the tools for this stage, the project charter is one of the most used. It can establish the project guidelines, scope, deliverables, milestones, risks, assumptions, background, main resources, and main goals. It is adaptable according to the problem in the analysis. Another widely used tool is the SIPOC diagram, which stands for Supplier, Input, Process, Output, and Customer, and gathers the information of each category to better understand the project [27], [32].

Another important tool is the Voice of the Customer (VOC), which serves as the project’s compass, by considering the opinions of the customers in order to define the problem. In addition, there is the Critical to Quality (CTQ) tree, that identifies critical issues on the quality characteristics of a service or product. It helps to ensure that the project focuses on the most important customer requirements, translating them into specific measurable characteristics that can be monitored throughout the project [27],

[32].

By using these tools and techniques, the Define stage can help in the visualization and clarification of the project scope, main characteristics, the problem that is trying to be solved, and the customer requirements. This lays the groundwork for the rest of the DMAIC methodology to be carried out effectively.

The second stage of DMAIC, involves the data collection for the initial state of the process under study. This data collection provides quantitative information about the problem [33].

This stage can be deployed in a sequence of 3 steps, which are, collecting data through performance measurements; measuring or calculating how far the initial state is from the desirable one; and using a mapping tool to visualize how to accomplish the desired results [28].

The data collection for the Measure stage can be done through tests to assess the baseline performance, [27]. Also, through the establishment of metrics to help monitor progress, [5]. Time studies that gather information about the duration of a process could also be implemented to collect data, [34]. A Value Stream Mapping (VSM) could also be used to evaluate the bigger picture of the process, [32], [35]. Additionally, a Failure Mode and Effect Analysis (FMEA) could also be used in this stage, once it helps the team to identify the risks and priorities within a process [28], [32].

Thus, the Measure stage presents the data of the production line in its initial state in a quantitative way. This information is essential for the next stage, once it facilitates the visualization of the problems, and consequently, the identification of their root causes [32].

According to [32], there is a thin line between when the Measure stage finishes and when the Analyze stage starts, once there are several projects that need to have those both stages happening simultaneously to check whether the data being measured is relevant for the progress of the project. Thus, the Analyze stage of DMAIC aims to analyze the data measured during the Measure stage and also identifies, some problems and the root causes addressed to them [28].

There are some specific tools that can be used during this stage, and those, can be adapted according to the project. Some of the common tools used in this stage are: Root cause analysis using Fishbone diagram, and root cause verification matrix; Graphical analysis using Pareto charts and box plots; Statistical analysis, using hypothesis testing, correlation, and regression analysis, [32].

The Fishbone diagram is used for root cause analysis to reduce the cost of poor quality, in [26]. Besides, in [34], a Pareto chart for a graphic representation of what activity takes more time compared to TT in a case study for cycle time reduction. A Pareto chart associated with a cause and effect study was made in [27]. Thus, this shows that multiple tools can be used simultaneously in this stage, according to the project specifications.

If the tools in the Analyze stage are correctly applied to each project, it can provide information that will allow better solution identification for the next stage, [28].

After determining the root causes during Analyze stage it is necessary to select the solutions to implement, this characterizes the Improve stage. Thus, the main goal of this stage is to develop and implement solutions to address the root causes of the problems identified in the previous one [32].

Common tools to be used during improve stage are for example Brainstorming, [26], [36], which could be used to come up with improvement ideas for the root causes previously set; Cost Benefit Analysis; Solution selection matrix, in case of the existence of many solutions for the same problem it could verify which one is the most suitable, [32]. Another tool commonly used in this stage is the Impact/Effort Matrix that assesses the solutions' impact against the estimated effort to perform them, [26].

Once the solutions are selected they can be tested in a real-life situation and/or through software simulation such as Arena [28]. The tests can be done to verify the impact of the improvement idea before indeed implementing it. Additionally, the planning of the improvement implementation can also be performed during this stage [32].

The Control stage plays a significant role in disseminating the project's successful outcomes to the team so they may apply those outcomes in their everyday work. It also ensures that the previous method used does not return, by ensuring more management

support for subsequent implementations and internal communication [37]. By monitoring and keeping track of the changes that have been developed and created during the Improve stage [28], [32], it also makes sure that the improvements made will have a long-term impact on how people work in the organization [38]. Standardization is also used as a way of guaranteeing that the improved process is going to be maintained [27].

The control charts, which can be used accordingly to the purpose of the process in the analysis are very important tools to this stage of DMAIC, [32]. In addition, for the Control stage, it would be interesting to create a control plan in order to keep track of the improved process indicators, and it can be built by setting some information such as, when, where, what and how to monitor the improved process, and how to solve any issue that may occur. Additionally, it could be provided some Visual control, that can vary according to the application, it could be for example, safety procedures or even posters to ensure the step-by-step of a specific task.

Chapter 4

Methodology

This chapter exposes the methods used in each stage of DMAIC, in order to improve the production process of the catalytic converter production line under study. It is divided according to the 5 stages of DMAIC.

4.1 Define

In this stage, the foundation for the rest of the project was set through a clear definition of the problem to be solved and the particularities of the production line under study in its initial state. In order to achieve this, there were 2 essential tools used: the Project Charter and the Supplier - Input - Process - Output - Customer (SIPOC) diagram.

The Project Charter was developed to align the project's goals and to provide a clear definition of the problem to be solved. For this case study, the following topics were described [32], [39]:

- ▶ **Description of the problem:** It represents what negatively affects the company or the discrepancy between the desired and initial states. It accurately and without commentary or opinion characterizes the issue that must be solved;
- ▶ **Project Goals:** It represents the transformation of the Problem Statement into objectives. It is also necessary to mention the intended outcomes.

- ▶ **Background:** It is a concise and clear description of the situation faced by the production line and operators, so that the importance of the project can be understood, giving a solid justification for investing resources in the project.
- ▶ **Team members:** It briefly describes the Project participant's roles inside the company.
- ▶ **Expected Deliverables:** It presents what the project will provide as an output, what is going to be the results of the project.
- ▶ **Expected Milestones:** The deadlines for each stage of DMAIC.
- ▶ **Risks:** It includes certain risks that may be found during the deployment of the project.
- ▶ **Assumptions:** It includes some assumptions made to start the project.

After understanding the problem, a SIPOC was built. Once it is necessary to have a clear vision of the project and the problem under study, it was interesting to associate both tools, the Project Charter and SIPOC. Thus, the SIPOC enables to understand what was the process involved in the catalytic converter production line, in terms of suppliers, inputs, outputs, and the customer.

Best practices for the completion of a SIPOC have reached an acceptable order, [32], which should be the following:

1. **Process**
2. **Outputs**
3. **Customer**
4. **Inputs**
5. **Suppliers**

Once the process was correctly understood, it was possible to define what were going to be its results, by asking simple questions such as: *What comes out of this process?* With this question answered, it was possible to complete the Output section of the SIPOC Diagram. The Customer is generally the answer to the question: *Who are the ones that are going to use the results of the process?*

After defining those points it was possible to ask: *Who and what is mandatory for the process to achieve its results?* This question gives respectively the Inputs and Suppliers needed. With that, the diagrams could be reviewed and later validated.

4.2 Measure

Once understanding what was going to be the project goals and specifications, the collection of data could start. Thus, for this stage of DMAIC, the measurement of the times for each one of the 5 operators, working on the morning shift (from 8:00 to 16:00) occurred continuously. Besides that, the flow of tasks for each operator was collected, by observing the cycle and collecting data, a scheme representing the layout of the production line and the flow of tasks was drawn using Microsoft Visio[®]. Through the gathering of information, it was possible to calculate the standard time [40]. Thus, in this stage of DMAIC, the Work Methods of the catalytic converters production line in its initial state were observed as well as the cycle times of each operator were measured, to finally, calculate the standard time.

The definition of Standard Time for each operator for the Measure stage of DMAIC is important to provide the visualization of the line in its initial state and it provides important information for the Analyse stage, once it allows one to verify whether the operators are performing a similar amount of tasks or the distribution of tasks is unbalanced among the operators (one operator has more work content than the other) as well as factors such as variability between tasks.

4.2.1 Work Methods Analysis

The production process of catalytic converters was observed and with that it was possible to understand and register the tasks performed by each operator.

For the present case study, it is possible to visualize the flow of tasks among the operators through a Flow Diagram, which illustrates each operator's task, using arrows to indicate their path in a cycle, summarizing the workflow. The diagram also contains the production line's layout, showing schematically which machines are present within it. The flow of each operator was enumerated.

4.2.2 Standard time

Based on the methodology presented in [12], a sequence of 8 steps was followed for each operator in order to calculate the standard time:

The first step, involves defining the task and the operator which will be measured. Following that, for the second step, this task was divided into measurement points (MP) in order to facilitate visualization and time measurement. It is important to highlight that, the construction of the Flow Diagram, took into consideration the number of MPs of each operator and their position in order to enumerate the flow. When the operator presses a button or makes any other movement that is clearly visible to the observer, the beginning and end points that mark an MP can be seen [12], [14].

For the third step, the sample size is iteratively calculated, starting with a preliminary sample size that should have been previously measured [12], [23]. Equation (4.1) represents this calculation:

\bar{x} : mean of the k time observations $x_i, i = 1, \dots, k$ collected in each iteration.

s : standard deviation of time from the k observations, calculated by $s = \sqrt{\frac{\sum_{i=1}^k (x_i - \bar{x})^2}{(k-1)}}$

z : number of standard normal deviate (or z-score) corresponding to the desired level of confidence selected.

p : desired precision or accuracy.

$$n = \left(\frac{z.s}{p.\bar{x}} \right)^2 \quad (4.1)$$

It is important to highlight that, for equation (4.1) the used value of accuracy, which corresponds to the acceptable error, was 5%, according to [23]. Considering the preliminary sample size k , the mean and standard deviation were calculated and the equation (4.1) is used to calculate subsequently a new value of n .

The value of n determines the iteration's stopping rule. If it is greater than the preliminary sample size, it means that one more iteration is needed, by collecting a new sample size. The iteration sequence ends as soon as the resulting n is smaller or equal than the sample size obtained in the previous iteration [12], [14], indicating that the stop condition is reached.

For the fourth step, it is important to highlight that, in order to reduce the influence of subjectivity into the time observations collection referred by [24], it is necessary to collect them continuously, from x_1 to x_k , making sure that working conditions are maintained as constant as possible over the measurement process. In this step the stopwatch lap button is pressed each time one measurement point ends and the next one begins, which ensures that not only the duration of the entire task but also the individual cycle components are measured.

The fourth step also involves the analysis of the operator's pace, in order to estimate a performance rating factor r_j for each MP_j . The production process needs to be observed multiple times in order to get an appropriate performance rating value. Additionally, benchmarking can be done with other businesses that have similar manufacturing lines in order to attain even better precision. Therefore, if the operator's r value is 1.05, it means that his performance was 5% better than average.

Box-Plots were built for each MP of the five operators using the Statistica[®] software, to identify outliers as they represent them in a more visual portrayal [32]. The points outside 1.5 times the interquartile range were removed from the calculations [41].

Thus, after the elimination of outliers, the fifth step, involving Standard Time definition uses equation (4.2) to calculate the average of each MP j , from x_1 to x_k for every MP j , denoted by x_{1j} to x_{kj} , respectively.

$$\bar{x}_{ij} = \left(\frac{\sum_1^k x_{ij}}{k} \right) = \left(\frac{x_{1j} + x_{2j} + \dots + x_{kj}}{k} \right) \quad (4.2)$$

Through equation (4.3) it was possible to calculate the normal time for the 6th Step of Standard Time definition for each MP_j .

$$NT_j = (\bar{x}_{ij} * r_j) \quad (4.3)$$

In equation (4.3), the performance ratings r_j observed for each MP_j on the 4th step was applied.

For the 7th step of Standard Time definition, it was made the sum of the Normal Times for each MP_j , $(\sum_1^j NT_j)$. Finally, the 8th and last step involves the calculation of Standard Time through equation (4.4).

$$StandardTime = \left(\frac{\sum_1^j NT_j}{1 - AllowanceFactor} \right) \quad (4.4)$$

The Allowance Factor, presented in equation (4.4), represents a way of quantifying the operator's work conditions quality provided by the company [12], [14]. It can be dependent on the facilities' location of the production line, as bathrooms and water fountains, once it directly influences the life quality and consequently the performance of the operators. Besides, it can also consider fatigue and delay allowances. According to what was found in the literature, [22], it was considered an allowance factor of 9%.

4.3 Analyze

The main goal of this stage was to identify the root causes for each problem indicated through the previous measurements. For this stage, it was calculated the production line's current TT, in order to compare it with the times measured; two Brainstorming sessions

were made to: (i) build the possible Root Cause Verification Matrix for afterward, (ii) perform a 5 Why's analysis of each one of the possible root causes until reaching the real one, for finally, (iii) categorizing those root causes in a Fishbone Diagram.

Firstly, it was made the comparison between the amount of time that operators took to produce one part (Standard Time) and the amount of time that the customer requested the same part from the production line (TT), in order to verify whether or not the production line was reaching the customer demand.

The TT involves the definition of the objective in terms of the number of products that the production line has to generate per shift in order to accomplish the customer demand. It considers the actual production time, which excludes the daily and per-shift scheduled breaks. It can be calculated by equation (4.5), [12].

$$TaktTime = \left(\frac{ProductionTime}{Demand} \right) \quad (4.5)$$

Then, the comparison between the Standard Time and the TT, for each operator, was visualized through a graph, with columns representing the Standard Time and a horizontal line representing the TT. If the columns surpass the horizontal line, it means that the operators are not reaching customer demand.

After analyzing the data obtained in the TT analysis and in the previous stage, it was time to find their possible root causes. One brainstorming session was performed with the members of the team and had the following goals:

1. Visualizing the problem through the analysis of the collected data;
2. Understanding what was directly causing the identified problems - possible root causes;
3. Applying the 5 Why's method to find the real root causes with the greatest levels of detail.

The possible root causes generated on the brainstorming were listed in the Root Cause

Verification Matrix, [32], with which it was possible to check whether the addressed possible root causes were really related to the problem in question. In this matrix the first column represents the problem; the second column represents the possible root causes, that were the most visible to the team members; the third column represented the method through which it was possible to verify that the possible root cause was addressed to the problem in question; the fourth column represented the reason for the verification method used; and the fifth column, finally represented whether the root cause were directly related to the problem or not.

In addition to that, to verify if the possible root causes validated using the Verification Matrix were the real ones, the 5 Why's method was applied in each one of them. Asking "why?" to the possible root causes several times, helped to understand that the real root causes of the problem were deeper.

Once the real root causes were found, they were organized in a Fishbone Diagram. In order to build this diagram, another brainstorming session was made to classify each identified root cause into one of the 5 major categories: Measurements, Materials, Methods, and Machine, [42], for better visualization.

4.4 Improve

The Improve stage established adequate solutions to the root causes of the problem identified in the previous stage. During this stage, it was required 2 brainstorming sessions in order to discuss ideas for suitable solutions addressed to the root causes.

The solutions that came up during the first brainstorming session were put into a Solution Selection Matrix [32], which can be completed by using:

- ▶ The first column with the problem statement;
- ▶ The second column with the validated root causes;
- ▶ The third column with potential solutions;

- ▶ The 4th, 5th, and 6th columns with the solutions' rating - varying in a range of 1-10, in which 1 is the lowest and 10 is the highest - for respectively effectiveness, feasibility and cost-benefit;
- ▶ The 7th column represents the overall rating of the possible solutions - obtained by multiplying columns 4th, 5th and 6th - and it can be used to prioritize them;
- ▶ The last column presents whether the action of implementing that solution based on the overall rating is going to be deployed or not.

It is important to highlight that, according to [32], effectiveness is measured by a scale from 1 - which indicates a solution is ineffective - to 10 - which indicates that a solution is effective - in terms of root cause elimination. Feasibility is measured by a scale from 1 - which indicates that is not possible - to 10 - which indicates that is highly feasible - in terms of the amount of work necessary to implement the solution. Cost-benefit is measured by a scale from 1 - which indicates that is costly - to 10 - which indicates that is costless - and it is a high-level estimate, if the solution implementation cost exceeds the project expenses, it is given the solution a low grade.

After rating, prioritizing, and choosing which solution to implement for every root cause, it was important to perform an analysis that could compare the solutions. Thus, an Impact-Effort Matrix [26] was constructed with the purpose of verifying the potential impact against the estimated effort to implement the solutions.

For this matrix, the solutions were analyzed considering 4 quadrants, the first of them representing high impact, but low effort; the second one representing high effort and high impact; the third one representing low impact and low effort; and finally, the last one representing the scenario of high effort but low impact. Figure 4.1 schematizes the Impact-Effort Matrix.

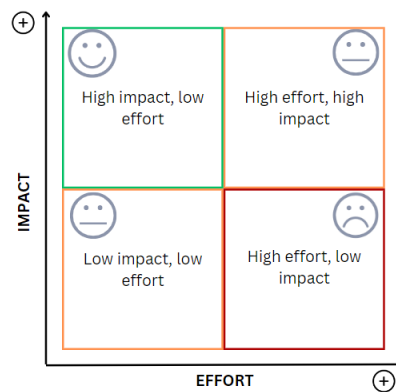


Figure 4.1: 4 Quadrants of Impact-Effort Matrix

4.5 Control

The Control stage is the final stage of the DMAIC process and focuses on ensuring that the solutions proposed during the previous stage are sustained over time. However, as only 2 of the solutions selected have been implemented, the Control stage aimed to provide a new time measurement and Box-Plot for operator 5 - which was the most impacted by the implemented solutions - to validate the solutions in terms of problem mitigation. The stage also provided a Gantt Chart of the execution and implementation of the missing solutions, as well as for validation of them through monitoring.

For the time measurement and construction of Box-Plots, the methodology was the same as in the Measure stage. In addition, concerning the Gantt chart, all of the mandatory tasks to implement the solutions as well as their order were presented. The monitoring and validation phases were also shown, in order to keep track of the solution, consequently guaranteeing the mitigation of the previously identified root causes in the production process.

The following steps were included while building the Gantt Chart:

- ▶ Implementation of solutions: Each key step to perform it as well as the responsible for the implementation and deadline;
- ▶ Documentation: All changes made to the process must be created, documented,

and recorded in a centralized database. There is also a deadline for this topic in the Gantt Chart. This ensures that the information is available to all relevant parties and can be easily accessed in case of any issue.

- ▶ Training: Planning of the training sessions was included in parallel with the monitoring of solutions to ensure that all employees involved in the process were aware of the new procedures and understood their roles in the implementation of the changes;
- ▶ Monitoring and Control Plan: A monitoring and control plan was scheduled in the Gantt Chart, to occur after the implementation of the solution, to track key process metrics and ensure that the new process was performing as expected;

By implementing these steps inside the Gantt Chart, the progress of solution implementation, and of the other essential topic is going to be followed by the team, in order to guarantee process improvement.

Chapter 5

Implementation of DMAIC on Work Standards' Improvement

This chapter discusses the results obtained in each stage of DMAIC. Firstly, it was highlighted, in the Define stage, the SIPOC and the Project Charter; in the Measure stage the sample size obtained for data collection, and the Standard time calculation for each operator were presented; for the Analyze stage, the visualization of the main problem of the line and the root causes addressed to it were also highlighted; for the Improve stage, the solutions found for each of the root causes were exposed; and finally, for the Control stage, a Gantt Chart created to follow up the improvement of the production line was presented.

5.1 Define results

The production line under study faced a significant problem: it was unable to meet customer demand during normal working hours, creating the need for weekend work and overtime shifts. The central problem was addressed by adopting the DMAIC methodology. The Define stage played the role of setting the foundation for the entire project. During this stage, a comprehensive analysis of the central problem was conducted, highlighting the project's specifications. By clearly defining the problem's scope and impact, the study

in this stage established a clear direction for subsequent stages.

Firstly, the Project Charter was built to better understand and visualize the project specifications. It was important to keep in mind that the project charter was taken into consideration at every stage of DMAIC.

Secondly, a SIPOC diagram was constructed by giving a high-level description of the catalytic converter production process, as can be seen in Figure 5.1.

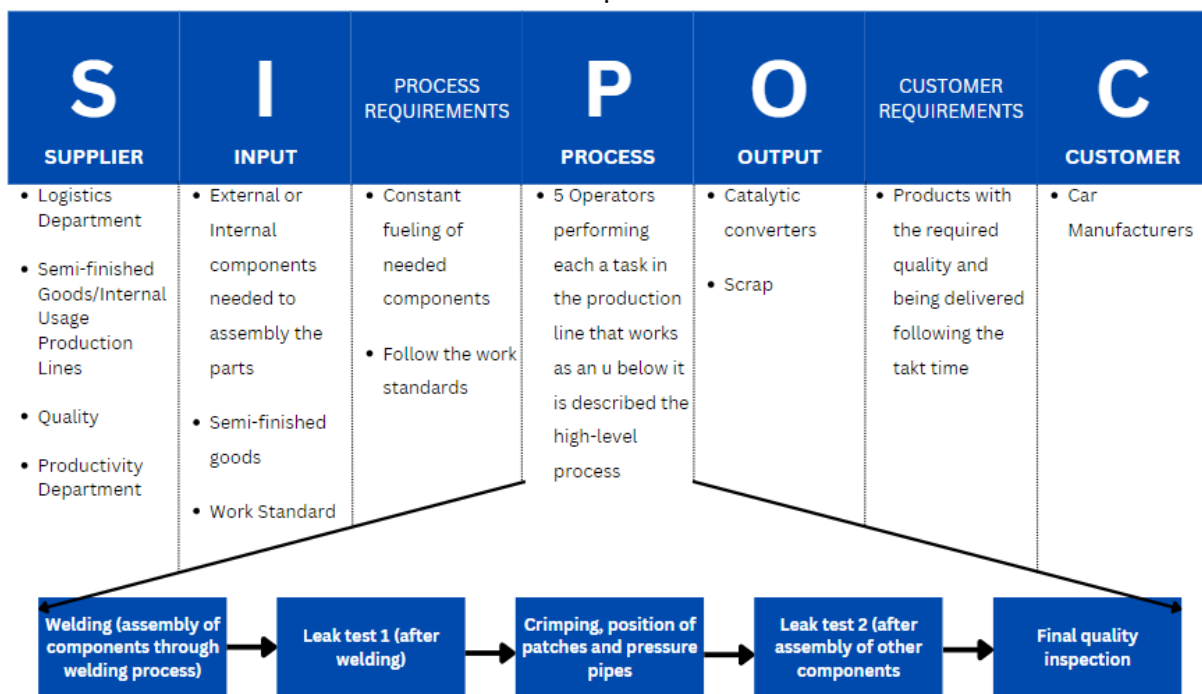


Figure 5.1: SIPOC for Catalytic Converter production process

PROJECT CHARTER

PROCESS IMPROVEMENT IN A CATALYTIC CONVERTER PRODUCTION LINE

PROJECT OVERVIEW

DESCRIPTION OF THE PROBLEM	The catalytic converter production line in May 2022 was unable to reach customer demand in normal working hours. The 5 operators working in the production line presented great variability while performing their tasks. The standard times used by the company were not compliant with the current state of the production line.
PROJECT GOALS	Improvement of the catalytic converter production process in a general way, aiming the reduction of the standard time and variability of the operators by the identification of root causes and the development of viable solutions. The project also aims to plan the implementation of those improvements.
BACKGROUND	During the beginning of 2022 it was identified that the production line needed to add shifts during the weekends when customer demand were higher and even when they were still 550 products a day. A superficial investigation surrounding what was causing this delay was made by the company, and it was noticed that the operators presented high variability in their tasks. Further and deeper investigation was required by the manager.
TEAM MEMBERS	2 Lean Manufacturing Engineers + 1 Productivity Manager + 1 Productivity Engineer + 1 Trainee

EXPECTED DELIVERABLES

EXPECTED DELIVERABLES
Standard time calculations for each operator
Task descriptions for each operator
Root cause analysis
Visualization of improvements
Improvement and Control plan

EXPECTED MILESTONES	
Define	Jun/2022 - Jun/2022
Measure	Aug/2022 - Sep/2022
Analyze	Sep/2022 - Nov/2022
Improve	Nov/2022 - Jan/2023
Control	Feb/2023 - Jun/2023

ADDITIONAL INFO

RISKS
Resistance from operators to changes in their work standards
Delays in obtaining necessary data and information
Unforeseen technical difficulties in implementing improvements

ASSUMPTIONS
Availability of data and info. necessary for the project
Cooperation from everyone involved in the production line
Availability of resources needed to implement improvements

5.2 Measure results

During the Measure stage of the DMAIC, key aspects of the production line's initial state were gathered. This involved a comprehensive understanding of the layout and flow of the production line through the creation of a flow diagram. Furthermore, the standard time, which involved defining sample size and measuring the operator's cycle times, was calculated. By obtaining this information, it was possible to represent the initial state of the line in a concise and quantitative way, allowing better visualization and quantifying the existing problem.

5.2.1 Work Method Analysis

For the Work Methods Analysis, it was drawn the flow diagram of each operator in the initial state of the line, using Microsoft Visio, as can be seen in Figure 5.2.

For the production process understudy, the line in its initial state has five operators distributed according to Figure 5.2. In this figure, tables T1 to T8 are used mainly for safety reasons, for the operator to place a part to cool down while the next operator produces another. It also guarantees that the process will continue if there is any delay since there will always be at least one part on the tables.

Thus, if the operator of the previous task has a problem, the next operator will use the part that is on the table to continue the subsequent task. The supply ramps represent the place supplied by the Logistics department, that contains components needed for assembling the part.

Additionally, the flow of each operator is represented by arrows. It is important to highlight that the numbers in the flow coincide with the number of Measurement Points (MPs) which will be explained in the next subsection. The sequence of steps taken by each operator, as seen in Figure 5.2 can be described as:

- ▶ Operator 1 starts the task by picking the part on T6 and loading it into the Leak Test 1. Next, he presses the cycle start button and moves to Welding Machine 2. After, he unloads the assembled part from Welding Machine 2 and places it on T2.

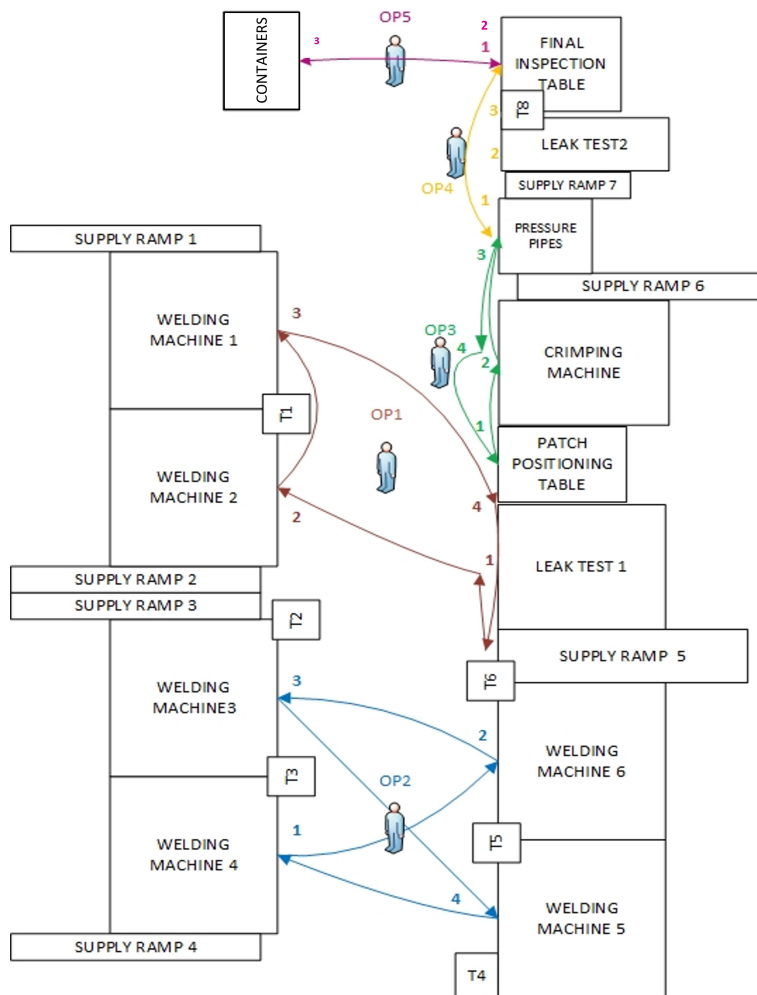


Figure 5.2: Flow diagram representing operators' task for the production line under study

Next, he returns to Welding Machine 2 to retrieve the main components from supply ramp 2 and T1 and loads them. After, he moves back to Leak Test 1 to unload the part and places it on the Patch Positioning Table, making the plug-in of some components using a drill. Finally, he returns to the start position on T6 to restart the cycle.

- ▶ Operator 2 starts by picking the part on Welding Machine 4 and lands it on T4. After, he returns and loads the components of Supply Ramp 4 and T3, and presses the cycle start button. Next, he goes to Welding Machine 6, unloads its part on T6, loads with components of Supply Ramp 5 and T5, and presses the cycle start button of Welding Machine 6. This process is made in a similar way for Welding Machines 3 and 5. Finally, he returns to Welding Machine 4 to restart the cycle, when the task in welding machine 3 is over.
- ▶ Operator 3 starts by attaching the patches to the part on Patch Positioning Table. Next, he positions the inferior thermal plate on the crimping machine, fitting the part, and then positioning the superior thermal plate on the part. Then, he presses the cycle start button on Crimping Machine. Next, the operator goes to the pressure pipes' table, tightening the pressure pipes. Next, he goes back to the crimping machine, unloads the part, and places it on the Pressure Pipes' table.
- ▶ Operator 4 starts by going to the part on the pressure pipes' table and performing the thread control, picks the part from the table, and loads it on Leak Test 2. Next, he performs the test. Finally, he unloads the part on the final inspection table and returns back to restart the cycle.
- ▶ Operator 5 does the quality control and verification of 9 points on the part. Those points are specified by the customer. Next, he verifies the weld beads, which are susceptible to cracks and pores. While performing the visual verification, the points are circled with the use of a pen, as a manner of checking that those points were indeed verified. After performing this verification, the operator places the part in

the container and returns to the final inspection table to restart the cycle.

5.2.2 Time Measurements and Standard Time

To perform the time measurements, the 8 steps included in the standard time calculation were followed.

For the first step, the tasks to be studied will be the ones involved in the Catalytic Converter Production Process. For the second step, it was defined the MPs for the tasks for each one of the 5 operators, denoting x_{ij}^p , the observation i for MP_j concerning operator p ($p=1$ to 5). The MPs were established to simplify the measurement process and are categorized based on the small tasks that the operator performs in each machine. The measurement process was carried out using a sample size of k .

For operator 1, the MPs adopted for the measurement were:

- ▶ The stopwatch start button is pressed when operator 1 touches the part on T6, marking the start point of MP_1 ;
- ▶ The beginning of MP_2 occurs with the Leak Test 1 start-cycle button push, the stopwatch lap button is pressed. Hence, the time between the start and end points of MP_1 for the first observation, x_{11}^1 , is obtained. Practically it represents the load of the part in the Leak Test machine;
- ▶ The beginning of MP_3 occurs with the Welding Machine 2 start-cycle button push, and the stopwatch lap button is pressed. This represents x_{12}^1 , the time between the start and end points of MP_2 for the first observation. Practically it marks the load of components in Welding Machine 2;
- ▶ The beginning of MP_4 occurs with the Welding Machine 1 start-cycle button push, and the stopwatch lap button is pressed. This is the third measurement for the first operator x_{13}^1 . Practically it represents the load of the components in Welding Machine 1 and the placement of the part on the Patch Positioning table;

- ▶ When operator 1 touches the part on T6 again, the stopwatch lap is pressed, marking the end point of MP_4 given by x_{14}^1 and the beginning of MP_1 of the second observation x_{21}^1 . Practically, x_{14}^1 represents the drilling of components and the displacement until T6.

For Operator 2, the MPs adopted for the measurement were:

- ▶ The stopwatch start button is pressed when operator 2 presses the start cycle button of Welding Machine 4, marking the start point of MP_1 ;
- ▶ The beginning of MP_2 occurs with the Welding Machine 6 start-cycle button push, and the stopwatch lap button is pressed. Thus, the time between the start and end points of MP_1 for the first observation, x_{11}^2 , is obtained. Practically, it represents the unloading of the part and load of new components in Welding Machine 6;
- ▶ The beginning of MP_3 occurs with the Welding Machine 3 start-cycle button push, and the stopwatch lap button is pressed. Thus, the time between the start and the endpoints of MP_2 for the first observation is obtained, x_{12}^2 . In practical terms, it represents the unload and the load of the parts in Welding Machine 3;
- ▶ The beginning of MP_4 occurs with the Welding Machine 5 start-cycle button push, and the stopwatch lap button is pressed. Thus, the time between the start and end points of MP_3 for the first observation is obtained, x_{13}^2 . This time observation represents the unload and the load of the components of Welding Machine 5;
- ▶ When the operator presses the start cycle button on Welding Machine 4 again, the stopwatch lap is pressed, marking the end point of MP_4 given by x_{14}^2 and the beginning of MP_1 of the second observation x_{21}^2 . Practically, x_{14}^2 represents the unload and load time of machine 1;
- ▶ The MPs are continuously collected until x_{kj}^2 observations are obtained for each MP_j of the task, keeping constant the working conditions.

For operator 3, the MPs adopted for the measurement were:

- ▶ The stopwatch start button is pressed as soon as the operator touches a patch in the Patch positioning table, marking the start point of MP_1 ;
- ▶ The beginning of MP_2 occurs when the inferior thermal plate is touched, and the stopwatch lap button is pressed. Thus, the time between the start and end points of MP_1 for the first observation is obtained, x_{11}^3 . This time observation in practical terms represents the patch positioning in the part;
- ▶ The beginning of MP_3 occurs with the Crimping Machine start-cycle button push, and the stopwatch lap button is pressed. Thus, the time between the start and the endpoints of MP_2 for the first observation is obtained, x_{12}^3 . This time measured represents the load of the part on the Crimping Machine;
- ▶ The beginning of MP_4 occurs when the tool to position the pressure pipes is touched, in the Pressure Pipes table, the lap button is pressed. Thus, the time between the start and end points of MP_3 for the first observation is obtained, x_{13}^3 . This time observation represents the fitting of pipes;
- ▶ When the operator touches the patches on the patch positioning table again, the stopwatch lap is pressed, marking the end point of MP_4 given by x_{14}^3 and the beginning of MP_1 of the second observation x_{21}^3 . Practically, x_{14}^3 represents the displacement plus unloading of the part on the Crimping Machine.

For operator 4, it is important to highlight that, for the measurements, only 3 MPs were necessary, the MPs adopted for the measurement were:

- ▶ The stopwatch start button is pressed as soon as the operator touches the part on the pressure pipes table, marking the start point of MP_1 ;
- ▶ The beginning of MP_2 occurs when the bar code reader inside the Leak Test 2 is touched, and the lap button is pressed. Thus, the time between the start and end

points of MP_1 for the first observation is obtained, x_{11}^4 . This time observation, in practical terms, represents the loading of the part in Leak Test 2;

- ▶ The beginning of MP_3 occurs when the thread control screwdriver is touched, and the lap button is pressed. Thus, the time between the start and the endpoints of MP_2 for the first observation is obtained, x_{12}^4 . Practically it represents the Leak Test 2 procedure time;
- ▶ When the operator touches the part on the pressure pipes table again, the stopwatch lap is pressed, marking the end point of MP_3 given by x_{13}^4 and the beginning of MP_1 of the second observation x_{21}^4 . Practically, x_{13}^4 represents the unloading of the part into the Final Inspection Table and thread control.

For operator 5, it was also visualized only 3 MPs during the measurements, which were:

- ▶ The stopwatch start button is pressed as soon as the operator touches the part on the Final Inspection Table, marking the start point of MP_1 ;
- ▶ The beginning of MP_2 occurs when the pen for visual verification is touched, and the lap button is pressed. Thus, the time between the start and end points of MP_1 for the first observation is obtained, x_{11}^5 . This time observation, in practical terms, represents the start of the verification for the final inspection;
- ▶ The beginning of MP_3 occurs when the bar code reader is touched, and the lap button is pressed. Thus, the time between the start and the endpoints of MP_2 for the first observation is obtained, x_{12}^5 . This time measured represents the visual verification of the part;
- ▶ When the operator touches the part on the Final Inspection Table again, the stopwatch lap is pressed, marking the end point of MP_3 given by x_{13}^5 and the beginning of MP_1 of the second observation x_{21}^5 . Practically, x_{13}^5 represents the unloading of the part in the container.

After that, for step number 3 it was possible to define what sample size should be used, through the statistical method presented in [12]. The preliminary sample size k for the study was set to 10 observations. For the definition of the sample size, operator 2 was observed, once the cycle was less variable and the activities were similar inside the machines, which lead to easier identification of MPs. The value of the sample size obtained from measurements of operator 2 was also used for the remaining operators.

Thus, the task was measured continuously from the start button on Welding Machine 4 to its completion ten times. The time observations, x_{kj}^2 , were recorded in seconds and presented in Table 5.1, which includes MPs numbered from 1 to 4, the number of time observations collected for each measurement point, and the total time for the four task elements corresponding to the cycle time.

MP j	x_{kj}^2									
	x_{1j}^2	x_{2j}^2	x_{3j}^2	x_{4j}^2	x_{5j}^2	x_{6j}^2	x_{7j}^2	x_{8j}^2	x_{9j}^2	x_{10j}^2
MP1	29,3	29,8	25,7	42,7	24,1	37,7	23,2	29,0	23,4	23,6
MP2	34,9	38,4	34,5	38,1	47,7	34,0	47,6	39,0	37,0	34,5
MP3	25,0	25,4	27,9	34,1	38,7	24,1	28,8	24,6	24,4	33,2
MP4	30,7	36,6	28,8	39,1	33,7	32,3	37,4	33,1	48,5	30,5
Cycle Time	119,9	130,2	116,8	153,9	144,2	128,1	137,0	125,7	133,3	121,9

Table 5.1: Data for $k = 10$ measurements (in seconds)

The last line of the second column in Table 5.1 represents the sum of times to complete the four task elements, and the first cycle time, denoted as x_1^2 . No observations were removed from the analysis, as all data fell within an acceptable range. Afterward, sequentially: (i) the mean ($\bar{x} = 128.0$) and the standard deviation ($s = 11.5$) of the cycle time (last line of the table), are calculated; (ii) the equation (4.1) is used to determine the new sample size for the second iteration, obtaining $n = 11.8$. Since it is bigger than the preliminary sample, it was required to collect $n = 12$ time observations for each element of the task, by using the same measurement process previously described, the measurements are shown in Table 5.2.

The data collected for the second iteration are presented on Table 5.2, in which no outliers are identified. The same sequence of calculations is performed: (i) the mean

MPj	x_{kj}^2											
	x_{1j}^2	x_{2j}^2	x_{3j}^2	x_{4j}^2	x_{5j}^2	x_{6j}^2	x_{7j}^2	x_{8j}^2	x_{9j}^2	x_{10j}^2	x_{11j}^2	x_{12j}^2
1	22,9	31,7	22,0	24,6	22,5	21,6	26,4	23,4	23,9	25,8	24,0	27,6
2	39,3	43,6	36,9	35,4	35,0	41,5	37,1	58,9	34,3	43,7	34,6	36,6
3	24,7	23,7	24,9	23,0	24,0	21,2	25,0	22,3	24,3	24,8	70,0	23,7
4	33,6	38,5	38,8	33,5	37,0	31,7	31,8	37,0	39,2	31,7	36,1	32,3
Cycle Time	120,4	137,3	122,7	116,5	118,5	115,9	120,3	141,6	121,6	125,9	164,7	120,2

Table 5.2: Data for $k = 12$ measurements (in seconds)

($\bar{x} = 127.0$) and the standard deviation ($s = 14.2$) of the cycle time are calculated; (ii) the equation (4.1) is used to determine the new sample size, obtaining the $n = 19.2$. Once again, this sample size is bigger than the one achieved on the second iteration, and a new iteration is necessary.

In the third iteration, it is required to collect $n = 20$ time observations for each element of the task, by using the same measurement process. The data collected for this iteration are presented in Table 5.3, in which an outlier 176.1 is identified and eliminated, resulting in a sample size of 19. For this sample, the following calculations are achieved: (i) the mean ($\bar{x} = 131.1$) and the standard deviation ($s = 13.7$) of the cycle time; (ii) the equation (4.1) enables to determine the new sample size, $n = 5.7$. Once, this sample size is smaller than the one used on the third iteration, indicating that the stop condition of the method is reached.

MPj	x_{kj}^2																			
	x_{1j}^2	x_{2j}^2	x_{3j}^2	x_{4j}^2	x_{5j}^2	x_{6j}^2	x_{7j}^2	x_{8j}^2	x_{9j}^2	x_{10j}^2	x_{11j}^2	x_{12j}^2	x_{13j}^2	x_{14j}^2	x_{15j}^2	x_{16j}^2	x_{17j}^2	x_{18j}^2	x_{19j}^2	x_{20j}^2
MP1	23,9	24,2	22,8	23,7	28,1	25,6	22,1	25,8	22,9	21,5	27,1	22,8	24,1	31,2	24,9	23,9	23,8	24,9	27,3	23,5
MP2	38,7	45,1	34,8	37,8	52,6	86,6	38,4	37,5	36,7	35,8	37,4	35,7	46,0	44,2	37,8	48,1	40,9	36,7	38,2	35,7
MP3	25,6	23,1	24,8	23,5	24,0	26,6	24,5	23,1	26,3	29,0	27,6	27,9	27,8	26,9	24,8	22,9	23,2	25,9	22,6	23,8
MP4	39,2	32,4	30,7	39,5	35,9	37,8	36,4	37,6	32,1	35,0	36,3	33,4	39,0	33,7	29,1	39,2	41,0	32,8	40,8	31,1
Cycle Time	127,3	124,8	113,1	124,5	140,5	176,6	121,3	124,1	118,0	121,1	128,4	119,9	137,0	136,0	116,7	134,2	128,9	120,3	128,9	114,1

Table 5.3: Data for $k = 20$ measurements for operator 2

Thus, obtaining the sample size necessary to perform a reliable measurement of 20 observations, the recording began continuously for each of the 5 operators. The measurements can be found in Tables 5.4, 5.3, 5.5, 5.6, 5.7 for each one of the 5 operators respectively. While measuring the times, the performance of each operator was seen, it was assumed that operator 3 was the fastest and most skilled one which reflected on how the others performed their respective tasks compared to him, marking the fourth step.

Figures 5.3, 5.4, 5.5, 5.6, 5.7, represents the Box-Plots for each operator, that allowed

CHAPTER 5. IMPLEMENTATION OF DMAIC ON WORK STANDARDS' IMPROVEMENT

MPj	x_{kj}^1																			
	x_{1j}^1	x_{2j}^1	x_{3j}^1	x_{4j}^1	x_{5j}^1	x_{6j}^1	x_{7j}^1	x_{8j}^1	x_{9j}^1	x_{10j}^1	x_{11j}^1	x_{12j}^1	x_{13j}^1	x_{14j}^1	x_{15j}^1	x_{16j}^1	x_{17j}^1	x_{18j}^1	x_{19j}^1	x_{20j}^1
MP1	47.1	37.5	46.1	53.8	44.0	40.4	39.7	35.3	36.2	43.5	37.5	36.8	42.6	41.9	39.0	42.0	49.8	34.9	35.6	39.3
MP2	27.1	31.1	24.8	23.9	20.7	32.0	23.1	20.6	21.7	23.8	26.5	28.2	20.8	23.5	21.9	24.9	23.3	28.0	21.5	21.0
MP3	37.7	36.0	38.5	41.9	51.9	37.0	37.3	38.8	47.1	34.2	45.1	41.6	36.9	36.3	37.2	34.5	38.1	41.5	39.8	35.9
MP4	24.3	27.9	28.1	26.1	26.6	27.9	24.3	25.3	32.1	23.6	26.0	25.1	26.0	25.6	28.7	28.3	32.7	26.6	25.4	26.2
textbfCycle Time	136,2	132,6	137,5	145,7	143,2	137,3	124,4	119,9	137,2	125,0	135,1	131,6	126,3	127,3	126,7	129,8	143,9	131,0	122,3	122,4

Table 5.4: Data for $k = 20$ measurements for Operator 1

MPj	x_{kj}^3																			
	x_{1j}^3	x_{2j}^3	x_{3j}^3	x_{4j}^3	x_{5j}^3	x_{6j}^3	x_{7j}^3	x_{8j}^3	x_{9j}^3	x_{10j}^3	x_{11j}^3	x_{12j}^3	x_{13j}^3	x_{14j}^3	x_{15j}^3	x_{16j}^3	x_{17j}^3	x_{18j}^3	x_{19j}^3	x_{20j}^3
MP1	29,6	39,8	27,7	26,1	28,4	30,4	38,0	36,6	54,3	42,1	52,3	32,9	47,1	25,9	50,0	31,9	46,0	33,9	29,7	37,0
MP2	13,0	12,7	10,2	19,3	18,7	16,5	12,6	14,9	10,7	15,1	12,6	26,4	16,3	13,4	13,0	23,9	11,2	13,1	11,7	13,6
MP3	43,2	39,0	42,0	45,8	39,4	33,2	40,4	33,6	40,3	42,1	33,6	49,3	45,1	42,0	31,4	34,0	35,5	47,1	60,7	31,6
MP4	17,8	17,7	19,5	19,0	19,3	15,4	18,3	16,8	17,1	19,6	23,3	27,1	14,1	16,9	14,2	15,4	15,9	16,4	15,1	17,0
Cycle Time	103,6	109,0	99,3	110,2	105,8	95,5	109,2	101,8	122,4	118,8	121,8	135,6	122,6	98,2	108,6	105,2	108,6	110,6	117,1	99,3

Table 5.5: Data for $k = 20$ measurements for operator 3

MPj	x_{kj}^4																			
	x_{1j}^4	x_{2j}^4	x_{3j}^4	x_{4j}^4	x_{5j}^4	x_{6j}^4	x_{7j}^4	x_{8j}^4	x_{9j}^4	x_{10j}^4	x_{11j}^4	x_{12j}^4	x_{13j}^4	x_{14j}^4	x_{15j}^4	x_{16j}^4	x_{17j}^4	x_{18j}^4	x_{19j}^4	x_{20j}^4
MP1	56,6	57,6	120,0	83,5	56,4	53,4	57,4	120,0	69,0	64,1	77,6	94,0	62,0	59,4	57,2	61,4	68,6	69,0	61,0	57,6
MP2	44,9	48,2	48,2	43,7	73,2	56,1	48,4	65,1	58,6	52,6	68,9	52,7	59,3	38,4	66,7	37,8	42,1	43,7	48,2	25,5
MP3	25,4	17,5	23,0	20,5	18,2	34,0	22,3	18,0	16,4	19,4	18,9	19,0	28,6	23,2	21,2	21,9	19,4	23,9	25,3	18,1
Cycle Time	126,9	123,2	191,2	147,7	147,8	143,6	128,2	203,1	143,9	136,0	165,4	165,7	149,9	120,9	145,1	121,1	130,2	136,6	134,4	101,3

Table 5.6: Data for $k = 20$ measurements for operator 4

MPj	x_{kj}^5																			
	x_{1j}^5	x_{2j}^5	x_{3j}^5	x_{4j}^5	x_{5j}^5	x_{6j}^5	x_{7j}^5	x_{8j}^5	x_{9j}^5	x_{10j}^5	x_{11j}^5	x_{12j}^5	x_{13j}^5	x_{14j}^5	x_{15j}^5	x_{16j}^5	x_{17j}^5	x_{18j}^5	x_{19j}^5	x_{20j}^5
MP1	115,0	117,0	84,5	89,6	72,1	86,4	98,4	112,0	88,8	128,0	81,0	70,8	79,8	69,6	109,4	105,2	55,1	60,6	75,9	64,6
MP2	21,8	27,6	33,8	21,2	25,6	27,5	19,6	32,6	54,1	22,6	23,3	21,6	21,7	37,7	53,0	53,7	34,5	32,2	25,7	33,0
MP3	6,5	8,2	9,3	9,5	6,3	10,7	8,1	9,6	9,7	11,0	8,5	10,2	10,0	10,2	8,1	8,8	8,0	12,8	8,9	7,6
Cycle Time	143,3	152,8	127,6	120,3	104,0	124,5	126,1	154,2	152,6	161,6	112,8	102,6	111,5	117,4	170,4	167,7	97,6	105,5	110,4	105,1

Table 5.7: Data for $k = 20$ measurements for operator 5

the visualization and elimination of outliers and extremes. It is important to highlight that the measurements x_{ij}^p that contained an outlier were eliminated from the next calculations.

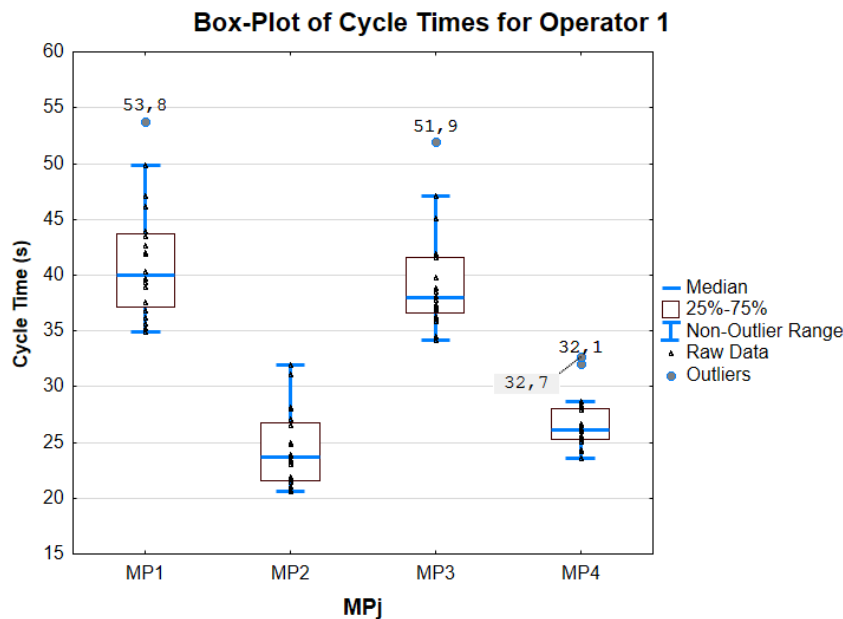


Figure 5.3: Box-Plot for each MP of Operator 1

In Figure 5.3, for operator 1, it can be seen that there are 4 outliers and that there is a high variability of times for the same MP. Thus, the measurements of 53,8 for MP₁, 51,9 for MP₃, and 32,1 and 32,7 for MP₄ were eliminated from the calculation of standard time.

In Figure 5.4, for operator 2, it can be seen that there are 2 outliers, and it can be seen that there is not much variability for MP's times. Thus, the measurements of 31,2 for MP₁, and 86,6 for MP₂ were eliminated from the calculation of standard time.

In Figure 5.5, for operator 3, it can be seen that there are 4 outliers and that there is a high variability MP's times. Thus, the measurements of 23,9 and 26,4 for MP₂, 60,7 for MP₃, and 27,1 for MP₄ were eliminated from the calculation of standard time.

In Figure 5.6, for operator 4, it can be seen that there are 2 outliers. Additionally, there is a higher distance between maximum and minimum values mainly for MP₁ and MP₂, which also indicates a big variability in MP's times. The measurements of 120,0 for MP₁ and 34,0 for MP₃ were eliminated from the calculation of standard time.

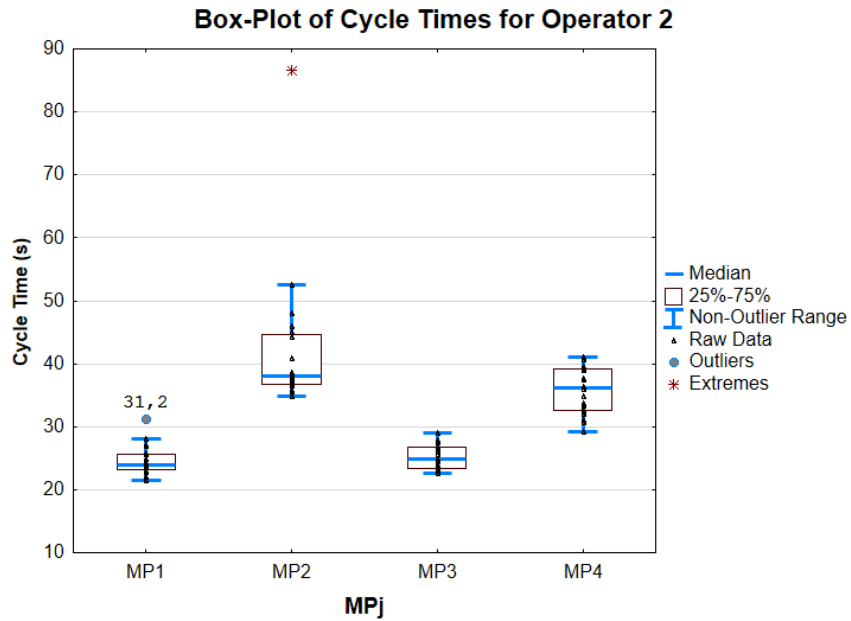


Figure 5.4: Box-Plot for each MP of operator 2

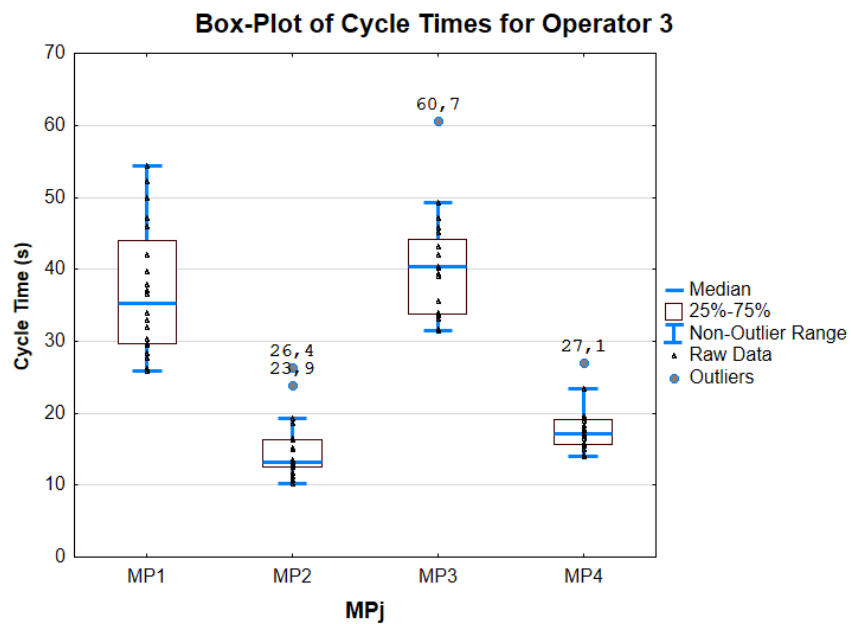


Figure 5.5: Box-Plot for each MP of operator 3

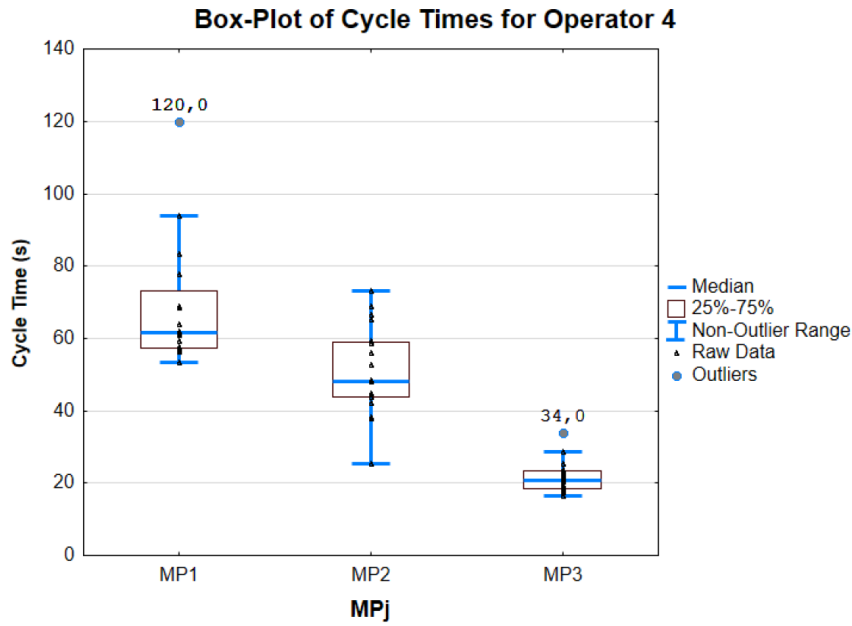


Figure 5.6: Box-Plot for each MP of operator 4

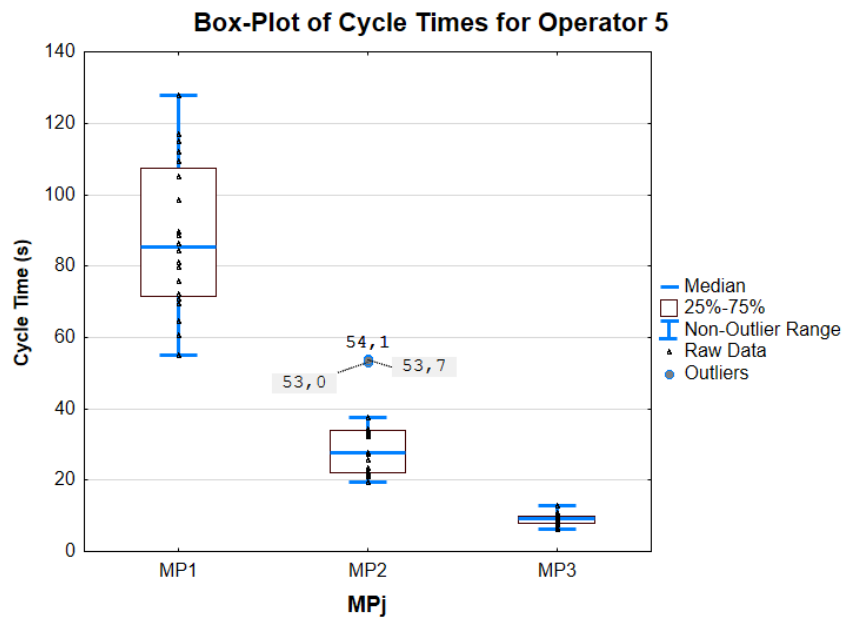


Figure 5.7: Box-Plot for each MP of operator 5

In Figure 5.7, for operator 5, it can be seen that there are 3 outliers from MP₃. The distance between the maximum and minimum cycle times of MP₁ is bigger when compared to MP₂ or MP₃, evidencing that the operator 5 may have more inconsistency while performing MP₁. The measurements of 53,0, 53,7, and 54,1 for MP₂ were eliminated from the calculation of standard time.

Thus, after the elimination of outliers, the average cycle time and the performance rating could be calculated as shown in Table 5.8. Assuming that operator 3 was the most skilled one and the others were maintaining a constant rhythm - when not influenced by external problems.

Operator	MPj	Average Cycle Time (s)	r
1	MP1	39,9	0,95
	MP2	24,9	0,95
	MP3	38,0	0,95
	MP4	26,2	0,95
2	MP1	24,3	0,95
	MP2	42,1	0,95
	MP3	25,1	0,95
	MP4	35,8	0,95
3	MP1	37,9	1
	MP2	13,9	1
	MP3	39,1	1
	MP4	17,6	1
4	MP1	65,4	0,95
	MP2	50,2	0,95
	MP3	21,1	0,95
5	MP1	85,9	0,95
	MP2	27,2	0,95
	MP3	9,1	0,95

Table 5.8: Results for Average cycle time and Performance rating r_j for each MP of each operator

Finally, it was possible to calculate the Normal times, in seconds (s), according to equation (4.3), for each MP, which are given in Table 5.9.

Thus, the standard time, in seconds (s), calculated through equation (4.4), for each operator can be seen in Table (5.10).

Upon analysis of the Measure stage of DMAIC, it was observed that there was a substantial amount of variability in the measured cycle times. Additionally, it was noted, that the operators did not consistently follow the same sequence of MPs. Besides, it

Operator	MPj	Normal Times (s)
1	MP1	37,9
	MP2	23,7
	MP3	36,1
	MP4	24,9
2	MP1	23,1
	MP2	40,0
	MP3	23,9
	MP4	34,0
3	MP1	37,9
	MP2	13,9
	MP3	39,1
	MP4	17,6
4	MP1	62,2
	MP2	47,6
	MP3	20,0
5	MP1	81,6
	MP2	25,8
	MP3	8,7

Table 5.9: Normal Times for each MP and each operator

Operator	Standard Time (s)
1	134,8
2	132,9
3	119,3
4	142,7
5	127,6

Table 5.10: Standard Times for each operator

was apparent that the tasks assigned to operators were unbalanced, with some operators having heavier tasks than others, resulting in an unequal distribution of tasks throughout the cycle.

5.3 Analyze results

Through the Analyze stage, the main problem of the production line was visualized in detail, and the root causes addressed to this problem were identified. For this purpose, the analysis of the data collected in the previous stage was made by (i) calculating the TT, for comparison with the standard time obtained; (ii) building the Root Cause Verification Matrix for visualizing the possible root causes; (iii) analyzing the possible root causes with 5 Why's until reaching the real one; and finally, (iv) categorizing the final root causes in a Fishbone Diagram.

Firstly, the TT was calculated through equation (4.5). Considering that the line works 3 shifts, eight hours each, theoretically, there would be a working time of 24 hours or 86400 seconds, but this does not reflect the time in which the operators are actually performing their tasks. The duration in minutes of each planned stoppage currently used by the production line is represented in Table 5.11.

Planned stoppage	Duration (min)
Pre-production preparation meeting	5
Coffee break	15
Lunch	40
Organization and cleaning	5
Maintenance interventions	2

Table 5.11: Duration of planned stoppages per shift

With this, 73 minutes or 4380 seconds can be deducted from production per shift, that is, the line effectively produces 73260 seconds (or 6 hours and 47 minutes) per shift. This is only considering the planned stops, without taking into account breakdowns or any unforeseen problems.

Currently, the customer demand is 550 products a day, thus the objective in terms of TT can be calculated as the expected amount of production time divided by the customer

demand. Hence, the TT of 133,2 seconds.

Next, Figure 5.8 was obtained in order to check if the operators were within an acceptable time interval. However, it represents that the operators did not find themselves in an acceptable interval, once it can be seen that operator 4 is exceeding TT by a significant margin, while operator 1 exceeds it by 1,6 seconds and operator 2 exceeds it by 0,3 seconds. Operator 5 is really close to reaching the TT, and considering the susceptibility of the process to have high cycle time variability, evidenced in the Box-Plots, it is possible that in certain cycles, these 2 operators may also exceed TT.

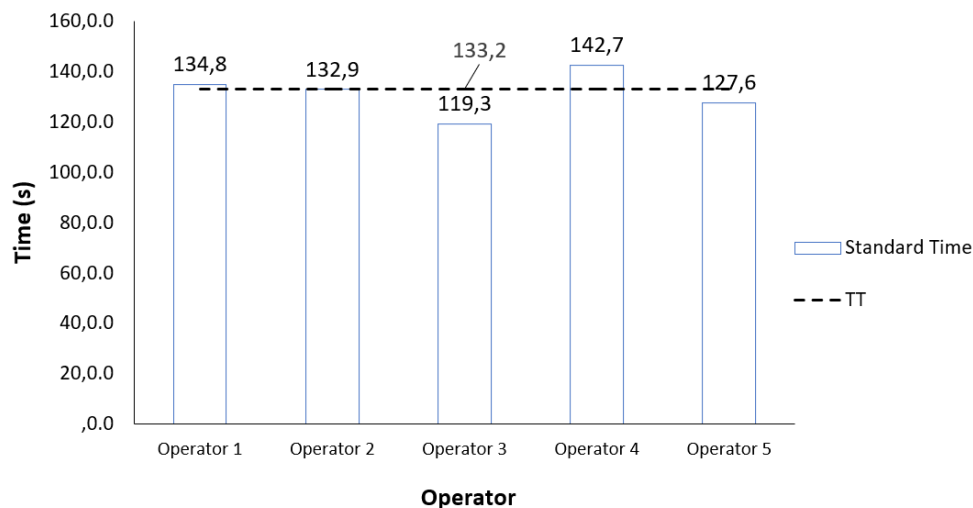


Figure 5.8: Cycle Time of each operator compared to the TT

In the first brainstorming session, the main problem was established as the surpassing of the TT by the standard time of the operators. There were 5 different possible root causes related to this problem.

The possible root cause (1) was observed during cycles, in which the operators needed to press the Welding Machine start-cycle buttons several times until it started to weld the components. This demonstrated that the machine's cycle start buttons were not working properly. It increased the cycle time of the operators, consequently influencing the overall production process.

The possible root cause (2) was observed during cycles where stuck levers, made it

difficult for operators to load and unload components from all machines in the production line. This, often required extra physical effort and time to complete the task.

The possible root cause (3) was observed for cycles where operators needed to use different tools. It was detected that, because the operators' tools were never set up in the same spot on the table, they would become lost when switching between tools. It was predominantly observed with operator 5. For instance, during the final inspection, operator 5 utilized several tools such as a bar code reader, brush, pen, and a small hammer. However, the tools did not have a fixed position. As a result, during many cycles, the operator had to spend extra time searching for misplaced tools, leading to lower efficiency and longer cycle times.

The possible root cause (4) was detected after analyzing work methods and observing the measured times from the previous stage. It became clear it was related to the problem identified during the first brainstorming session. It was found that some operators took more time than others to complete the MPs, evidencing an unbalanced distribution of tasks. Upon further analysis and cycle observations, it was discovered that some MPs from one operator could be transferred to another without severe impact on the cycle times, thereby reducing the load on the overburdened operator and creating a more balanced production line.

The possible root cause (5) was evidenced also after analyzing work methods and observing the measured times from the previous stage. It was identified by the interquartile distance of the Box-Plots, which showed a high variability in cycle times.

Thus, to validate and document the possible root causes assumptions, the Root Cause Verification Matrix was built, as shown in Table 5.12. Through this matrix, it was possible to see the method of verification used to validate each one of the root causes, the reason for the method to be chosen, and whether the possible root cause was verified or not.

Additionally, after the possible root causes were verified, a 5 Why's analysis was performed. This allowed the team to determine if the possible root causes were the actual real root causes of the problem or if a deeper analysis was needed. Figures 5.9, 5.10, 5.11, 5.12, and 5.13, represent the 5 Why's analysis for possible root causes (1), (2), (3), (4),

Problem	Possible Root Causes	Method of Verification	Reason for verification method	Verified
The operators standard time are surpassing or close to the TT	(1) Welding machine buttons not working properly	Cycle Observations	It provides real-life information	Yes
	(2) Levers for loading of components sticking on Welding Machines	Cycle Observations	It provides real-life information	Yes
	(3) Operators getting lost in tasks that involve different tools	Cycle Observations	It provides real-life information	Yes
	(4) Unbalanced tasks	Work Method's Analysis and Time measurement observation	It provides visual and quantitative representation per operator	Yes
	(5) The operators have significant amount of variability in cycle times	Box-Plot of Cycle time per operator	Provides visual representation of variability per operator	Yes

Table 5.12: Possible Root Cause Verification Matrix

and (5) respectively.

It was possible to notice that possible root causes 1 and 2, from Figure 5.12, were related to the machine performance. While the possible root cause 1, in Figure 5.9, is more related to technical problems of the machine, possible root cause 2, in Figure 5.10, is related to cleaning and restoring mechanical parts. Both of them could be corrected if the planned maintenance sessions, done by the Maintenance department, were made regularly. That is why the root causes for both of them were related to the organizational problems with the scheduling of Planned Maintenance.

As it can be seen in Figure 5.11, the possible root cause (3) is related to the lack of a simple tool identification system. It is important to highlight that a tool identification system already exists and has already been implemented in the company, presenting great historical results in facilitating the procedures that involve several tools.

The possible root cause (4), in Figure 5.12 is related to a lack of studying the state of the line periodically. It is associated with time studies, once only these kinds of studies

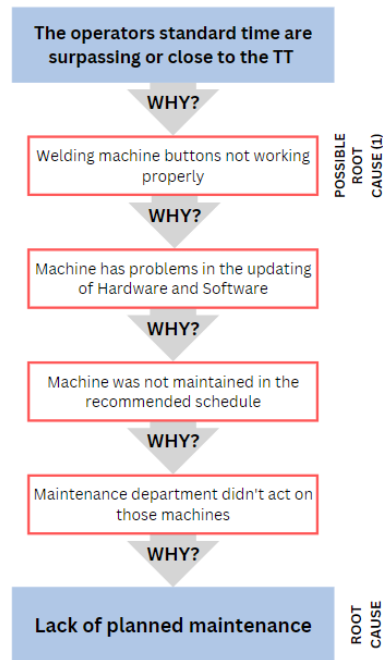


Figure 5.9: 5 Whys applied to the direct cause 1: Welding Machine buttons not working properly

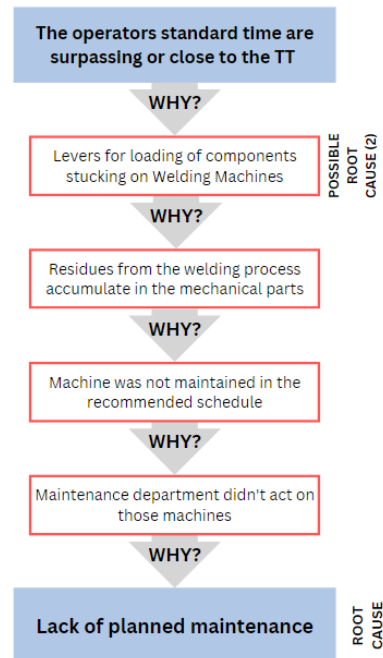


Figure 5.10: 5 Whys applied to the direct cause 2: Levers for loading of components sticking on Welding Machines

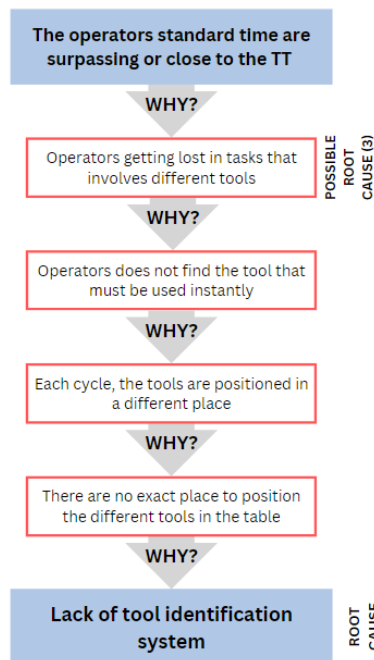


Figure 5.11: 5 Whys applied to the direct cause 3: Operator getting lost in tasks that involve different tools

would allow one to identify important information that could lead to identifying the presence of unbalanced tasks. Additionally, however it may be tempting to try solving this by redistributing the operator's tasks, but it is important to consider the long-term implications of this solution. This redistribution may only provide a temporary reduction in time and not address the underlying root cause of the issue.

In Figure 5.13, the possible root cause (5) is presented as due to the lack of easy-to-access updated video standards of the tasks. These videos could facilitate the operators understanding of the task. At the same time, the possible root cause (5) is also related to the lack of training and monitoring of the operator's performance.

Thus, 5 different root causes were evidenced, and they can be summarized as:

- ▶ Lack of planned maintenance;
- ▶ Lack of tool identification system;
- ▶ Lack of time and work method studies;

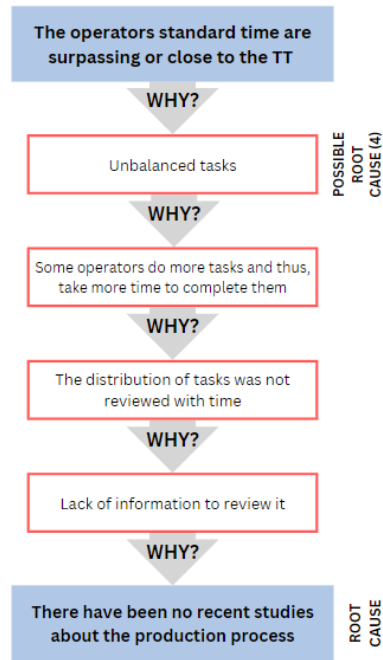


Figure 5.12: 5 Whys applied to the direct cause 4: Unbalanced tasks

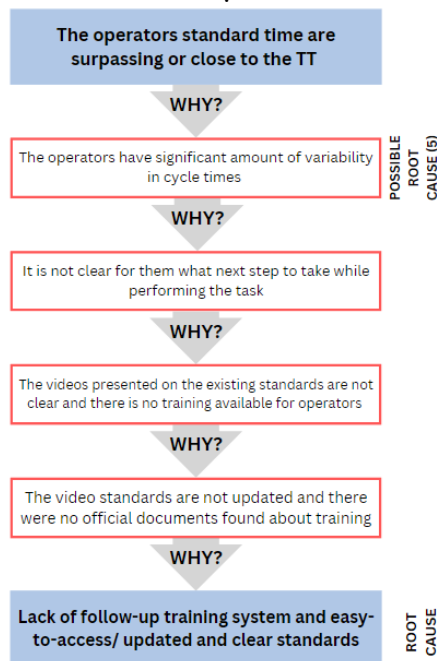


Figure 5.13: 5 Whys applied to the direct cause 5: The operators have significant amount of variability in cycle times

- ▶ Lack of updated and easy-to-access video standards;
- ▶ Lack of follow-up of operator's training and qualification.

After recognizing each root cause associated to the previously established problem, it was time to represent it in a more visual manner with the use of a Fishbone Diagram, categorizing each one of the root causes inside the categories Method, Machine, Measurements, and Materials, as represented in Figure 5.14.

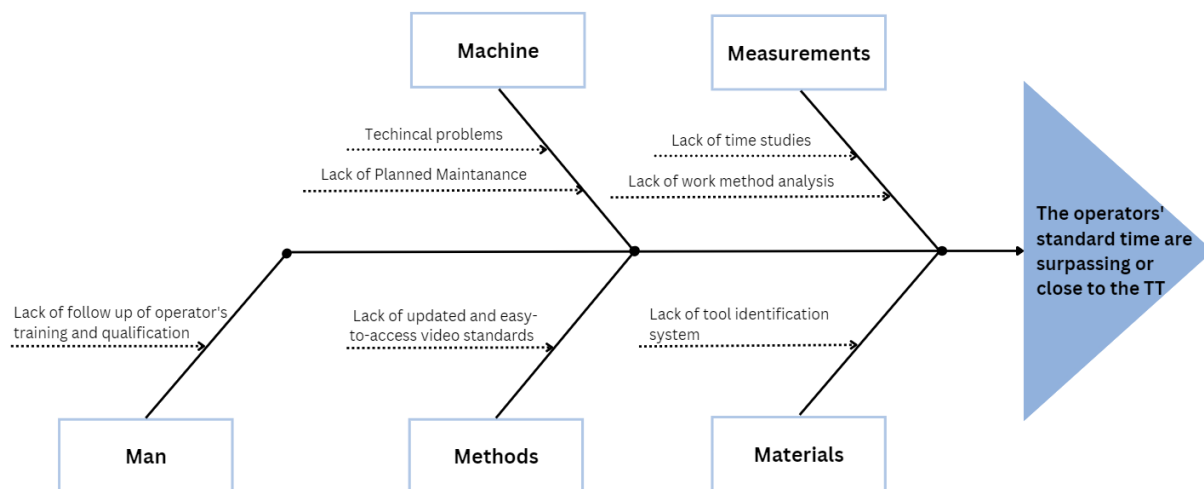


Figure 5.14: Fishbone Diagram presenting the root causes of the problems classified on 5 different categories

It is possible to see in Figure 5.14, that, for the machine category, the associated topic is lack of planned maintenance, which was found to be a root cause of some machine problems related mainly to the functioning of buttons and levers. The materials category is associated with the lack of a tool identification system, which contributed to the operator's difficulty in finding and using the right tools for a given task. Additionally, the measurement category is related to the lack of time and work method studies, which led to unbalanced task distribution. Besides that, the method category includes the lack of updated and easily accessible video standards, which resulted in confusion and errors. Those errors consequently led to the high variability of times during the execution of a task. Finally, the man category includes the lack of follow-up on the operator's training, which also led to the high variability of the tasks execution time.

By categorizing the root causes, it was easier to identify the underlying patterns in the problems affecting the production process. Additionally, it was possible to facilitate the visualization of where the solutions should act. This led to a targeted approach by developing solutions that address the real root causes rather than the possible ones. By focusing on the root causes, it is possible to create sustainable improvements in the production process that will help to increase efficiency and productivity over the long term.

5.4 Improve results

The Improve stage was focused on identifying and implementing effective solutions to the root causes identified in the previous stage, aiming to improve the production process. For the identification of solutions, 2 brainstorms were made to develop a solution selection matrix, an Impact-Effort matrix, and the results of the implementation of some solutions.

Firstly, the first brainstorming session in this stage provided solution ideas. Those ideas were listed in the solution selection matrix, which facilitated the evaluation and comparison of various potential solutions. It allowed a systematic assessment of each solution in terms of effectiveness, feasibility, and cost-benefit.

Three potential solutions were identified for the root cause "Lack of planned maintenance", figure 5.15. The first solution involves regularly planned maintenance programs to be executed by the Maintenance department. This includes regular inspections, repairs, software reviews, cleaning of machine components, and replacements, if necessary. The solution received a rating of 8 for effectiveness, 10 for feasibility, and 8 for cost-benefit on a scale of 1-10. If this solution is implemented, there are high chances of success in terms of root cause elimination. Additionally, it involves only manpower and tools that already work in the company, not requiring any considerable investment.

For the second solution proposed for the root cause "Lack of planned maintenance", it was suggested to implement new software, from an external company. This software would manage the Maintenance schedule planning automatically, through a user-friendly

Problem Statement	Validated Root Cause	Potential Solutions	Practical Method	Effectiveness	Feasibility	Cost-Benefit	Overall	Take Action?
The operators' standard time are surpassing or close to the TT	Lack of planned maintenance	Regular inspections, repairs, software reviews, cleaning of residues from machine components, and replacements of key components	Implement with Maintenance department a planned maintenance program with schedules that must be accomplished	8	10	8	640	Yes
		Made the planning from Maintenance program in a more automatic way, with a user friendly interface that could facilitate the communication between operators and Maintenance technical staff	Implement a new external software to manage and plan maintenance programs	10	4	4	160	No
		Use reactive maintenance to reduce problems as they arrive	Schedule maintenance programs as soon as the machines starts giving signals of failure (reactive maintenance)	2	7	2	28	No

Figure 5.15: Solutions Selection Matrix for root cause "Lack of planned maintenance"

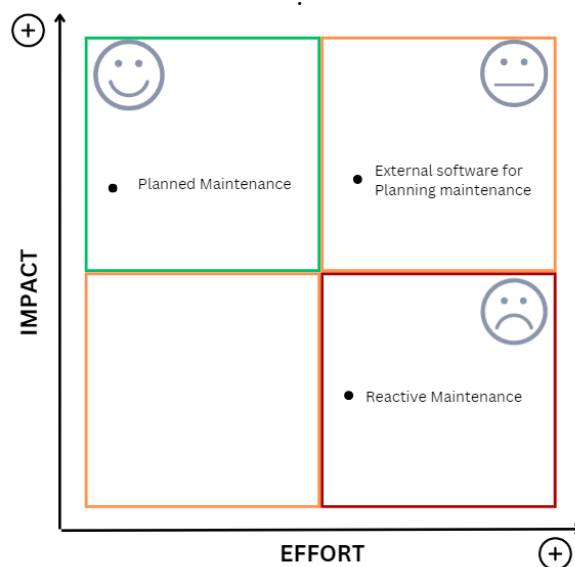
interface, and facilitate the communication between operators and technicals. Although this solution is highly effective, the short-term cost-benefit and feasibility are not high, since the process of contracting an external software would take more time and money when compared to the first solution.

The third solution proposed for addressing the "Lack of planned maintenance" root cause was to use reactive maintenance. This kind of maintenance involves treating the machines only when they start showing signs of failure. While this approach may be feasible, it is not an effective solution and does not offer significant cost benefits. In addition, reactive maintenance can lead to increased downtime and production losses, as machines may fail unexpectedly and require immediate attention. It is important to note that reactive maintenance should not be the primary maintenance strategy, as it is more costly and less efficient than preventive or predictive maintenance approaches.

After that, in the same brainstorming session, the impact-effort matrix was built for each solution. This matrix prioritizes the selected solutions based on their potential impact and the effort required for implementation. Additionally, it provides valuable information about the solutions that might be easily implemented and would generate the greatest impact.

Regarding the solutions addressed to the root cause "Lack of planned maintenance",

the first one would have a high impact, once the periodical maintenance of the machines would reduce downtime drastically. In addition, the first solution would also require low effort, including creating a maintenance plan and following it. For the second solution, the impact would be great, once it is similar to the first one in terms of planning. However, implementing external software requires greater effort and money. Finally, the third solution would require high effort, once the maintenance department would have to be prepared to react any time a production line had a machine problem. It also has low impact, once with time, machines might deteriorate and fail. Thus, the solutions were represented in an Impact-Effort matrix in Figure 5.16.



Source: Adapted from Prashar(2014)

Figure 5.16: Impact-Effort Matrix for root cause "Lack of planned maintenance"

With Figures 5.15, and 5.16 it was evident that, overall, implementing a planned maintenance program is the most effective solution for reducing downtime and increasing machine reliability in the long run.

For the root cause of "Lack of tool identification system", three potential solutions were identified, Figure 5.17. The first one involves the development of a simple drawn support system. This kind of support was already used in other production lines in the company

and worked as a visual aid for the operators. This solution requires low investment, and it is also highly feasible due to its simple design, which can be easily adapted in case of any tool changes in the production line.

The second solution addressed the root cause "Lack of tool identification system" involves the purchase of a 3D magnetic support to attach the tools. This solution is very effective in terms of keeping the tools fixed in the same position. However, it will require an external purchase and will not work if there is any plastic tools on the table.

The third solution addressed the root cause "Lack of tool identification system involves a more complex, but highly effective system of barcoding technology that would be "red" if the tool was in the wrong place, notifying the operator that the tool should be placed in another position. However, even being effective this system would require a lot of money and a mapping of the suppliers available in the market.

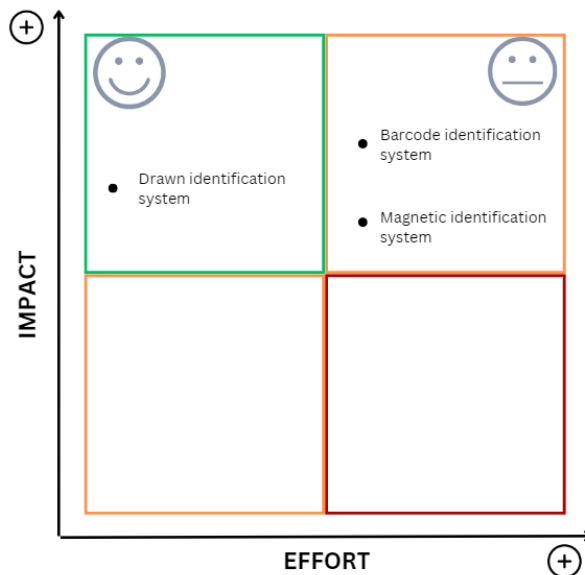
Figure 5.18 represents the Impact-Effort matrix for each of the possible solutions, considering that, the first one would give a great impact, once it would solve the problem of not knowing where to place a tool. The first solution would require nothing more than a pen to draw where the tools would be, hence, low effort. The second solution would generate great impact in terms of position location, but not as much as the first one, once it does not work for every tool. However, it would require the effort of finding a supplier for magnetic pieces and arranging the setup. The third solution, even having a high impact, would require a lot of effort in finding a supplier for the bar code automatic system as well as for arranging the setup.

With Figures 5.17, and 5.18 it was evident that, overall, implementing a drawn tool identification system, would be costless and would reduce the confusion of operators working with several tools.

For the root cause of "Lack of studies about the production process," the team proposed two possible solutions, planning workshops and preparing audits to make the studies of the process mandatory, as shown in Figure 5.19. In terms of efficiency and long-term impact, the first solution was more suitable, as it involves gradually creating a culture of continuous improvement within the company. This approach prioritizes employee involvement and

Problem Statement	Validated Root Cause	Potential Solutions	Practical Method	Effectiveness	Feasibility	Cost-Benefit	Overall	Take Action?
The operators' standard time are surpassing or close to the TT	Lack of tool identification system	Use similar solution from other lines (simple drawn identification system)	Create a simple identification system as it is done in other similar production lines, with pins for securing larger tools and identification designs that represent the outline of the tool	9	7	9	567	Yes
		Prepare a magnetic 3D support to attach the tools	Buy in external companies a magnetic support that are adapted for each of the tools that needs to be identified	8	6	4	192	No
		Develop automatic system that uses barcoding technology	Buy in external companies a system using barcoding technology to track the location and usage of all tools in the production line	10	4	4	160	No

Figure 5.17: Solutions Selection Matrix for root cause "Lack of tool identification system"



Source: Adapted from Prashar(2014)

Figure 5.18: Impact-Effort Matrix for root cause "Lack of tool identification system"

empowerment in the pursuit of process improvement. On the other hand, even if the second solution of mandatory audits may be met with resistance from employees, it is also highly effective and feasible. Therefore, both of the solutions were selected.

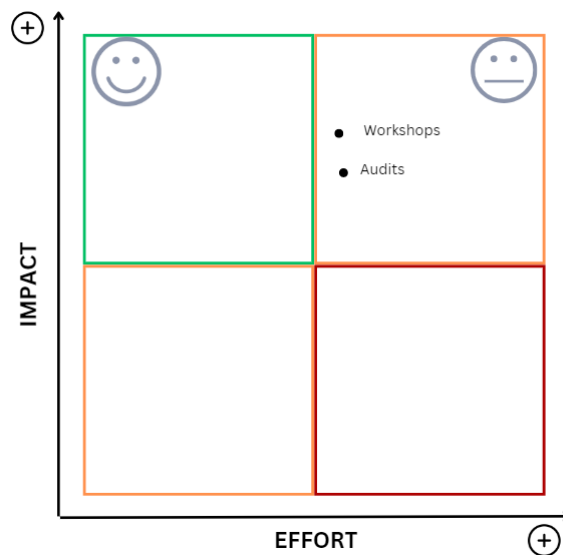
In terms of impact and effort, both solutions are nearly at the same level, once the preparation of an audit and the preparation of workshops would require similar effort and would result in similar impact. Figure 5.20 represents that in the matrix.

Problem Statement	Validated Root Cause	Potential Solutions	Practical Method	Effectiveness	Feasibility	Cost-Benefit	Overall	Take Action?
The operators' standard time are surpassing or close to the TT	Lack of studies about the production process	Plan workshops regularly to review and optimize work processes	Planning of workshops, previously inviting workers from different departments using Microsoft Outlook calendar, for previous preparation that will implement DMAIC methodology and recognize process improvements	8	8	7	448	Yes
		Plan internal audits that will force supervisors to update and correct their documentation	Planning of internal audits, that follows a sequence of steps of evaluation, in order to make it mandatory to the supervisors to update and correct the documents, consequently making it necessary to perform further studies of the process	5	7	6	210	Yes

Figure 5.19: Solutions Selection Matrix for root cause "Lack of studies about the production process"

Also during the first brainstorming session, it was determined that the root cause of "Lack of updated and easy-to-access video standards" could be solved in conjunction with the previous solution. The team came to a consensus that during the planning workshops, the workers could be trained on the new process improvements and, afterward, record videos of the updated standards. These videos could then be uploaded to a platform that the company already has in place, providing easy access to the operators. This approach not only addresses the root cause but also leverages the company's existing resources. Furthermore, it promotes a culture of continuous improvement and encourages knowledge sharing among the operators. In addition to that, the solution concerning the audits would reinforce the correction of the video standards and documents.

The root cause "Lack of follow-up of operator's training and qualification" had two



Source: Adapted from Prashar(2014)

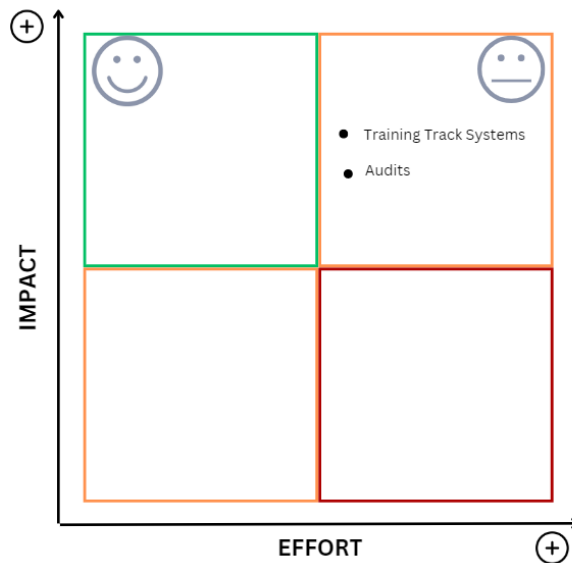
Figure 5.20: Impact-Effort Matrix for root cause "Lack of studies about the production process"

possible solutions. One of them is to program audits to evaluate the operator's capacity to follow the standards, which is the same as the previous solution. Also, the second solution was a training tracking system to ensure that all operators receive regular training and follow-up evaluations, as can be seen in Figure 5.21. These solutions were considered to have similar levels of effectiveness, as they both aim to ensure that operators are properly trained and qualified. Both solutions were feasible, with the training tracking system being slightly more feasible than program audits, once it involves fewer people. In terms of cost-benefit, the program audits had slightly better grades.

For the Impact-Effort matrix, the first and the second solutions present similarities in terms of impact, once they would guarantee the constant training of the operator. Also, in terms of effort, they present similarities, once the preparation for an audit and the creation of a training track system could have the same levels of difficulty, Figure 5.22. As a result, both solutions will be implemented, with program audits being used as a complement to the training tracking system. This approach will ensure that operators receive continuous training and evaluations, leading to improved performance and adherence to standards.

Problem Statement	Validated Root Cause	Potential Solutions	Practical Method	Effectiveness	Feasibility	Cost-Benefit	Overall	Take Action?
The operators' standard time are surpassing or close to the TT	Lack of follow-up training system	Program audits to the operators in which their qualification and capacity to follow the standards are evaluated	Planning of audits in order to evaluate the levels of compliance to standards and qualification from the operators	9	7	8	504	Yes
		Training tracking system that ensures all operators receive regular training and follow-up evaluations	Simple tracking system, using Excel, to follow the operators, training schedule and also their performances in follow up evaluations	9	8	7	504	Yes

Figure 5.21: Solutions Selection Matrix for root cause "Lack of follow-up of operator's training and qualification"



Source: Adapted from Prashar(2014)

Figure 5.22: Impact-Effort Matrix for root cause "Lack of follow-up of operator's training and qualification"

Thus, the solutions obtained for each of the root causes addressed to the problem identified in the Analyze stage were:

- ▶ Creation of a planning for maintenance program for the production line;
- ▶ Implementation of a simple tool identification system that can be adapted if there is any change of tools in the production line, which construction requires resources that already exist in the company;
- ▶ Planning of workshops, at least, once a month, requiring at least 5 people - the number of people will depend on the requirements of the line under study - which would study the production process of the line, participate in brainstorming sessions, find root causes, address solutions, validate them and plan their implementation. After this implementation, videos of the qualified operators performing their tasks according to standard, are going to be recorded and uploaded to the company's official platform in order to be available for everyone;
- ▶ Programming audits to evaluate the qualification and capacity of operators to follow the standards and creating a training tracking system with the use of an Excel file, to ensure all operators receive regular training and follow-up evaluations.

5.4.1 Partial implementations

For the case study of the present work, not all of the solutions were implemented because of time and lack of availability in part of the company, which also had other priorities concerning other production lines. The first implemented solution was the tool identification system. Figure 5.23 shows how the tools were organized in a box before the improvement presented on Figure 5.24. For final inspection table, it was also implemented a screwdriver support for better identification of tools, as it is presented on Figure 5.25.

Another solution implemented was the creation of video standards for the production line. Once the time studies and work method analysis had already been done throughout this work, it was possible to record videos of the most skilled worker performing the tasks



Figure 5.23: Tool organization before the solution implementation



Figure 5.24: Tool organization after the solution implementation



Figure 5.25: Solution implemented for operator 5: Creation of supports on tables to put the screwdrivers

in each machine. The performance of the tasks was done in a slower way in order to record every detail. The videos of each operator were uploaded to the platform that the company already has in place.

5.5 Control results

In this stage, the goal is to ensure that the implemented solutions are sustained and address the problem identified in the Analyze stage. It also aims to keep track of the missing solutions implementation.

Aiming to ensure the implemented solutions (tool identification system and video standards) addressed the problem of operators exceeding the TT, a new set of time measurements was conducted. It is important to note that these measurements were carried out in mid-February, several weeks after the implementation of the solutions in late January. Thus, the measurements were focused only on operator 5. This particular operator was chosen, once it was expected to experience the most significant impact from the tool identification system solution as the only one using several tools in the same task. The effects of the video standards solution on other operators were expected to have an impact in the long term. Hence, the comparison measurements were limited to operator 5 for this evaluation.

Table 5.13 presents the measurements for operator 5 and Figure 5.26 presents the Box-Plot for operator 5 after the implementation of the tool identification system. It was seen that with this implementation, in addition to the updated video standards implementation, the variability of the MPs time has decreased, once the interquartile range is smaller when compared to Figure 5.7. After the elimination of the outliers presented on Figure 5.26, the standard time for operator 5 after the solution implementation was calculated as 95,8 seconds. This gives a difference of 31,8 seconds representing a decrease of 24,9% when compared to the previous standard time.

With this, it could be verified that the implemented solutions have successfully mitigated the problem of operators exceeding the TT, particularly for operator 5. The tool

identification system and video standards have contributed to decreasing the confusion of the operator while dealing with several tools. Hence, these improvements contributed to reducing the variability and ultimately enhanced productivity in the production process.

Furthermore, it is important to note that there is still work to be done in addressing the TT issue for other operators. That is why, for this stage of DMAIC a Gantt chart was built in order to ensure that the other solutions will be implemented, Figure 5.27. This chart was also built to monitor the problem mitigation, through new measurements.

MP _j	x_{kj}^5																			
	x_{1j}	x_{2j}	x_{3j}	x_{4j}	x_{5j}	x_{6j}	x_{7j}	x_{8j}	x_{9j}	x_{10j}	x_{11j}	x_{12j}	x_{13j}	x_{14j}	x_{15j}	x_{16j}	x_{17j}	x_{18j}	x_{19j}	x_{20j}
MP1	67,6	63,5	63,4	78,8	61,9	58,6	53,6	73,4	57,9	62,6	62,9	60,7	65,1	62,1	63,4	64,8	61	64,2	67,6	65,7
MP2	27,3	30,1	26,7	32,4	28,3	28,4	29,3	30,4	27,3	27,8	29,4	27,3	28,5	26,3	28,3	27,3	26,4	26,4	26,8	27,4
MP3	10,3	10,4	9,9	9,5	9,4	9,6	9,4	8,9	23,9	9,5	9,3	9,4	10,2	8,7	10,4	9,9	9,5	9,4	9,6	9,4
Cycle Time	105,2	104,0	100,0	120,7	99,6	96,6	92,3	112,7	109,1	99,9	101,6	97,4	103,8	97,1	102,1	102,0	96,9	100,0	104,0	102,5

Table 5.13: Data for $k = 20$ measurements for operator 5 after the implementation of tool identification system

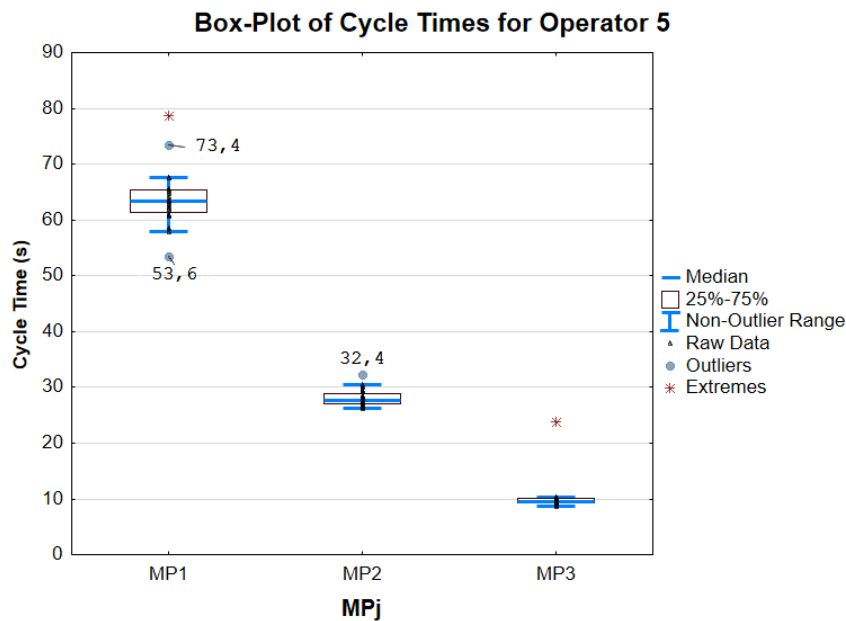


Figure 5.26: Box-Plot for Operator 5 after solution implementation

It is important to highlight that, for this stage of DMAIC, the milestone exposed in the Project Charter was accomplished. According to the Gantt Chart, what was planned for the Control stage is going to happen from February/2023 to June/2023.

CHAPTER 5. IMPLEMENTATION OF DMAIC ON WORK STANDARDS' IMPROVEMENT

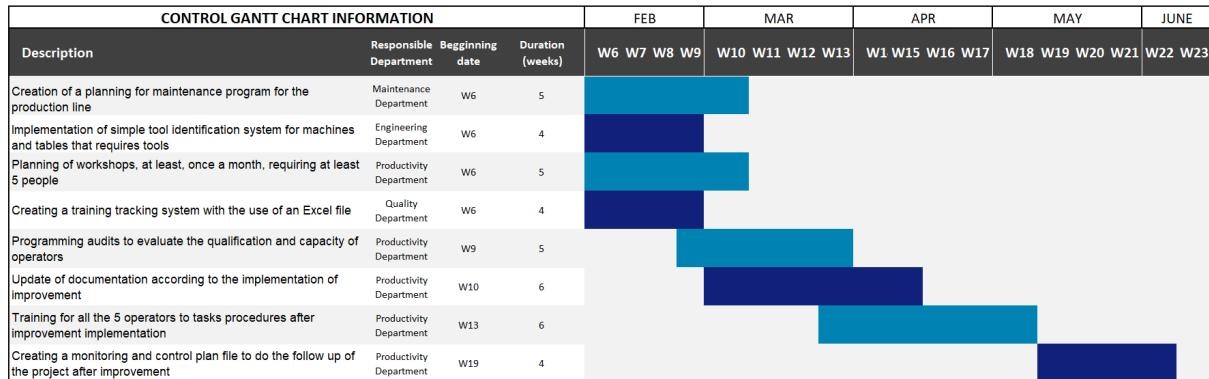


Figure 5.27: Gantt Chart for Control Stage of process improvement in catalytic converter production line

Additionally, the duration for each activity in the Gantt Chart was based on historical data from the company, once similar activities have already been planned and implemented. Thus, as a result, the current Gantt chart will be a helpful tool to inform the responsible departments about the implementation plan and make sure that everyone is aligned regarding the timeline and responsibilities.

Chapter 6

Conclusions and future work

The present work was a result of an internship at an automotive components company, in which the presented case study in a catalytic converter production line was made. The internship has contributed significantly to the understanding of the production line problems and opportunities. By implementing DMAIC methodology and proposing effective solutions, this work has made a valuable contribution towards the production line's improvement, and each of the stages of the DMAIC methodology generated relevant results that contributed to this improvement.

The main objective of the case study was precisely to investigate which problems in the production line made it unable to meet customer demands within normal working hours, seeking to find possible solutions to this problem, using the DMAIC methodology.

Such methodology acted in the clear definition of the problem faced by the production line and in the characterization of the project, with its milestones and team members. It also performed the measurements of the initial conditions of the production line. In addition, it acted in the analysis of the quantified problems, in order to assign them a root cause, for consequently, acting on the creation of possible solutions that worked precisely in the mitigation of the root causes identified. Finally, the methodology acted in the follow-up and control of the implementation of such solutions.

The Define and Measure stages provided the foundation for DMAIC. The first one, through the generation of a Project Charter and a SIPOC diagram, that clarified and

specified the project's needs, and the problem characterization. On the other hand, during the Measure stage, it was possible to gather quantitative data from the production line. One of the main contributions of this stage, was the definition of a sample size of 20 time observations, to generate more reliable measurements. The data measured worked as input for the Box-Plots, which, through the interquartile range, showed considerable variability in MPs times. Another important concept calculated in this stage was the standard time for each operator, that worked as main input for the next stage.

Thus, with the input provided by the Measure stage, it was possible to start the Analyze stage. In which, through brainstorming sessions, it was identified the main problem of the production line: the operator's standard time was surpassing the TT. Once the problem was identified, the Analyze stage addressed the root causes of this problem. This prevented the company from insisting on the implementation of quick solutions that would act on the possible root causes, but which in the long term would not solve the main problem.

The Improve stage presents itself as one of the greatest contributions of the present work. It acted on the selection of simpler, easier-to-implement, less costly, and more efficient solutions to address the problem of the production line. These solutions were: the implementation of a tool identification system; planning workshops, programming audits, recording video standards, and creating a training tracking system.

Finally, the Control stage, not only provided a plan for the monitoring and follow-up of the solution implementation, but also - since only 2 solutions were implemented - validated those solutions in terms of problem mitigation. In this stage, a Gantt Chart was built to monitor the implementation of solutions and the results generated by the ones already implemented. In this stage, it was revealed that the implementation of the tool identification system, in conjunction with the updated video standards, has led to a reduction of the operator 5 standard time in 24,9% compared to the measurements obtained for the same operator before the solution implementation.

The main limitations found throughout this work were related to the speed of changes that occurred in the organization, in relation to operators, supervisors, shifts, and other

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

factors; the cooperation of operators during measurements in relation to compliance with the standard while carrying out their tasks; the divergence of information found in the standard documentation; difficulty in proposing improvements that were not blocked by the budget, safety department, and machine regulations; the date definition for planning the implementation of improvements, due to the agenda of other departments and their priorities.

Despite the pointed-out limitations, overall, this study can be useful for other companies facing similar challenges and work as a starting point for further research in the field of process improvement.

Therefore, one of the main suggestions for future work would be the implementation of a more automated way to obtain time measurements that would make these measurements more accurate and less susceptible to human errors, such as the use of the machines' own sensors to measure times.

Another area for potential improvement is in the development of a system to monitor and track the progress of the improvements made, in order to ensure that they are sustained over time. Additionally, it could be beneficial to investigate the possibility of implementing automation or robotics in certain aspects of the production process, in order to further increase efficiency and reduce the risk of human error.

Overall, this case study has provided valuable insights into the use of DMAIC methodology for improving the production process of catalytic converters. However, there is still room for further investigation and refinement, and future works can continue to build upon the foundation laid by this study.

Bibliography

- [1] E. Commission. “Co emission performance standards for cars and vans”. (2022), [Online]. Available: https://climate.ec.europa.eu/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/co2-emission-performance-standards-cars-and-vans_en (visited on 05/12/2023).
- [2] E. A. M. A. (ACEA). “Position papers – proposal for a euro 7 regulation”. (2023), [Online]. Available: <https://www.acea.auto/publication/position-papers-proposal-for-a-euro-7-regulation/> (visited on 04/17/2023).
- [3] Z. M. Research. “Catalytic converter market - growth report”. (2023), [Online]. Available: <https://www.zionmarketresearch.com/report/catalytic-converter-market> (visited on 04/17/2023).
- [4] E. James and W. Lindsay, “An introduction to six sigma & process improvement”, *South Westem, Singapore: Thomson*, 2005.
- [5] P. Jirasukprasert, J. A. Garza-Reyes, V. Kumar, and M. K. Lim, “A six sigma and dmaic application for the reduction of defects in a rubber gloves manufacturing process”, *International Journal of Lean Six Sigma*, vol. 5, pp. 2–22, 2015.
- [6] A. Mittal, P. Gupta, V.Kumar, A. A. Owad, S. Mahlawat, and S. Singh, “The performance improvement analysis using six sigma dmaic methodology: A case study on indian manufacturing company”, *Heliyon*, vol. 9, 2023.
- [7] W. H. Crew, “The american standards association-our colleague in standardization”, *Proceedings of the IRE*, vol. 34, no. 11, pp. 874–875, 1946.

BIBLIOGRAPHY

- [8] K. B. Zandin, *Maynard's Industrial Engineering Handbook*. McGraw-Hill New York-USA, 2001.
- [9] A. Adeodu, M. G. Kanakana-Katumba, and M. Rendani, "Implementation of lean six sigma for production process optimization in a paper production company", *Journal of Industrial Engineering and Management*, vol. 14, no. 3, pp. 661–680, 2021.
- [10] D. Losonci, K. Demeter, and I. Jenei, "Factors influencing employee perceptions in lean transformations", *International Journal of Production Economics*, vol. 131, no. 1, pp. 30–43, 2011.
- [11] J. K. Liker and D. Meier, *Toyota way fieldbook*. McGraw-Hill Education, 2006.
- [12] J. Heizer, B. Render, C. Munson, and A. Sachan, *Operations management: sustainability and supply chain management, 12/e*. Pearson Education, 2017.
- [13] F. Khairat *et al.*, "Preventing accidents through the implementation of the work standards in the welding workplace", in *5th International Conference on Health Sciences (ICHS 2018)*, Atlantis Press, 2019, pp. 102–109.
- [14] W. J. Stevenson, M. Hojati, and J. Cao, *Operations management*. McGraw-Hill Education Chicago-USA, 2014.
- [15] K. S. Al-Saleh, "Productivity improvement of a motor vehicle inspection station using motion and time study techniques", *Journal of King Saud University-Engineering Sciences*, vol. 23, no. 1, pp. 33–41, 2011.
- [16] J.-C. Lu, T. Yang, and C.-Y. Wang, "A lean pull system design analysed by value stream mapping and multiple criteria decision-making method under demand uncertainty", *International Journal of Computer Integrated Manufacturing*, vol. 24, no. 3, pp. 211–228, 2011.
- [17] L. F. da Silva de Novais, I. F. dos Santos, and G. D. O. Costa, "Uso do diagrama de espaguete no setor de armazenagem de matérias-primas em uma indústria do ramo alimentício em goiânia-go", *Encontro Nacional de Engenharia De Produção*, 2021.

BIBLIOGRAPHY

- [18] V. Peralta, C. Sims, P. Palma, *et al.*, “Increasing productivity in garments manufacturing through time standardization and work measurement”, in *Proceedings of the International Conference on Industrial Engineering and Operations Management, 2019 (MAR)*, 2019, pp. 1719–1726.
- [19] G. Salvendy, *Handbook of industrial engineering: technology and operations management*. John Wiley & Sons, 2001.
- [20] A. U. Rehman, M. B. Ramzan, M. Shafiq, A. Rasheed, M. S. Naeem, and M. M. Savino, “Productivity improvement through time study approach: A case study from an apparel manufacturing industry of pakistan”, *Procedia Manufacturing*, vol. 39, pp. 1447–1454, 2019.
- [21] A. Baines, “Work measurement—the basic principles revisited”, *Work Study*, 1995.
- [22] G. Kanawaty, *Introduction to work study*. International Labour Organization, 1992.
- [23] A. Gill, C. Bector, and O. Hawaleshka, “Sample size formula in work measurement under a fuzzy environment”, *International Journal of Operations & Production Management*, 1994.
- [24] Y. L. Chan and Y. Yuan, “Dealing with fuzziness in cost-volume-profit analysis”, *Accounting and Business Research*, vol. 20, no. 78, pp. 83–95, 1990.
- [25] M. P. Groover, *Work systems and the methods, measurement, and management of work*. Pearson Prentice Hall Upper Saddle River, NJ, 2007.
- [26] A. Prashar, “Adoption of six sigma dmaic to reduce cost of poor quality”, *International Journal of Productivity and Performance Management*, vol. 63, no. 1, pp. 103–126, 2014.
- [27] P. A. de Albuquerque Marques and R. Matthé, “Six sigma dmaic project to improve the performance of an aluminum die casting operation in portugal”, *International Journal of Quality & Reliability Management*, vol. 34, no. 2, pp. 307–330, 2017.

BIBLIOGRAPHY

- [28] A. Y. Alqahtani, “Improvement of maintenance orders lead time in public universities: Dmaic approach”, in *2020 IEEE International Symposium on Systems Engineering (ISSE)*, IEEE, 2020, pp. 1–8.
- [29] J. D. Mast and J. Lokkerbol, “An analysis of the six sigma dmaic method from the perspective of problem solving”, *International Journal of Production Economics*, vol. 139, no. 2, pp. 604–614, 2012.
- [30] M. Kumar, J. Antony, F. J. Antony, and C. N. Madu, “Winning customer loyalty in an automotive company through six sigma: A case study”, *Quality and Reliability Engineering International*, vol. 23, no. 7, pp. 849–866, 2007.
- [31] M. Kholil, A. Suparno, S. B. H. Hasan, and M. Rizki, “Integration of dmaic, vsm and valsat to reduce waste in disk brake cutting process using dmaic, vsm and valsat method approach (case study: Company im)”, *International Journal Of Scientific Advances*, vol. 2, no. 2, 2021.
- [32] C. Setter, “Six sigma: A complete step-by-step guide: A complete training & reference guide for white belts, yellow belts, green belts, and black belts”, *The Council for Six Sigma Certification*, 2018.
- [33] C.-Y. Cheng and P.-Y. Chang, “Implementation of the lean six sigma framework in non-profit organisations: A case study”, *Total Quality Management & Business Excellence*, vol. 23, no. 3-4, pp. 431–447, 2012.
- [34] C. Gangala, M. Modi, V. K. Manupati, M. L. Varela, J. Machado, and J. Trojanowska, “Cycle time reduction in deck roller assembly production unit with value stream mapping analysis”, in *Recent Advances in Information Systems and Technologies: Volume 3 5*, Springer, 2017, pp. 509–518.
- [35] M. Prasanna and S. Vinodh, “Lean six sigma in smes: An exploration through literature review”, *Journal of Engineering, Design and Technology*, vol. 11, no. 3, pp. 224–250, 2013.

BIBLIOGRAPHY

- [36] P. Mishra and R. K. Sharma, “A hybrid framework based on sipoc and six sigma dmaic for improving process dimensions in supply chain network”, *International Journal of Quality & Reliability Management*, vol. 31, no. 5, pp. 522–546, 2014.
- [37] L. Barjaktarovic and D. Jecmenica, “Six sigma concept”, *Acta Technica Corviniensis-Bulletin of Engineering*, vol. 4, no. 4, p. 103, 2011.
- [38] C. Lin, F. F. Chen, Y. M. Chen, G. Kuriger, *et al.*, “Continuous improvement of knowledge management systems using six sigma methodology”, *Robotics and Computer-Integrated Manufacturing*, vol. 29, no. 3, pp. 95–103, 2013.
- [39] M. Bhargava and S. Gaur, “Process improvement using six-sigma (dmaic process) in bearing manufacturing industry: A case study”, in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, vol. 1017, 2021, p. 012034.
- [40] C. A. D. JUNIOR, N. D. S. D. SANTOS, and V. J. D. SOUSA, “Aplicação da metodologia dmaic para melhoria de processo”, *XII FATECLOG - GESTÃO DA CADEIA DE SUPRIMENTOS NO AGRONEGÓCIO: DESAFIOS E OPORTUNIDADES NO CONTEXTO ATUAL*, 2021.
- [41] A. H. Chawsheen, I. S. Latif, *et al.*, “Detection and treatment of outliers in data sets”, *IRAQI JOURNAL OF STATISTICAL SCIENCES*, vol. 6, no. 1, pp. 58–74, 2006.
- [42] L. Liliana, “A new model of ishikawa diagram for quality assessment”, in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, vol. 161, 2016, p. 012099.