Universidade do Minho
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Electromagnetic Behaviour in Valves: Study of Hysteresis Curves for Conformity Assessment

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Dissertação de Mestrado
Mestrado em Engenharia e Gestão da Qualidade

Trabalho efetuado sob a orientação do(a)
Professor Doutor Eusébio Manuel Pinto Nunes
Professora Doutora Cristina Maria dos Santos Rodrigues

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DECLARAÇÃO DE INTEGRIDADE

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Electromagnetic Behaviour in Valves: Study of Hysteresis Curves for Conformity Assessment

Abstract

The automotive industry is one of the most competitive branches of industry worldwide, due to its demand for a better product. The concept of quality and conformity is important to get an edge towards other competitors in the market, while continuous improvement is one of the keys to adapt and improve in an industry where lower production costs are as important as the innovation for new and better products.

The present dissertation has the main goal of implementing a control to ensure quality conformity for EGR Valves, using its hysteresis in its operation, and its target is to identify non-conform parts where its components have a mechanical defect that influences the functionality and specification of the product. Mechanical defects lead to either a variation in the current consumption or a higher current consumption of the motor, which is the component of the EGR valve responsible for the mechanical movement. These parts lead to quality costs associated with production line indicators as well as customer claims and warranties. This approach is supported by the FMEA methodology, working towards the continuous improvement of the production line and its products.

The work presented was successfully implemented in an international automotive industry context, where the implementation of the control method was supported by the organisation and the results obtained were aligned with the expectations of this work of lowering quality and warranty complaints, lowering the first rejection rate, and increasing the total output of the production line.

Keywords: Automotive Industry, Current Hysteresis, EGR Valve, FMEA, Quality

Comportamento Eletromagnético em Válvulas: Estudo das Curvas de Histerese para Avaliação da Conformidade

Resumo

A indústria automóvel é um dos ramos mais competitivos da indústria mundial, devido à sua demanda por um produto melhor. O conceito de qualidade e conformidade é importante para obter uma vantagem sobre os concorrentes no mercado, enquanto a melhoria contínua é uma das chaves para adaptar e melhorar numa indústria onde os baixos custos de produção são tão importantes como a inovação por novos e melhores produtos.

A presente dissertação tem o principal objetivo de implementar um controlo para conformidade na qualidade de Válvulas EGR, usando a histerese na sua operação, e o alvo é identificar as peças não-conformes onde os seus componentes têm um defeito mecânico que influencia o funcionamento do produto. Defeitos mecânicos levam a uma variação no consumo de corrente ou a uma maior corrente de consumo por parte do motor, sendo este o componente responsável pelo movimento mecânico da válvula EGR. Estas peças levam a custos de qualidade associados com a linha de produção juntamente com reclamações e garantias dos clientes. A estratégia é suportada pela metodologia AMFE, trabalhando para a melhoria contínua da linha de produção e dos seus produtos.

O presente trabalho foi implementado numa empresa multinacional da indústria automóvel, onde a implementação do método de controlo foi suportada pela organização e os resultados foram alinhados com as espectativas de reduzir as reclamações de qualidade e garantias, baixar a percentagem da primeira rejeição, e aumentar o volume total da linha de produção.

Palavras-chave: Indústria Automóvel, Corrente de Histereses, Válvula EGR, AMFE, Qualidade

Index

Figure Index

List of Tables

List of Abbreviations

5Why	Five Whys
5W2H	Five W’s two H’s
8D	Eight Disciplines of Problem-Solving Process
ASIL	Automotive Safety Integrity Level
CAN	Controlled Area Network
CFT	Cross Functional Team
CoQ	Cost of Quality
CUSUM	Cumulative Sum
DC	Direct Current
DFMEA	Design FMEA
DV	Design Verification
EOL	End-of-Line
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EV	Electric Vehicle
EWMA	Exponentially Weighted Moving Average
FMEA	Failure Mode and Effect Analysis
IT	Information Technology
KPI	Key Performance Indicator
NOx	Nitrogen Oxides
PFMEA	Process FMEA
PN	Part Number
PV	Product Validation
PWM	Pulse Width Modulation
RPN	Risk Priority Number
SOP	Start of Project
SPC	Statistical Process Control
VAT	Value-Added Tax

Chapter 1 – Introduction

Throughout the history of industrial production, there have been several cases of products manufactured in a production line that did not comply within the specifications of the product. As a result, certain parameters and variables must be monitored and controlled to ensure product quality, while also pushing for continuous improvement to maintain process control and ensure customer satisfaction.

1.1. Framing overview and motivation

With the process of globalization, many companies establish high standards for their products and services. In this level of competition, where profit margins are also very slim, it is necessary to take into consideration all areas of the processes that can be improved and optimised. It comes with establishing a culture that pursues continuous improvement inside the respective organisation to get an edge over the rest of the market competition.

The quality of a product has never been so important in an industrial context. In the automotive industry, more specifically with Exhaust Gas Recirculation (EGR) valves, it is vital to ensure the functionality of the valve and its conformity with customer specifications. If it is not ensured, it poses a safety risk to the vehicle and, therefore, a safety risk for the driver and its surroundings.

In this scope, this dissertation focuses on the study of the electromagnetic behaviour of EGR valves, more specifically its hysteresis during operation, to define an evaluation method that intends to ensure product conformity and its correct functioning. This evaluation method, put together with the diverse existing quality tools, will allow to identify mechanic non-conformities in the product while also supplying statistical data to support the analysis of problems associated with these non-conformities. It will support the identification of root causes as well as the decision-making associated with the continuous improvement of the production process to ensure the quality of the product for the customers.

Lastly, the topic of this project is incorporated into the vision of the company, in which it pursues continuous improvement of its own production processes. It is a multinational company in the automotive industry that has an innovative and sustainable approach to the market, being one of its biggest suppliers of parts. It gives an opportunity to be in an international environment within a large-scale worldwide operation. Not only that, but the variables that are necessary to monitor and control are within the electronics engineering area, which is my academic background. And, having this opportunity to take the lead in gathering technical knowledge, which is very useful for professional growth, makes this project interesting overall.

1.2. Objectives

The current project has the main objective of defining a control method for an electric test to be implemented as product quality control in order to ensure product conformity. It will be applied to a production line in several references of a specific product, the EGR valve, and intends to identify specific mechanical non-conformities in the product as well as supporting the continuous improvement in the production process. Therefore, it has several stages, starting with the study of the problem and gathering data on the hysteresis curves to proceed to a statistical analysis and ending with a proposal of the control method and the parameters to be evaluated. After this method definition, it is necessary to implement it at the End-of-Line (EOL) of the production line and proceed to the validation of the data obtained.

The expected results of this dissertation consist of the improvement of Key Performance Indicators (KPIs) of the production process, especially the first time right and the output rate, as well as the mitigation of the costs associated with customer complaints. And lastly, the writing of this document, which intends to detail both the procedures and the knowledge obtained in both the implementation of this control method and in the analysis of the non-conformity defects found, thus enabling the possibility of replicating the same control in other production lines with similar products, pushing towards the continuous improvement of other production processes.

1.3. Dissertation Structure

The present dissertation, aside from the introduction section, has five main chapters, each of which is divided according to its respective content. The next chapter includes a literature review, in which research is done on the automotive industry regarding quality control and the implications of faulty parts. Research is also done on the applications of the concept of Failure Mode and Effect Analysis (FMEA) and its importance, as well as the hysteresis concept in other existing applications. Then it follows with a chapter about an overview of the problem and its framework, going into more detail regarding the application of this project to the desired product and its production line. The subsequent chapter focuses on the development and implementation of the control method with the monitoring post-implementation of the values related to the control method, and lastly, a chapter for the discussion of the results. This document finishes with a conclusion and future work.

Chapter 2 – Literature Review

In this chapter, a literature review is done on the main concepts relevant to this dissertation, together with research on similar projects. The reliability and failures of the automotive industry are previewed to introduce the topic, followed by a description of the usage of FMEA in the industry for similar faulty cases of product non-conformities, enhancing its importance, and lastly, a revision on the application of the hysteresis concept in other projects.

2.1. Quality and conformity assessment

The automotive industry is one of the biggest worldwide in terms of sales as well as investment in research and development of better technologies. Nowadays, this development adds to the increased usage of electronic components and software systems incorporated into one vehicle. One of its primary focuses with this increase in technology is to ensure the safety of the usage of the vehicle, which needs to take into account a wide range of factors.

There was a qualitative study conducted (Törner & Öhman, 2009) regarding the drivers, the safety cases, and the issues regarding the latter ones. Their goal was to explore the reasons for the introduction of new safety cases based on a sample of drivers with experience developing safety-related systems in the automotive industry, as well as the potential usage and issues of those same cases in the automotive context. It is vital for a product or service to comply with safety standards, and these cases posed an interesting approach to the study as they focused on the drivers in a way to introduce new safety cases and how the automotive industry perceives them. This can be interpreted step-by-step as, firstly, defining the safety objectives of a system, then establishing the connection between the evidence found to relate to the desired goals, and, lastly, collecting all the necessary data that needs to support the procedure. This helped in doing an assessment of the risks and its usage, which provided potential support towards system development and improvement. This study required interviewing drivers in order to get their feedback and input on the topic, and a generic overview of the design behind the study can be observed in Figure 1 along with the analysis steps.

There were three levels of consideration for product development in these cases, the first being to identify how the functionality behaves from a customer perspective based on a function or feature. Then, a perspective on the developed system solution, in which its implementation fulfils the functional requirements and enables integration with other systems, and, lastly, the actual implementation and the design in detail.

Figure 1 - Overview of Study Design and Analysis Steps (Adapted from Törner & Öhman, 2009)

Post-interview results were segregated according to different categories based on their answers, and in Figure 2 are displayed the different cases mentioned from the samples taken regarding the safety cases related to the drivers, the usages, and the issue.

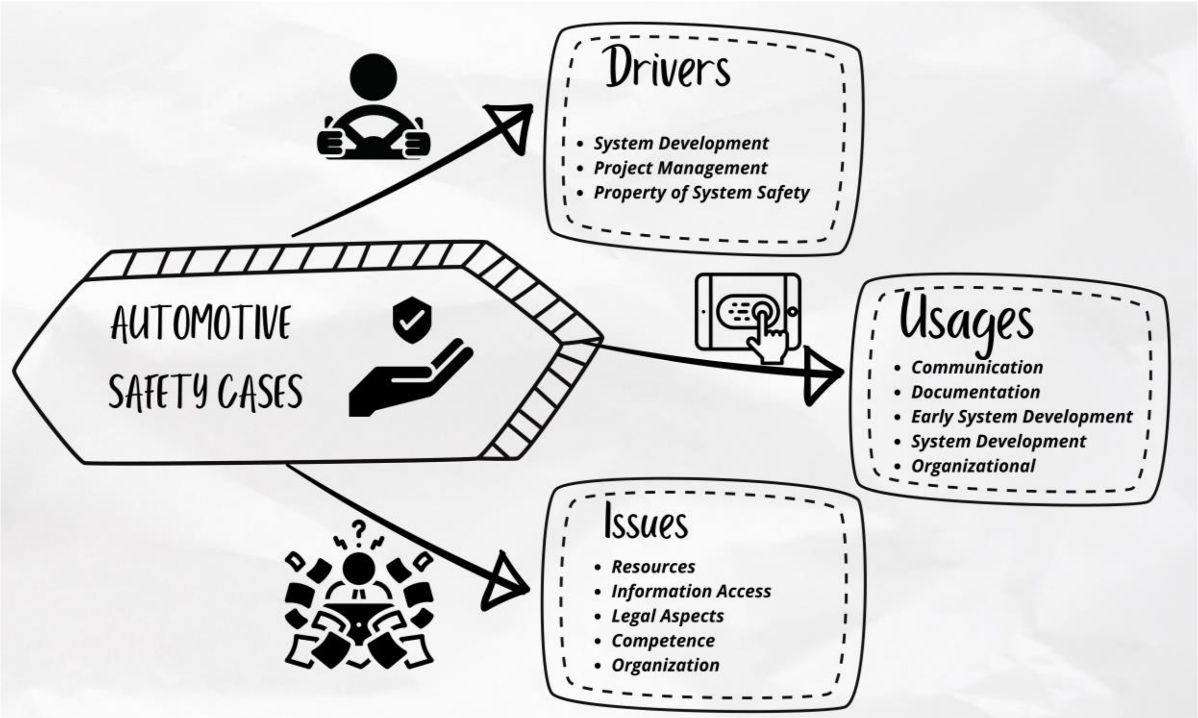

Figure 2 - Hierarchy of Categorization (Adapted from Törner & Öhman, 2009)

This study gives an idea of how the introduction of safety development in the automotive industry is perceived by a sample of its workers and how a safety case is perceived as a method that benefits both system development and project assurance. But generally, safety is perceived as one of the most important topics in the industry, with room for constant improvement.

Having this understanding of how safety is perceived is something that relates to the topic of this dissertation, since in this case, the concept of product quality and having non-conformities according to specifications can compromise the safety of the system. If there is a product that is not within the specifications, depending on the severity of the situation, it can have a huge impact on the flow of the supply chain towards the end customers.

Regarding the impact and disruption in the supply chain, there was a study (Shahbazi *et al.*, 2013) that focused on experienced people in the automotive industry to identify and assess the risks associated with the potential disruptions. Risks can be grouped as internal, like machine breakdowns and Information Technology (IT) problems, or external, like man-made activities that cause issues. A survey was done regarding what each person considered to be risks in the supply chain, and the results can be seen in Table 1 alongside additional information.

Table 1 - Descriptive statistic of risks (Adapted from Shahbazi et al., 2013)

Risks	N	Mean	Standard Deviation	Standard Error Mean
Increasing Raw Material Prices (External)	19	3.63	1.065	0.244
Machine Breakdowns (Internal)	19	3.63	1.012	0.232
Supplier Failure (Internal)	19	3.58	0.838	0.192
Supplier Quality Problems (Internal)	19	3.58	0.838	0.192
Delivery Chain Disruptions (Internal)	19	3.47	0.905	0.208
Change In Customer Demand (Internal)	19	3.42	0.838	0.192
Transportation Failure (Internal)	19	3.32	0.946	0.217
Malfunction of IT System (Internal)	19	3.16	1.119	0.257
Natural Disaster (External)	19	2.84	1.302	0.299
Oil Crisis (External)	19	2.79	1.032	0.237
Import or Export Restriction (Internal)	19	2.79	1.084	0.249
Technological Change (Internal)	19	2.79	0.855	0.196
Accident (Internal)	19	2.74	1.046	0.240
Increasing Customs Duty (Internal)	19	2.74	0.872	0.200
Strike (External)	19	2.63	1.257	0.288
Terrorist Attack (External)	19	2.26	1.147	0.263

Taking the data into consideration, half of the higher risks consist of supplier issues, which indicates that selecting the right suppliers plays a vital role in the management of the supply chain. The authors also mentioned that supplier quality problems and failures are the most critical since they have both a higher probability and a greater impact. It should be noted that since most of the mentioned risks are internal, it is important to work towards continuous improvement.

Looking at the topic of continuous improvement, an application in the automotive industry (Matope *et al.*, 2022) looked towards achieving cost savings in a production line by optimising the usage of its resources through time and method studies. In an ever-changing customer perspective, automotive companies face the challenge of meeting needs at the minimum cost, with the optimisation of internal resources being one of the most effective and fastest ways to achieve the minimum cost associated with the product. The authors focused on identifying excess raw material input and non-value-adding activities regarding the production line, determining the current factory capacity and its usage, and implementing improvements to increase productivity in the production line. Their approach was to identify the numbers of operators and workstations in the production process, analyse the work for producing the components, determine the sequence of operations, and standardize the methods. This methodology can be seen in Figure 3.

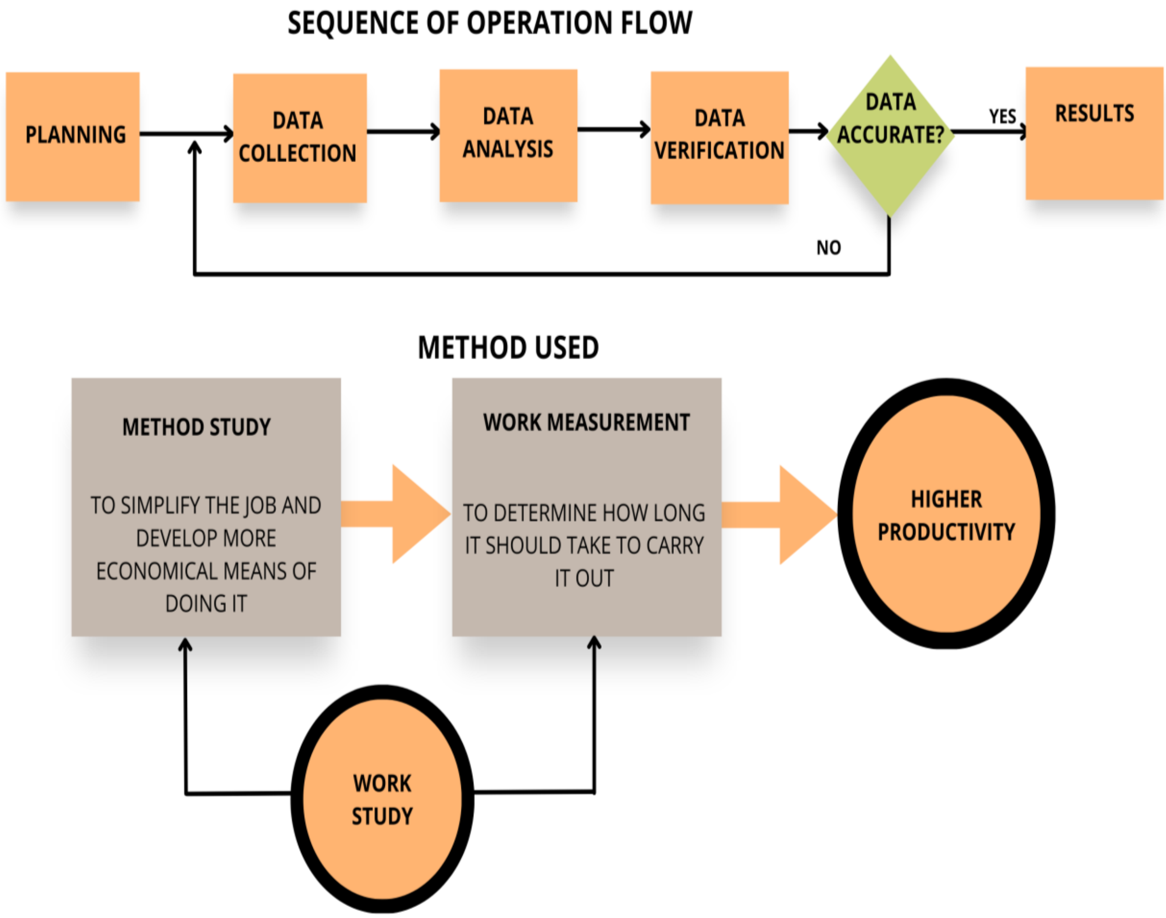

Figure 3 - Methodology taken by the authors (Adapted from Matope et al., 2022)

This analysis of this study and its application in the production line, considering the optimisation done to its resources and processes, led to a 50% increase in productivity, efficiency, and quality, while contributing to a reduction in production time and waste.

It is important for companies to constantly look out for and maintain a low Cost of Quality (CoQ), which is essentially the cost associated with ensuring product quality both internally and externally. It can be achieved internally by eliminating unnecessary production routes while reducing cycle time and waste. For this, it is necessary to analyse and understand the root cause of both problems and product non-conformities. The study case of Nagyova *et al.*, (2019) reinforces this point-of-view, especially in the automotive industry, where having quality issues can have a big impact on the competitiveness of the company. And, while finding the root-cause of the issues is very important, implementing preventive and corrective measures to avoid having the same problems in the future is equally important.

The authors mention the usage of quality tools and methodologies to support the root-cause analysis, with the FMEA at its core to document everything and connect the data findings with the actions taken. Quality tools are the seven basic quality tools (check sheet, flow chart, histogram, Pareto chart, Ishikawa diagram, scatter diagram, and control chart), and the methodologies are Five Whys and Two Hows (5W2H), Root Cause Analysis, Five Whys (5Why), and the eight disciplines of problem solving (8D) methodology. These are used generally in the automotive industry, providing several cross-functional teams (CFTs) with the necessary tools to tackle problems and challenges.

For this specific case, the problem revolved around the non-conformity of car keys, with one part missing a pin that connected the two main components of the key. Using the 5W2H method, the problem was identified and how it came to be, as well as all the necessary data and factors that generated the non-conformity. Then the root cause analysis was done to investigate the potential causes that originated the problem. Having identified the causes, the 5 Whys method was applied to see step-by-step what was missing in the process and in its FMEA analysis. Having this defined, the Process FMEA (PFMEA) was updated with all the data acquired, while preventive and corrective actions were planned accordingly, and the 8D report was filled in for each of the steps mentioned below:

- D1: Establishing the CFT to tackle the issue;
- D2: Describing the non-conformity;
- D3: Immediate measures taken (which include measurements and sortings);
- D4: Cause of the defect (can establish several factors together as the cause);
- D5: Corrective measures are planned;
- D6: Corrective measures introduced in the process;
- D7: Preventive measures to avoid the repetition of the faults;
- D8: Acknowledgement of the team and valuation of the costs (the costs associated with the claim of one single key proved to be, by the authors, at least ten times more expensive than the cost to produce one key).

It is extremely important for organisations to manage customer complaints properly, solving issues associated with them while working towards continuous improvement. The end goal of using these tools and methodologies in the most effective way is so that the customers, after the implemented measures, will not find another part with the same defect detected in the past, therefore improving relations between both parties and improving confidence in the organisation. These tools, methods and procedures relate to the policy of the company in how it handles its own customer complaints, and it will be understood in detail during the problem overview.

The topics of quality and conformity are always associated with costs. During the industrialization of a manufacturing process, many quality controls are applied to ensure product conformity, some initially planned in the design phase of the product development, others coming as a need later due to a better understanding of the product and its relevant variables. These latter ones are important to control and monitor due to their impact on the functionalities of the product or its application by several customers. Depending on where the need to add quality control is situated in the timeline of the product, its cost can vary from a smaller one if detected in the design phase of the product to a huge if detected by the customer. Problems detected at the customer are not always due to the supplier being at fault, but when they are, it creates a massive risk for a financial setback that can compromise the supplier manufacturer. A simple schematic to illustrate the impact of the detection costs on quality can be seen in Figure 4. In the scope of this project, the Non-Conformity Parts are the main focus step of quality detection.

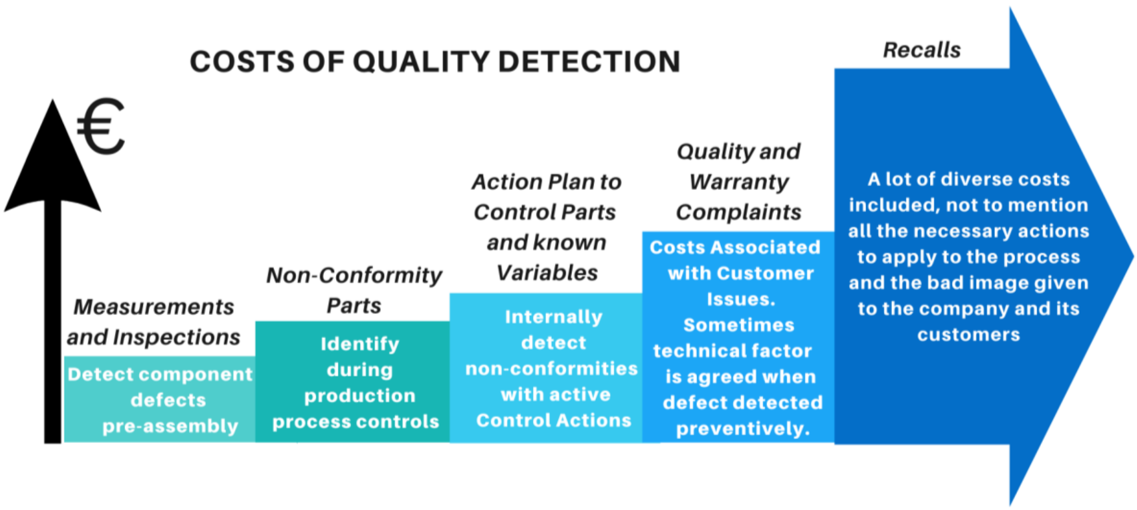

Figure 4 - Flux of the impact of costs of Quality Detection

The concept of CoQ can be defined in several ways, but for the purpose of this dissertation, it will be considered as follows in Figure 5.

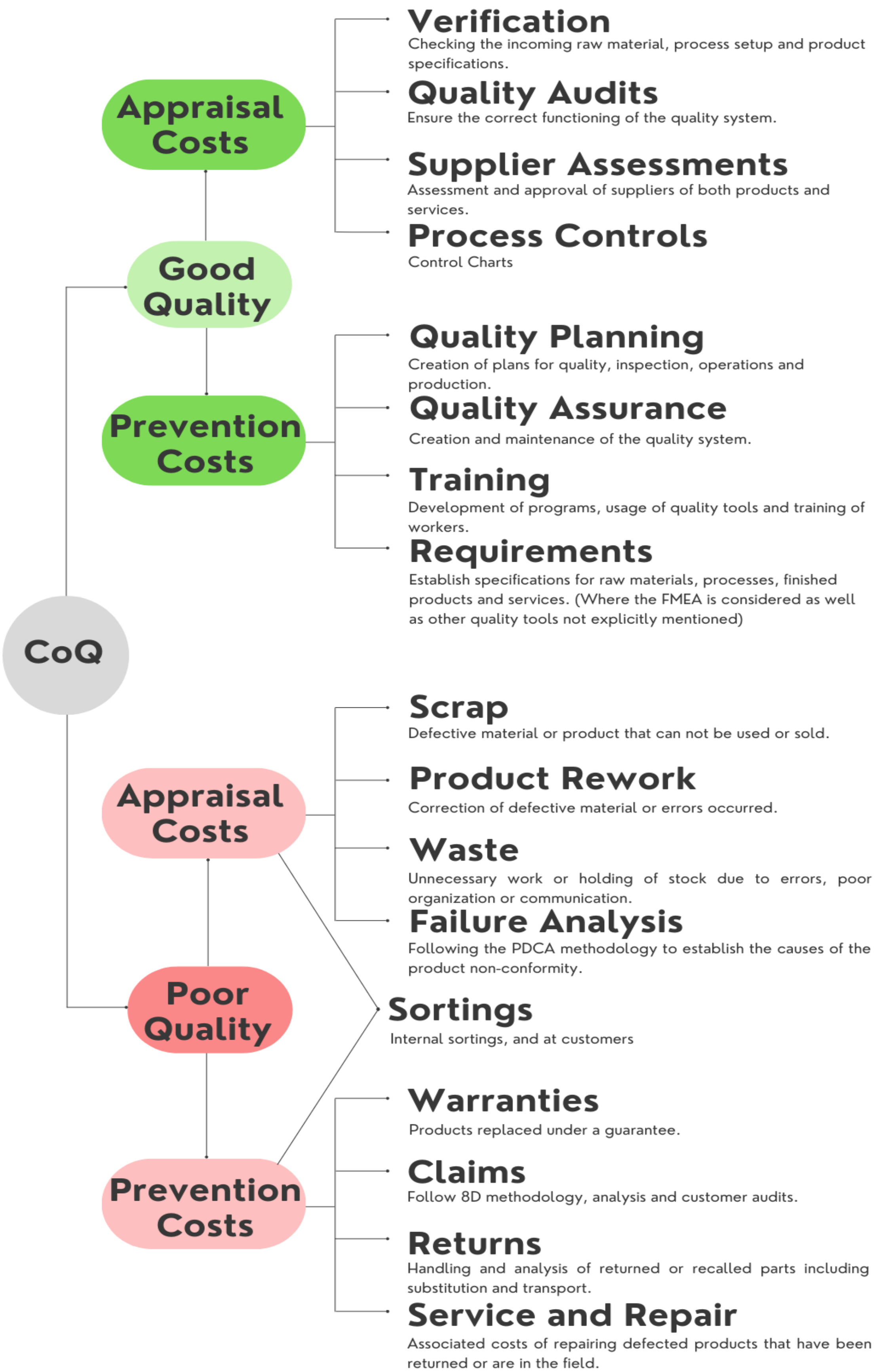

Figure 5 - Defining Cost of Quality

Based on the concepts presented, it is critical to understand the FMEA methodology and its context in the industry. With this methodology, the safety factor can be preserved while avoiding supply chain disruption, mitigating associated risks and costs of quality, working toward continuous improvement, and determining the root cause of product non-conformities.

2.2. FMEA in Automotive Industry

The automotive industry is an ever-evolving industry. Few decades ago, most of the cars available had minimal technology in them, being mainly built on mechanical systems. Cars now contain an increasing amount of technology, ranging from extensive software programming to sensors, cameras, navigation, and so on. With this increase in technology, there is also an increase in the complexity of the systems, meaning that the risks associated with failures or faults also increase. As a result, it is critical to evaluate the risk associated with the product from conception to production in order to not only optimise costs but also to consider certain risks and develop actions to eliminate or mitigate them, which can be supported by the FMEA.

Failure Mode and Effect Analysis is an analytical methodology that ensures that potential problems have been considered and addressed, meaning that it is used to anticipate and identify possible failures during the design (DFMEA) phase and in the manufacturing process (PFMEA) phase. This structured approach intends to discover and identify failure modes in order to prioritize and limit them. The effects of these failures include waste, defects, and any other negative impact on the customers. It does not work solely, but rather it serves as a tool to enhance the continuous improvement and good engineering of the assigned CFT by reviewing the design and process of the product and assessing its risk of failure. Also, other quality methodologies and quality tools are used together with the FMEA.

Its goals are to prevent failures, improve safety, and increase customer satisfaction. While the FMEA is to be looked at as a preventive tool, it can also be used to identify potential improvements after its conception or process development. Figure 6 depicts a simple way to understand the flow of the process of making a FMEA.

The topic of FMEA is addressed in the following chapters of this dissertation document as it relates to the topic, but for a more in-depth read on FMEA, including a detailed step-by-step approach to the automotive industry, the AIAG & VDA FMEA Handbook (2022) provides all information related to this method and its application in the automotive context.

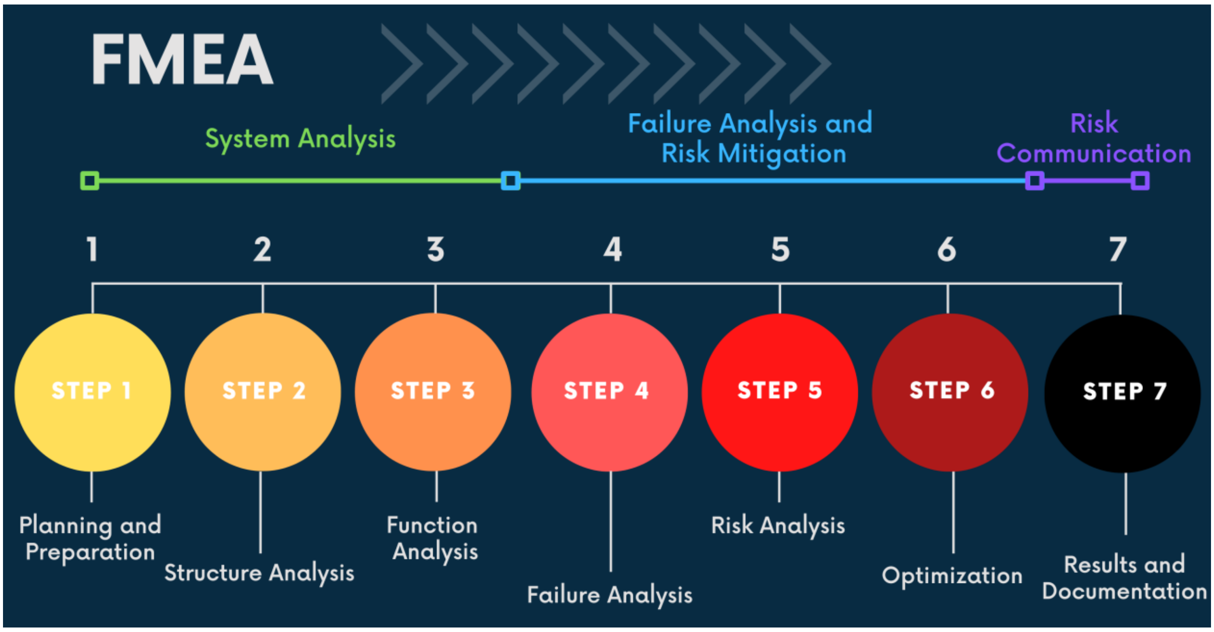

Figure 6 - FMEA step-by-step flow diagram

FMEA has an infinite number of applications, and additional steps can be taken depending on the complexity of the system and the application intended. A case study was done in the automotive industry using this methodology (Petrescu *et al.*, 2019), in a more detailed version, to assess the risks of failures in the communication of the electrical and electronic equipment of a vehicle. The Controller Area Network (CAN) Bus Harness, displayed in Figure 7, is an essential part of the communication among the several parts of the vehicle, and it becomes a key part of the vehicle in terms of safety as well. There are standards required to be fulfilled, which is the focus point of the usage of the FMEA for this specific application.

Figure 7 - Example of CAN Bus Harness (Petrescu et al., 2019)

To begin, the authors considered three different types of FMEA: Conceptual, Design and Process FMEA. The dependencies between each of them are also established initially, as can be seen in Figure 8. It took a different approach and detailed ten different steps taken into assembling the different stages in the elaboration of the FMEA in this case, which are displayed in Figure 9.

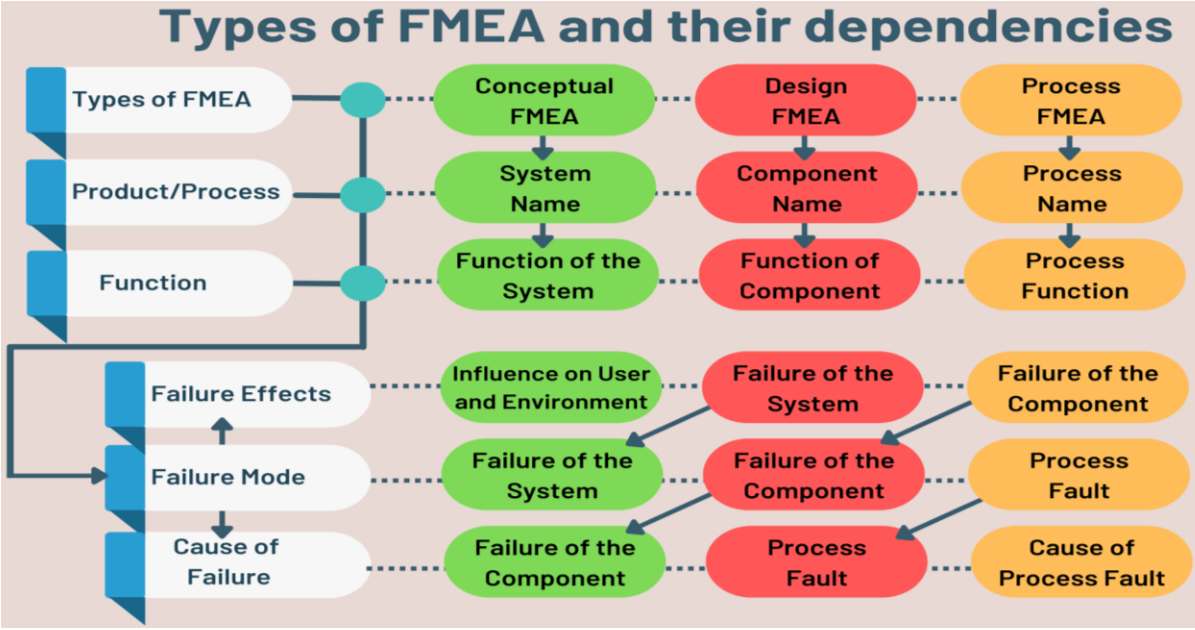

Figure 8 - Types of FMEAs and their dependencies (Adapted from Petrescu et al., 2019)

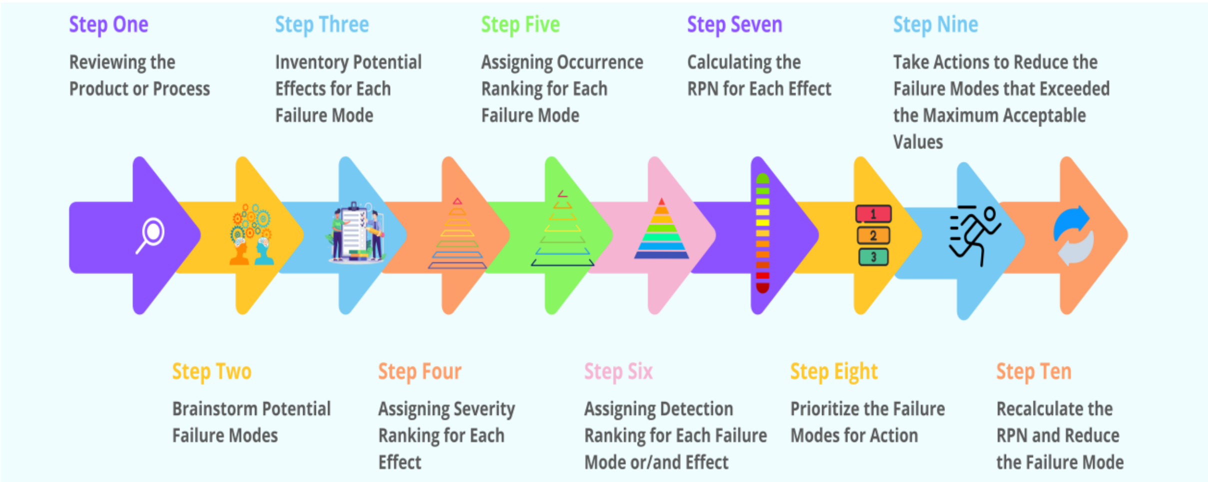

Figure 9 - Steps Considered into making a FMEA (Adapted from Petrescu et al., 2019)

As showcased, the data from the product was reviewed by a team assigned to making the FMEA, which performed an analysis on the failure modes, their frequency, and the associated risks to their failures. A list was elaborated based on the three single indicators FMEA utilizes and had a Risk Priority Number (RPN) indicator for each failure mode considered, as shown in Table 2. Based on this indicator, the assigned team was able to identify the most critical failures of the product in the system and establish ways to control them, whether by detecting them, preventing them, or mitigating their risk. After actions are implemented for each considered risk, the RPN index will be reviewed afterwards. Performing this analysis and having the RPN indicator go down on several of the failure modes means that the FMEA achieves its goal.

Table 2 - Resulting RPN of the FMEA for this example (Adapted from Petrescu et al, 2019)

Failure Mode		Effect	Severity	Causes	Occurrence	Controls		Detection	RPN
Function	**Failure**					**Prevention**	**Detection Criteria**		
Routing sensor data	Low resilience to noise	Data Corruption	6	Designing mistake	3	Detection during verification at the EOL	Start up tests to conduct on ECU the check Power Supply	3	54
Insure the connection between the equipment and the bus	Signal bouncing due to the vibrations	Transfer data interruption	9	Material degradation in time caused by temperature (positive and negative)	6	No	Software detects communication loss	6	324
	EM perturbations	Transfer data interruption	8	Installation near EM sources (alternator starter)	2	The system can prepare before starting the high current consumers	Software detects erroneous frames with a high probability. Illegal data not processed	8	128
	SCG (short circuit to ground)	Missing data	9	Wrong communication (human factor). Bending radius not respected	2	No	Software detects communication loss	2	36
	SCB (short circuit to battery)	Missing data	9	Wrong communication (human factor). Bending radius not respected	3	No	Software detects communication loss	2	54
	OC (open circuit)	Missing data	9	Wrong communication (human factor). Bending radius not respected	2	No	Software detects communication loss	2	36
Assembly Process	Wrong Way Connection	Process time prolonged due to repair	6	Human Factor	6	No	Detection at the end of the assembly line	7	252

Another case study in the automotive industry was done in order to improve the effectiveness of the FMEA (Ványi, 2016). The FMEA was introduced in a similar manner as in the previous case study (Petrescu et al., 2019), with a special emphasis on applying best practices and gathering internal know-how in the team to be assessed, allowing companies to ensure a faster application of this methodology. Sometimes companies with many independent departments might have slightly different perspectives, which leads them to overlook certain steps they might consider redundant, generating latent quality gaps and risks. It is also important to have FMEAs from different systems connecting in the same way that components or products are interacting with each other. To exemplify, the author mentions that in a complex automotive system there should be a division in hardware, software, and mechanical components and proceeds into describing the different types of FMEAs, their dependencies and their applications, as described in Figure 10.

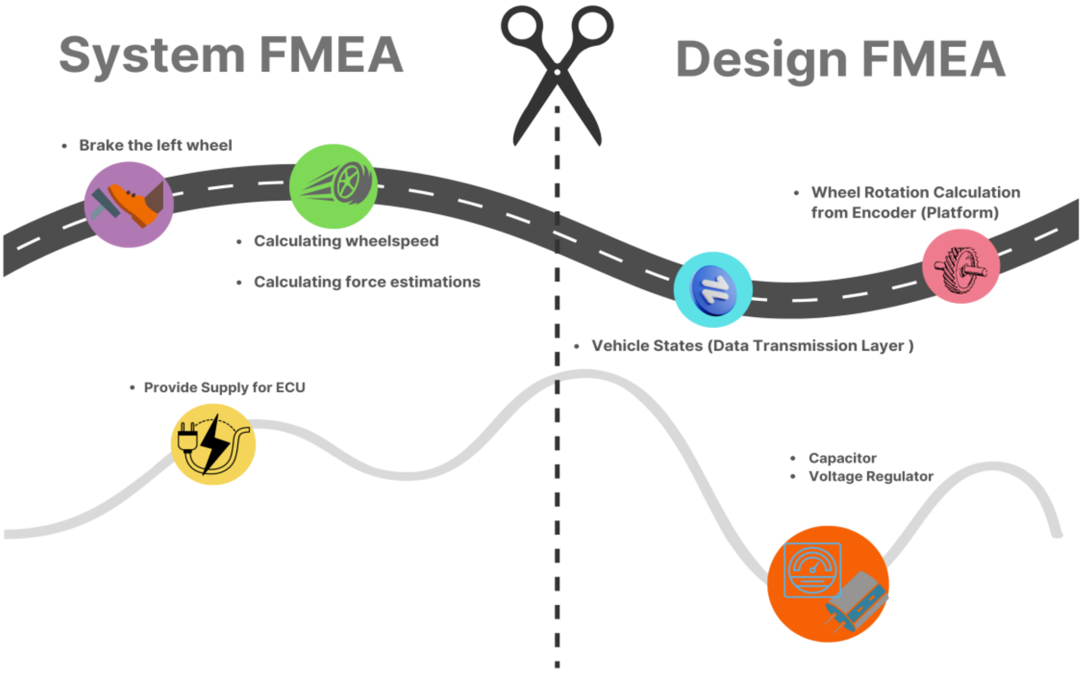

Figure 10 - Electronic hardware and software FMEAs connections (Adapted from Ványi, 2016)

There is an important role in the Design FMEA, which is to identify potential failures for each function of the product or component, therefore identifying the special characteristics of the product (or simply, the most critical characteristics).

In any case, the bigger challenge is motivating people to actively participate in the FMEA methodology within deadlines because brainstorming some questions is an important part of risk assessment. This risk evaluation of the designed functions is getting more and more important in the automotive industry, because on one hand, caution is taken regarding the specific product by having a team doing the risk evaluation, and it enables feedback to flow in both directions, allowing the design engineers to get feedback from developers and adjusting the product each way. On the other hand, through brainstorming with the FMEA team, several areas for improvement can be identified, allowing for cost optimisation and system efficiency.

In another example of the importance of FMEA (Kosuru & Venkitaraman, 2022), it is enhanced that it plays a vital role in the design phase of all Electronic Control Units (ECUs) in the automotive industry. Being an ECU one of the most complex and critical components of a vehicle, it is crucial to contemplate all the potential failures that it can have or lead to. That means identifying possible failures in an ECU in both its hardware and software, assessing it in the FMEA and ranking it in terms of Severity and Impact of Failures, together with the preventive actions and measures that can be taken in its design phase. The approach by the author for the design FMEA was very simple and it is displayed below in Figure 11.

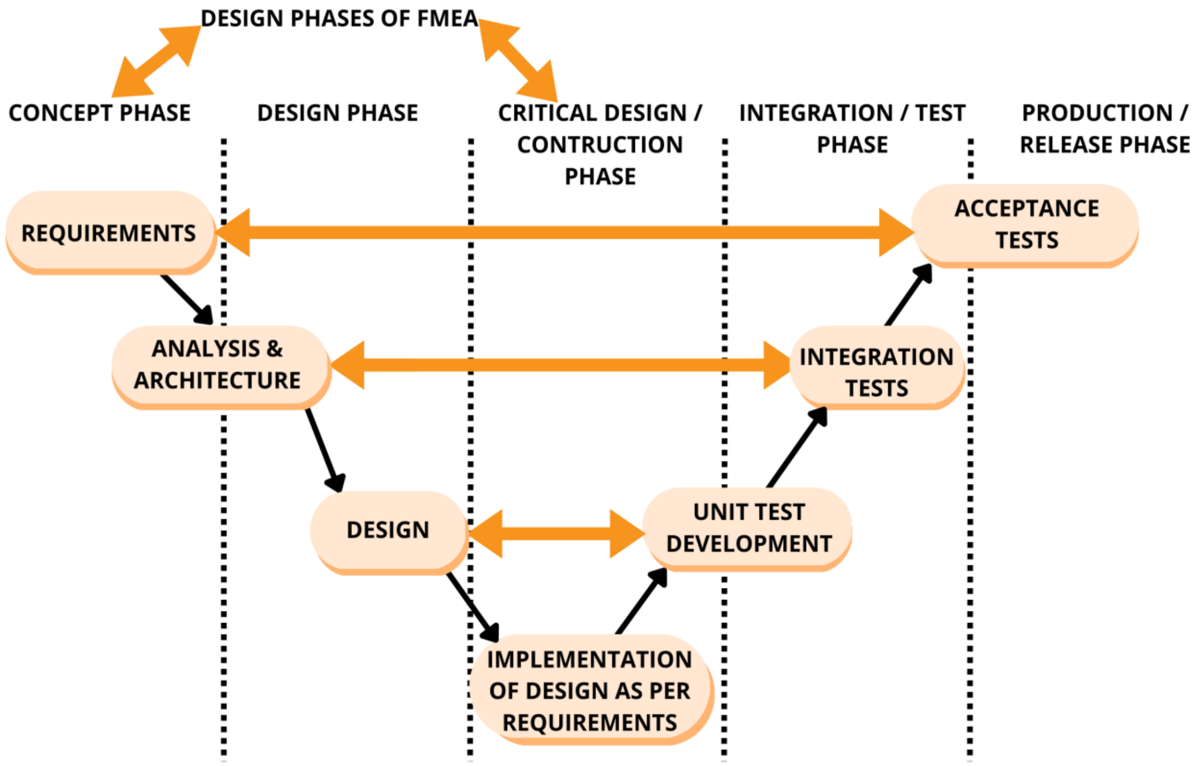

Figure 11 - Design phase of FMEA for the ECU (Adapted from Kosuru & Venkitaraman, 2022)

This example poses an interesting point of view, since there are dependencies between components and systems, hardware and software, respectively, and the FMEA can be separated accordingly to simplify the analysis. The scope of the system as a whole and its sub-systems was considered, as displayed in Figure 12, while in order to fill out the FMEA, the strategy followed was organised into a flowchart, which is represented in Figure 13.

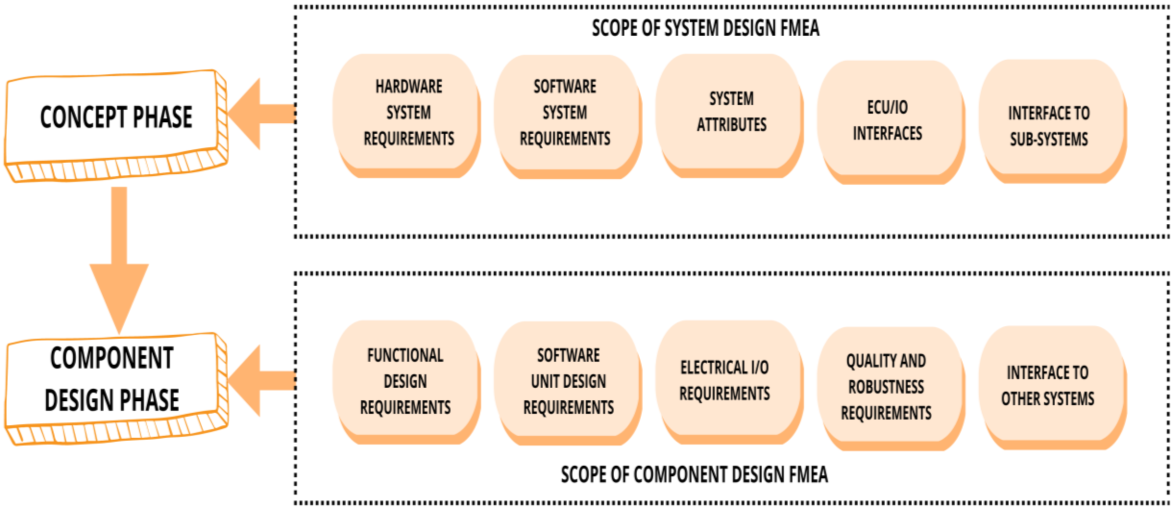

Figure 12 - Scope of the System (Adapted from Kosuru & Venkitaraman, 2022)

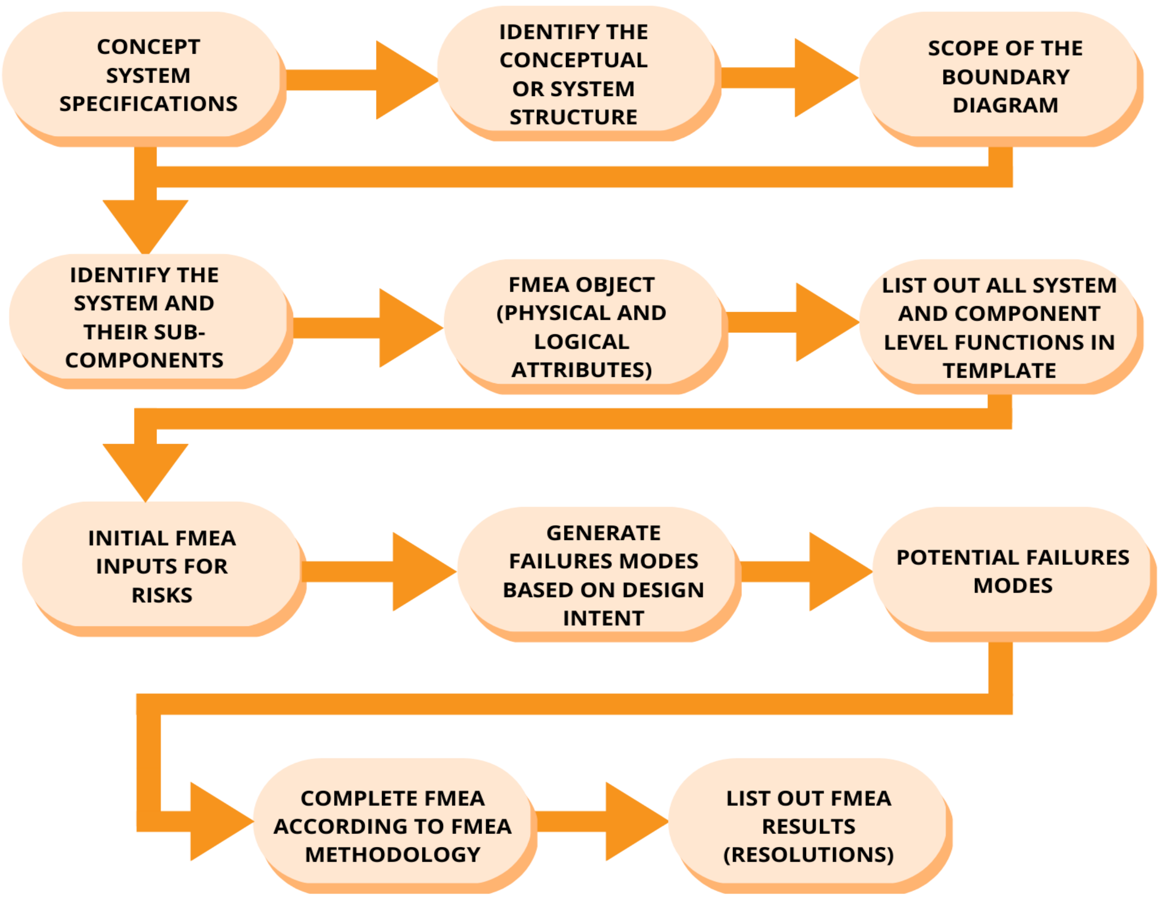

Figure 13 - Strategy for assessing the Design FMEA (Adapted from Kosuru & Venkitaraman, 2022)

Going more specifically into the approached product, the steering ECU was considered for the Design FMEA. It contemplates all the potential defects that can disturb the steering of the wheels by the driver, and it is considered a critical point in the system since it poses a serious topic regarding safety, therefore it must be considered for all possible defects in its design phase. There is a risk classification system in the automotive industry called Automotive Safety Integrity Level (ASIL), defined in the standard ISO 26262 (Road Vehicles – Functional Safety, ISO 26262:2018, 2018), and depending on it, this might mean that an even more detailed FMEA is a better approach to prevent future defects.

All the examples previously mentioned are good to reiterate the importance of the FMEA method when reviewing any system in the automotive industry. Considering the focus of this dissertation, the technical concept of the project must be understood so that this methodology can support its analysis.

2.3. The function of an EGR Valve

During the combustion process, the gases produced include a reactive gas named nitrogen oxides, or NOx, which is harmful. The EGR valve "*allows a precise quantity of exhaust gas to re-enter the intake the system, effectively changing the chemical makeup of the air entering the engine. With less oxygen, the now diluted mixture burns slower, lowering temperatures in the combustion chamber by almost 150°C, and reducing NOx production for a cleaner, more efficient exhaust*" (DELPHI, 2023).

The EGR valve's functioning varies between two primary settings: open and closed. When the engine is starting up, the valve is closed. At low speeds, the valve gradually opens. If more power is required, the valve closes to ensure as much oxygen enters the cylinder as possible. As well as reducing NOx, EGR valves can be used in downsized gasoline direct injection (GDi) engines to reduce pumping losses, improve the efficiency of the combustion, and improve knock tolerance. In diesel engines, the EGR valve can also help reduce diesel knock at low speeds (DELPHI, 2023).

2.4. The Hysteresis Loop

The word hysteresis translates the idea of a delay (lag behind) between the inputs and the outputs of a certain system when there is a change in direction, meaning that if the input changes direction, there will be a delay in the change of the output value. This occurs with magnetic materials, so when applying a magnetizing signal, the magnetism that results from this follows the initial signal, but with a certain delay that varies depending on both the system and the materials in use. Figure 14 illustrates this principle: When the input signal opens, the system moves in one direction (blue curve); when the input signal is turned off, the system resumes the starting position (red curve) with a delay relative to the initial curve (the black arrow represents the highest delay). The scales are omitted since they can represent different values in the hysteresis curves.

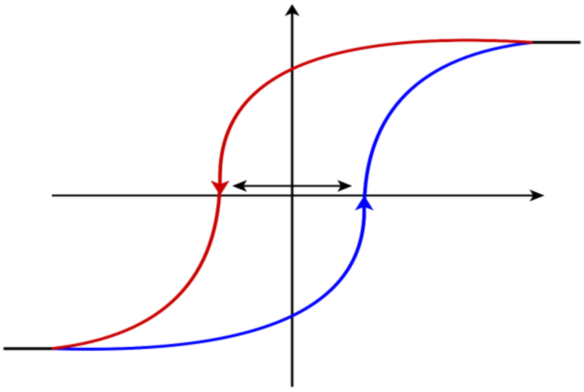

Figure 14 - Example of Hysteresis Curves

In this literature review, no studies were identified with the application of this concept as a control method in the production of EGR valves, but it has several applications and is embedded in different branches of industry. Some examples are analysed here to compare with the problem to be solved in this dissertation. One application of this was done on an aeronautic valve (Ribeiro *et al.*, 2015), in which by monitoring its hysteresis curves, it can be determined when it has deteriorated from its original working function. The hysteresis curve in Figure 15 follows the same working principle as in Figure 14, with its current input determined by the given time and output pressure determined by the current input.

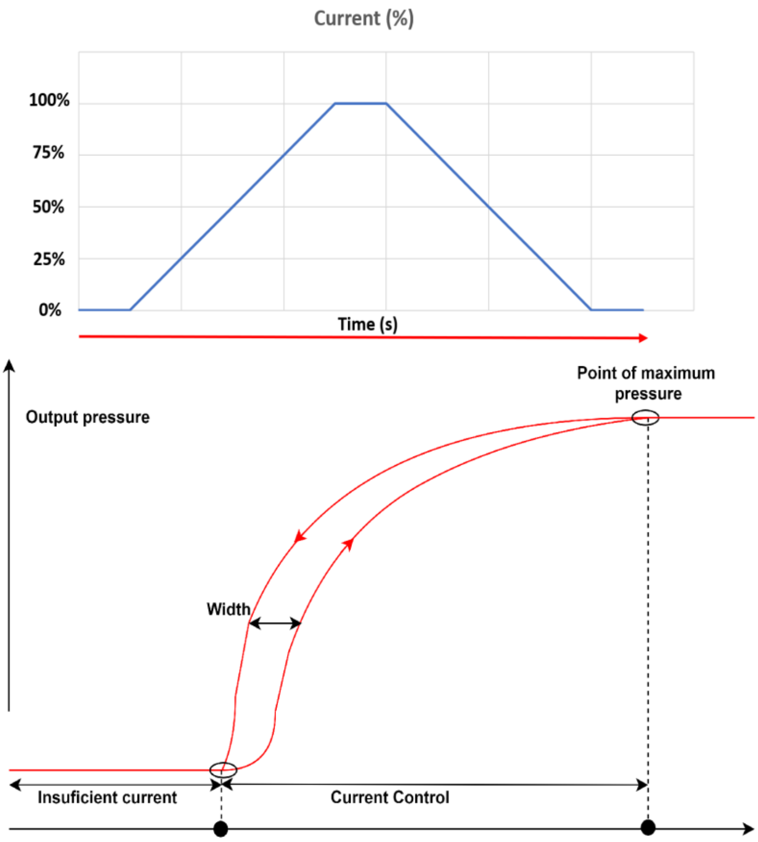

Figure 15 - Hysteresis in an aeronautic valve actuation (Adapted from Ribeiro et al.,2015)

There are several variables that influence the behaviour of the system: the dimensions of the valve, the pressure to which it is subjected, and the implied gain of the system, all of which exert variability on the hysteresis curve. Following the simulation of the system, some mathematical models were developed that could predict the deterioration of the aeronautic valve based on its hysteresis curve.

There are different kinds of valves, and each of them has its own application. Another application of this principle can be seen in the valve operation of a solenoid, in which its mechanical operation is observed when opening and closing (Riley, 2013). Taking into account the flux behaviour as well as the energy loss in its mechanical operation, the effect of hysteresis on the model can be seen as a delay in the output of the system, as displayed in Figure 16.

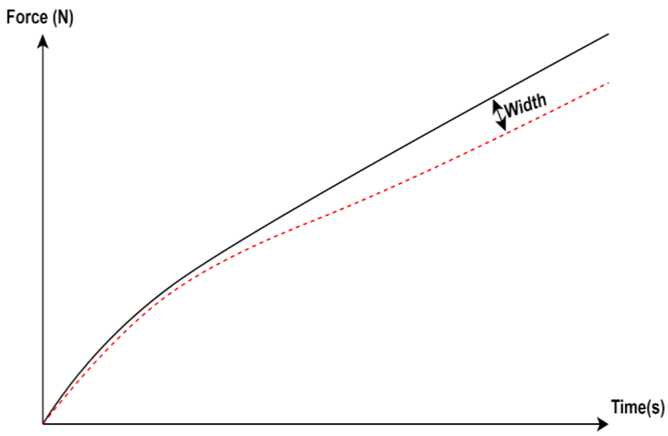

Figure 16 - Hysteresis effect in a Solenoid Valve operation (Adapted from Riley, 2013)

As described up until now, this concept can be used for different applications, with the focused examples being other types of valves that illustrate the behaviour of their respective systems, where there is not much need for extensive control. When a system is more complex, there may be a need to implement a more detailed control to properly monitor the variables involved, since a small change in any of these variables might represent a deviation in a product characteristic.

2.5. Synopsis

The hysteresis concept is rather interesting since it can be observed from the references that it has a variety of uses. In this dissertation, it will be used to implement a control to detect mechanical defects in the function of the valve through its current, and therefore several ideas are discussed as a team in order to monitor its values, while at the same time, considering the FMEA and working in the continuous improvement of the production line. In the next chapter this topic as well as the others described in the literature review will be considered in the context of the problem that this dissertation is focused on.

Chapter 3 – Problem Overview

The targeted product of this dissertation is EGR valves, and in their production process there are several steps of assembly, ending at the EOL where functional tests are performed. The focus will be understanding the current hysteresis measurements and values in the EOL to be able to contextualize the problem and what is intended to do.

3.1. Defining the problem

EGR is a method used to control the Nitrogen Oxides (NOx) emissions that are produced during the combustion process. It consists of reusing the exhaust gas to lower the emissions by reintroducing this gas together with the air that goes into the combustion chamber. The quantity of gas reintroduced depends on the application, and it can be controlled by a control module associated with the valve and the engine. Figure 17 depicts an example of an EGR module (that integrates an EGR system) that combines an EGR valve, an EGR cooler, and an EGR tube.

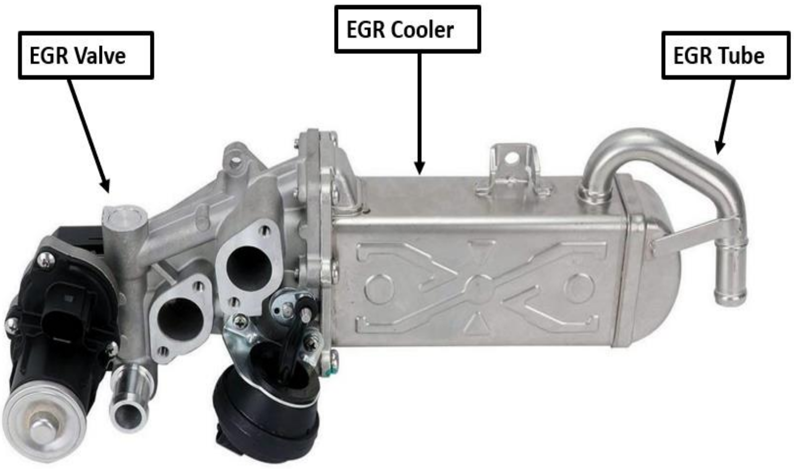

Figure 17 – Example of an EGR Module

The function of an EGR valve is controlled by the Engine Control Unit of the vehicle. This control unit sends electrical signals to the valve, which reacts accordingly to its programming. In order to connect with the hysteresis topic, an example of the motor voltage input signal can be seen in Figure 18, along with the resulting outputs of measured points from both the motor current value and the sensor voltage value. There are both a sensor and a magnet that are assembled individually in each of the EGR valves. This position sensor is programmed at the EOL to interpret the magnetic field given by the magnet and translate that into a voltage value. There is a DC torque motor in the EGR valve that, when supplied with voltage to its terminals, actuates the mechanism, and the magnet, due to the movement, generates a rotating magnetic field with the sensor, whether the valve is opening or closing. The current consumption of the motor varies depending on the mechanical movement, and the sensor voltage value can only change when there is movement. This can be perceived by observing when both the sensor voltage and the motor current have variations in the displayed values.

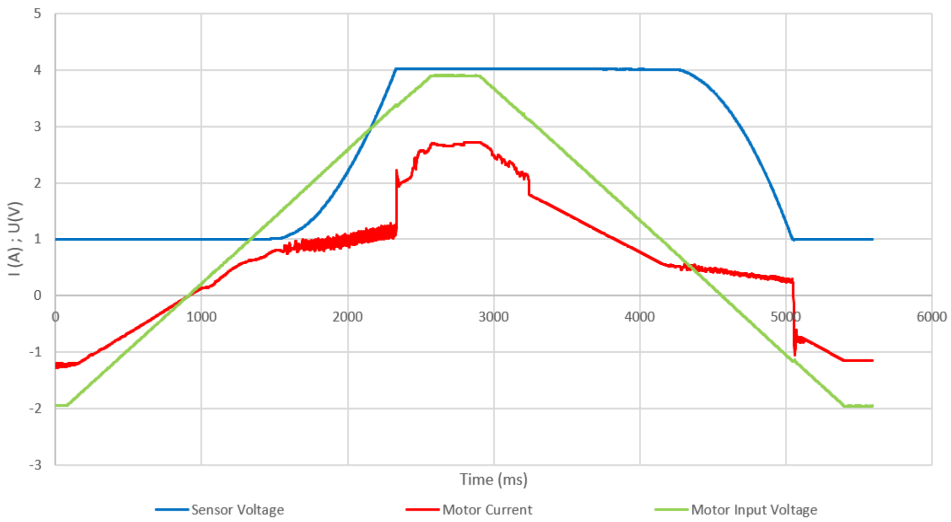

Figure 18 - Important signals of the valve to understand

The example from Figure 19 takes the values from Figure 18 and displays them as the motor current for each sensor voltage point. When comparing the values taken during the opening and closing of the valve, the hysteresis can be seen in the current values. The movement away from the natural position will require more current, whereas the movement towards the natural position requires less. For the purposes of this dissertation, these curves will be graphical represented as valve open (blue curve) and valve closed (red curve).

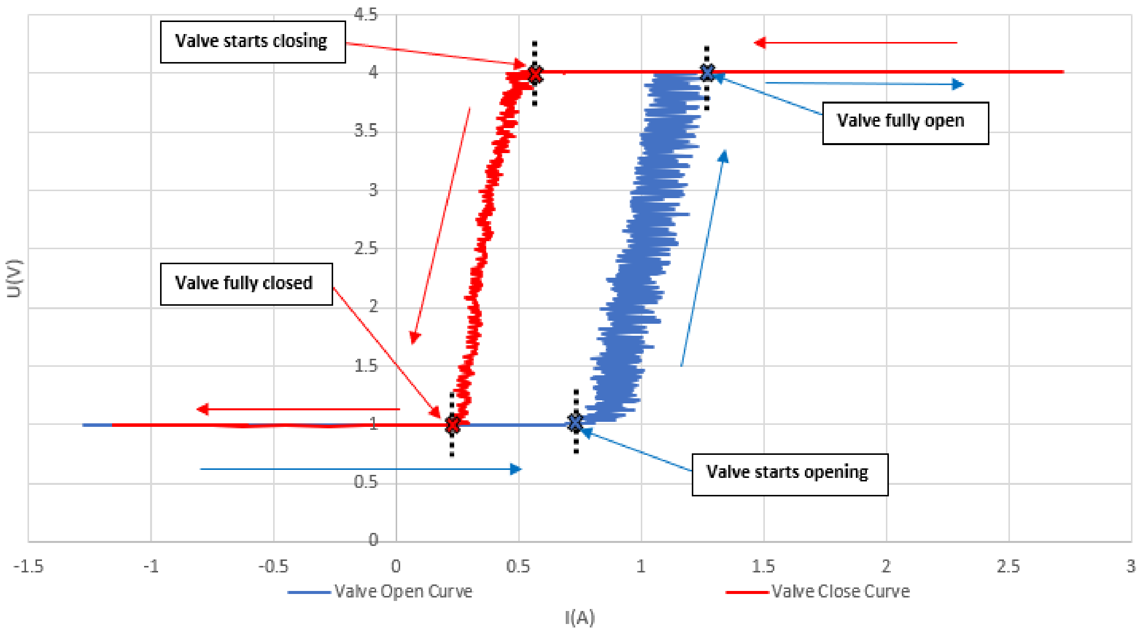

Figure 19 - Example of the valve current hysteresis measurement flow and main areas

The hysteresis concept is incorporated in the actuation of the valve, and it is desirable to have a control designed for the EOLs of the production line that can identify parts that have mechanical defects by evaluating its current hysteresis. These defects can give inaccurate measurements of the gas flow to the Engine Control Unit, making it work inefficiently and having the possibility of causing damage to other system components over time. The production line manufactures one product, the EGR valve, and has several different references, each with its own specifications. Each reference is manufactured in batches of certain amounts of parts to satisfy customer demand.

Certain behaviours of parts in their current hysteresis can also lead to necessary adjustments to the process or additional control in order to be prevented. Considering that every reference from the production line is developed to fit specific systems, each of them has slightly different motor current and sensor voltage output values due to their different specifications. This indicates that the general approach to be taken for the control method must consider these differences when applied.

Even when inspecting 100% of the products, there is not a 100% reliable method to avoid errors at inspection, including error type I (faulty parts that are sent to the customer) and error type II (good parts for rework). Since it is a complex product and production process, certain defects are only detected in the customer application or directly in the end customer, thereby increasing the associated costs due to poor quality and requiring action plans to eliminate or mitigate the risks.

3.2. Production Line of EGR Valves

The industrialization of the production line is done according to the product specification, and the Design FMEA has an important role in understanding the potential risks associated with each step of product assembly. However, both the product specifications and the Design and Process FMEA suffer changes due to product improvement or due to problems detected in later stages. In order to protect the confidentiality of the data from the company, the mentioned data will be given as a percentage value instead of an absolute value.

During the start of project (SOP) of the product, there was not much knowledge amongst the team members. The design FMEA serves as a guide for the industrialization of the manufacturing process of the product. Additionally, it is a standard in the industry to perform both design validation (DV) and product verification (PV) testing with prototype parts before moving forward with the manufacturing process. These tests are done to check both the specifications and the functionalities of the product, so further functionality tests not considered in the design FMEA might not be done. The standard visual representation of the OK measured values of each reference in the current hysteresis test was taken from these PV tests.

Detecting defects only in the customer application or directly in the end customer leads to an increase in the associated costs due to poor quality and requires action plans to eliminate or mitigate the risks. These defects are caused by a combination of non-controlled factors as well as non-monitored variables. The latter is related to the topic, as when some of these parts were analysed, there could be seen an irregular pattern in its current consumption of the motor per sensor voltage value during its current hysteresis test, which graphically represent the hysteresis of the part in its current. And so, due to a proactive attitude, there was an understanding that these values should be monitored and controlled to avoid having valves with irregular patterns delivered to customers, thereby mitigating errors at inspection, both type I and type II.

The key factor in understanding the need for a control was that, during the SOP of the several references, only one had contemplated a partial control for the current hysteresis values in its requirements and design FMEA (later also included in the Process FMEA). It consisted of a four-point control with two points on each curve, which will be mentioned in the next section of this document. Nonetheless, this was not a customer requirement but an internal engineering specification, but the lack of any control impacts the customer and brings unexpected additional costs, which internally require action.

In 2021, the valves' production line had only one EOL but was already under the implementation of a second EOL to ensure a dedicated EOL to each type of product: poppet valves and throttle valves. Since the bottleneck of the line was the EOL, it allowed an increase in production of up to 20%. The implementation of the second EOL was concluded at the end of the second trimester of that year.

When it comes to the control mechanisms in place in the production line, there are several stages of control in each machine and each step of the process, most of them being automatic, such as functional electric tests to measure both opening and closing response times as well as the failsafe response. All the values are stored in the centralized database of the production line.

There are also standard parts per machine and a first part measurement policy at the start of shift to ensure the several variables are kept under control; however, they were not enough to filter out all the non-conforming parts. Disregarding the cases in which the valve does not have movement, the non-conforming parts mentioned relate to parts in which the mechanical defects affect the correct functionality of the movement, a fact supported by the existence of customer quality and warranty complaints. But, for the EOL electric testing of the part, the current hysteresis test had no control apart from the partial control in the reference that was mentioned previously.

Each valve is tested at the EOL two times, the second in case of failure in the first test, and the average first-time rejection rate of the EOL in 2021 was around 18%. Also, to be noted, the internal costs associated with the non-conformities are not accounted for in this document due to confidential information. This needs to be improved as well, regardless.

In order to understand the non-conformity that the control method intends to filter as well as the improvement of the production line KPIs, it was necessary to better understand the product and identify the mechanical defects that could be filtered by the current hysteresis test. It was a slow process at first due to the lack of knowledge, but necessary in order to establish the design for the desired control method. The analysis of valves in both the production line and the valves from both customer quality and warranty complaints provided insight for the next steps of this dissertation.

The number of valves associated with customer complaints, as well as its associated costs and KPIs for the production line, will be a reference for the impact of the control method on the targeted defects as well as for the results of this dissertation.

3.3. Customer Complaints

There are several customers associated with the products of this production line, each of which has different approaches as well as different demands, depending on the orders each of them has for the parts manufactured. Logically, the references that have more production needs represent the customers that have more weight in their demands. As a definition, customer complaints include quality complaints and warranty complaints, whereas quality complaints relate to 0 Kilometre parts (parts with defects detected before the end customer) while warranty complaints refer to field claims (parts with defects detected in the field after usage by the end customer).

Regarding customer complaints, in 2021 they accounted for approximately 0.052% of all cases compared to the produced parts, 37% of which were quality complaint cases and 63% were warranty complaint cases. In those cases, in which the company was liable, the customer had to be compensated for their costs, which included labour costs, the cost of product not sold, transportation costs, the time spent by the part operating in fault, and damages done to the system, among others. It should be noted that of the total percentage of cases for this year, 41% can be related to the variables this control intends to monitor.

A standard procedure exists for handling customer complaints. An 8D procedure and report must be performed for each case, having it represented in a simple way in Figure 20 with all of the relevant details included. This procedure is very similar to one study case analysed in the literature review (Nagyova *et al.*, 2019), including the methods and tools used across. It is not always necessary to perform all eight steps, especially if there is enough evidence to prove the issues are known and controlled or if there is evidence that the customer is at fault for the failure of the parts.

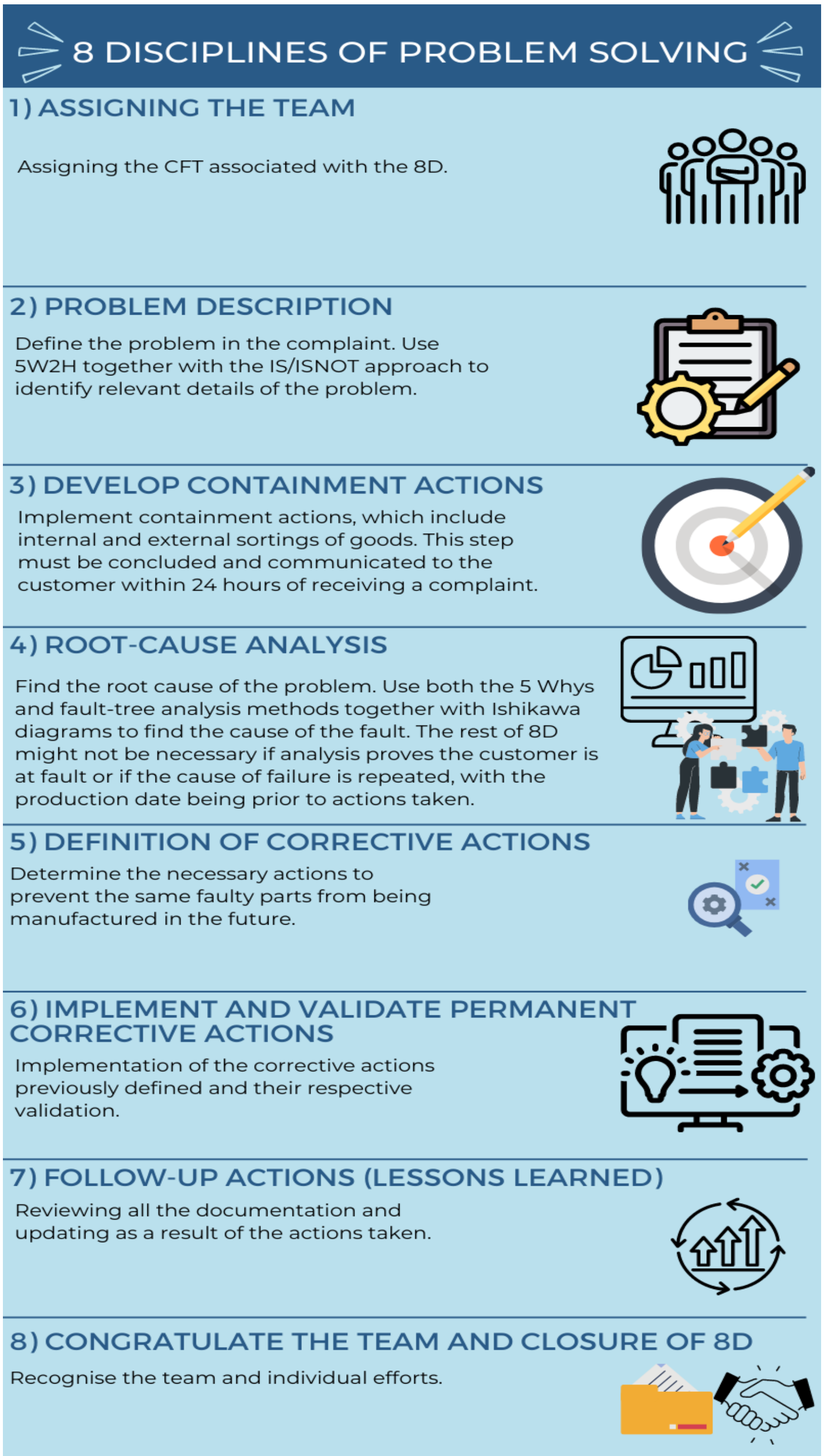

Figure 20 - 8D procedure for customer complaints

Usually, the procedure is simpler for warranty complaints due to known issues or parts in old condition, which simplifies the response procedure for customers. Whereas for quality complaints, it is more complicated because there are more actions required by customers aside from the 8D report. In cases where the company is liable, the shipments of parts to customers must be controlled (usually the first 3 shipments) and a quality wall must be implemented at the end of the production line, which can only be removed after 90 days without the identified defects. All of these internal actions also add up in terms of costs to the associated complaints, having the possibility of being combined with the costs required by the customer for the cases in which the company is liable. Sometimes the discussion with customers can last longer than the actual analysis and actions taken, since it is not always clear who is responsible for the failure of parts. However, both the 8D procedure and the complaint case can only be closed if accepted by the customer.

To sum up, the standard procedure would be to use quality tools and methodologies, going from a simple cause-and-effect diagram in a part detected in the production process to a complex 8D done due to a claim from a customer that has an impact on the production line. In more complex complaints, both preventive and corrective actions might have to be permanently implemented to safeguard the same defects from being manufactured again and escalate the topic further with the customers.

3.4. Process FMEA

The current hysteresis values were not considered in the PFMEA as something that needed to be monitored and controlled, since they were also not taken into consideration during its design phase. Simulating a 6-8 index for Severity (defect causes loss of efficiency of a valve in the engine), a 3-5 index for Occurrence (knowledge of operators as well as effective preventive maintenance in the production line are important), and an 8 for detection (no active control directly, only indirectly by the knowledge of the team), brings the RPN index up to between 144 and 320 and it is considered risky, with the possibility of becoming critical. Actions are necessary to mitigate the risks associated with its inclusion in the PFMEA, so it requires actions to mitigate the index. This PFMEA of the product is not shared with the customer, nor was this topic communicated for the time being.

The only reference that had some kind of specification in the PFMEA regarding the topic, as mentioned in the previous section, will be the one used as an example to classify the indexes of Severity, Occurrence and Detection, as well as updating the other PFMEAs with the RPN index. The PFMEA will not be analysed in this document outside of the current hysteresis test due to intellectual property concerns.

3.5. Synopsis

Understanding the problem at hand and the available data from the product is the starting point of this approach to designing the desired control. Also, it can be understood that this desired control must be implemented to ensure a positive impact on the reduction of both the rejection rate of the production line and the number of customer complaints in the medium- to long-term forecast. It requires, however, working parallel to the design of the control to recreate parts with the mechanical defects detected in the production line or using the ones from customer complaints that would be detected by the desired control. A learning process that took months and involved a team to identify the causes and monitor certain defects in order to design the control method. However, after gathering product knowledge, the method could be designed to serve the intended purposes, which is what the next chapter describes.

Chapter 4 – A New Control for Valve Current Hysteresis

Considering the problem overview, this chapter describes the method of evaluation designed, implemented, and validated in the production line for the purpose of this dissertation to ensure quality control of the hysteresis curves.

4.1. Understanding the Valves

There are two very different groups of valves that are manufactured in this production line: poppet valves and throttle valves, with some differences between them and each having its own EOL. However, the procedure for data acquisition is the same. In the EOL electrical tests, there is an actuation of the valve by supplying voltage to the motor terminals, similar to Figure 18. The flow of operation to consider throughout this chapter is that the part goes from a fully closed position until it is fully open, and then it goes back to a fully closed position. Displayed in Figure 21 are two examples of graphs that represent the sensor voltage output versus the motor current value of two individual parts: a poppet valve (a), and a throttle valve (b).

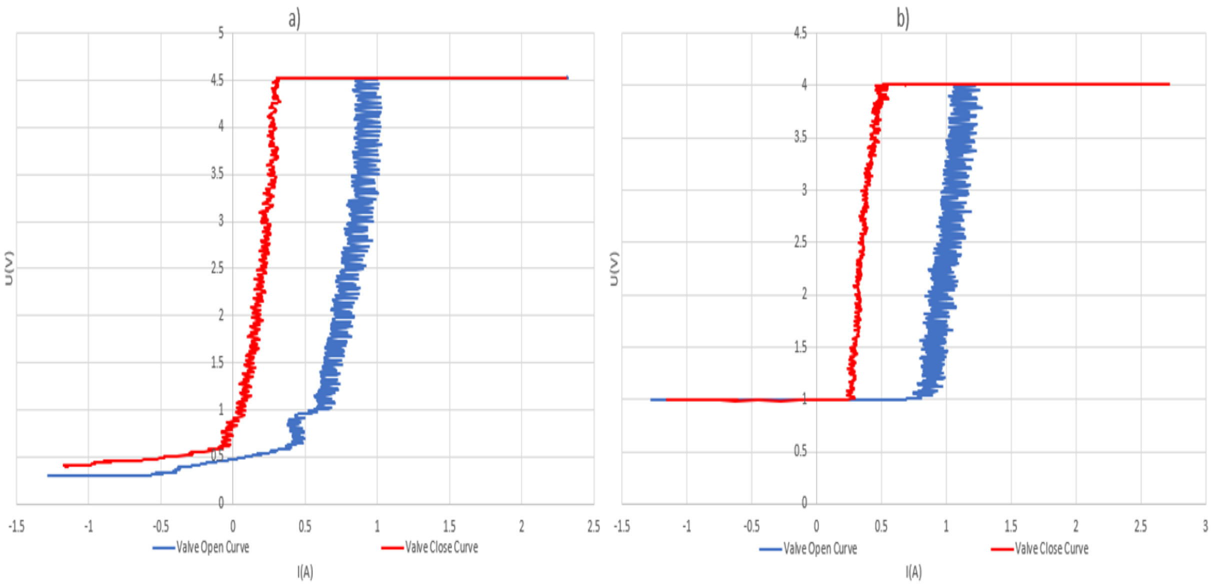

Figure 21 - Sensor Voltage Output versus Motor Current of two references

Considering the valve is naturally closed, there is a bigger variation in the current during the Open Curve due to forcing the valve out of its natural position compared to the Close Curve where it is returning to the natural position. However, it is important to understand what each part of the curve translates to. That essentially means which zones of the valve operation are relevant for the design of the control method. Figure 22 has a breakdown analysis of the curve A from Figure 21, where it is divided according to its functionality. As can be understood, zones 2 and 3 in both curves are the ones this control intends to monitor. It should be noted that the zone 2 described is exclusive to the poppet valves, as perceived in Figure 21 previously.

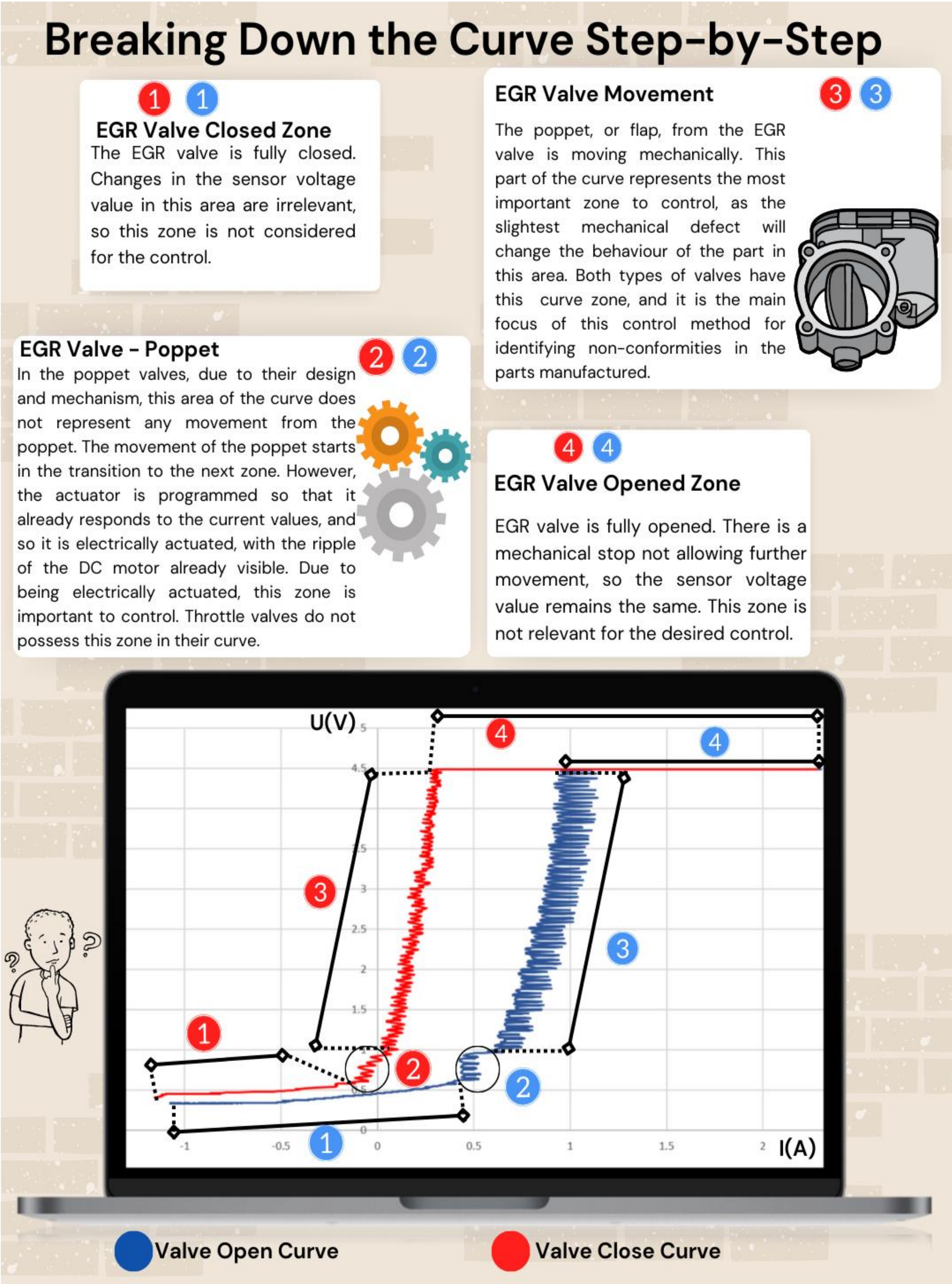

Figure 22 - Analysis of Curves divided by Zones

There are eleven references in total between these two groups: eight poppet valves and three throttle valves, and in between each group, references have slightly different parameters specified, which means slight differences in hysteresis curves amongst them. Between groups, however, apart from one exception, there is a large difference that is clear in Figure 21, and each group goes to its own respective EOL, so the control method can be adjusted based on this.

4.2. The Control Method

Understanding the product and its production process, it is now possible to define step-by-step how the control method will be implemented. Figure 23 represents a general view of each step of the procedure, starting off with the gathering of data from the production process of each product reference, followed by a statistical analysis to determine the boundaries for the software control implementation that will determine the conformity of a valve. During the first and second steps, product knowledge is also gathered, which helps to distinguish the potential defects identified as non-conformities by the control and, together with the CFT, understand their impact and update the Process FMEA accordingly.

As mentioned in the previous chapter, where one of the references had internally defined a four-point control (two points of control for each curve), this will be replicated for the other references of this production line, due to having this possibility through the software in both EOLs and since it would not require any external costs. The four-point control limits will be based on the statistical analysis and will be in place until the implementation of full curve control. Meanwhile, the supplier will also be contacted to proceed with the development of this control in the software of the production line.

The software supplier will then provide a date for the implementation of the control, and it will be necessary to test it in order to have its validation as a proof that it performs as intended. Subsequently, it will be put into place the use of statistical process control (SPC) charts so that these values can be monitored and provide information to the CFT to take a proactive approach and act preventively upon process variations, determining their causes.

Lastly, all the procedures taken must be fully documented, and the process FMEA must be updated accordingly. Since this control was internally developed, all of these steps disregarded the validations by customers as a part of the procedure taken.

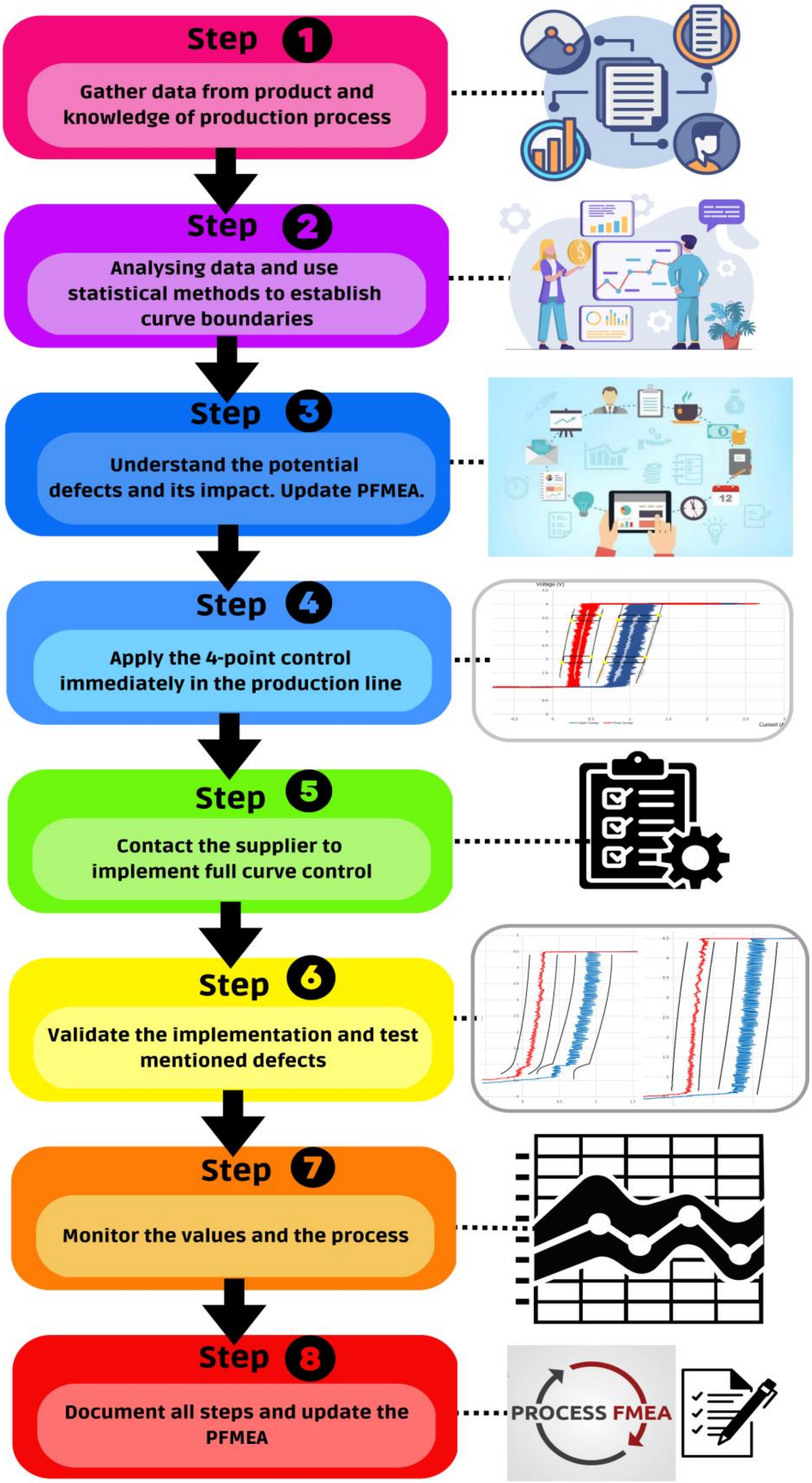

Figure 23 - Step-by-step procedure of the practical approach to implement the control method

4.2.1. Gathering Data from Product

The first step taken was to gather data for each reference. The procedure established was to take a random sample of fifty conforming parts produced in different batches of production. Considering the production line is subjected to reference changeovers very often, this procedure must contemplate the variations in between production batches. Also, for the purpose of this document, the general procedure applied in the production line will be described by giving examples of one of references each for poppet valves (A) and throttle valves (B).

Displayed in Figure 24 is an overlap of fifty samples from the same references as the examples displayed in Figure 21 previously. It can be seen that, although the values of each sample have slight differences, they all follow the same data pattern for each reference. This is the data that will be used for the statistical analysis.

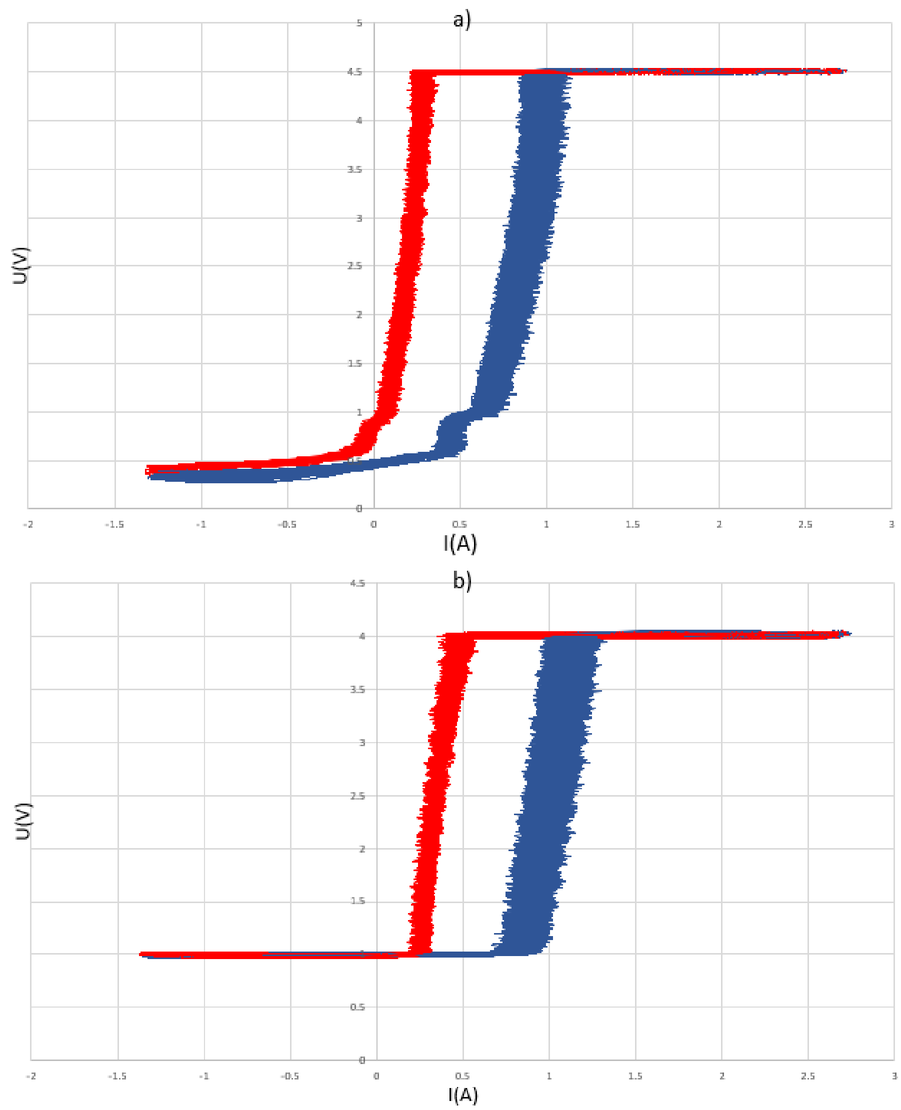

Figure 24 – Overlap of fifty samples of two references A and B

4.2.2. Statistical Analysis

Taking the data available from Figure 24, a statistical analysis is done on the data in order to establish the desired limits. There were considered the principles of two methods: Cumulative Sum (CUSUM) and Exponentially Weighted Moving Average (EWMA). The CUSUM method attributes equal weight to the data, whether the data is ancient or recent, while EWMA gives more value to the more recent information and is more efficient at detecting smaller variations in the process. For these reasons, CUSUM was used for references with lower volumes, while EWMA was used for references with higher volumes that are more exposed to variations due to their frequency of production, hence frequent changeovers and adjustments in the production line, as well as more exposed to the wearing out of their tooling. The principles of these methodologies were used to establish a baseline that would be updated by adding newer data in the future to update the values of the limits of conformity established.

Considering the example from Figure 24, the principle used for both will be from the EWMA method since they are both references with higher volumes. There are two thousand and eight hundred points in each curve of one data sample, and the average was calculated for each of these points. Subsequently, on each point, the standard deviation was calculated and applied three times to the average values, with the results displayed in Figure 25 for reference A and in Figure 26 for reference B, designated as such for reasons of confidentiality. It is also displayed in the zones in which it is intended to control, in the same way as seen previously in Figure 22 earlier in this chapter.

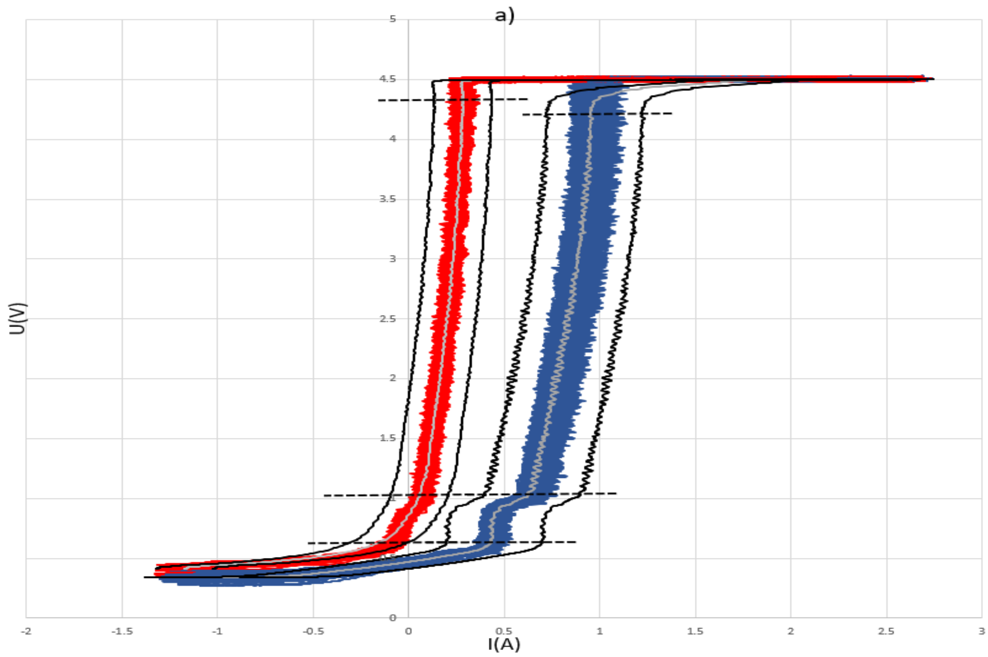

Figure 25 - Analysis done to reference A

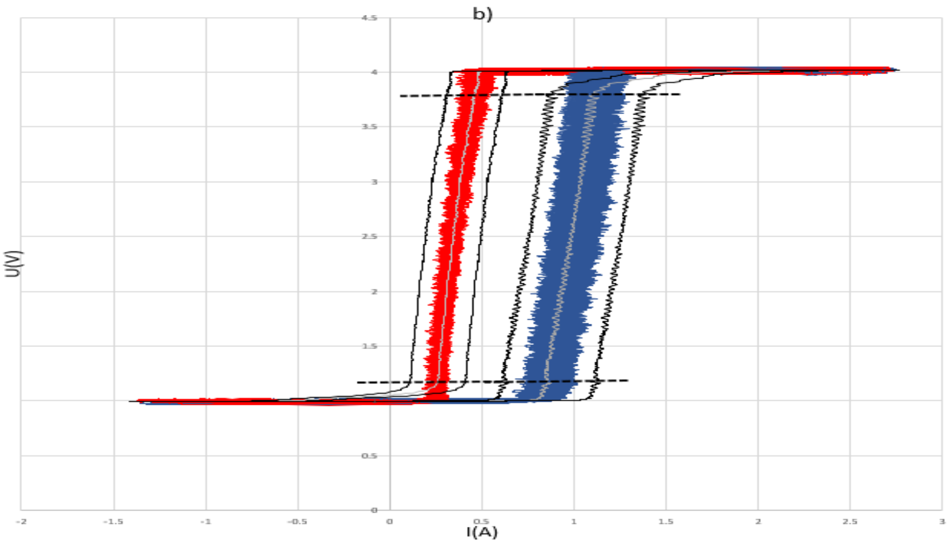

Figure 26 - Analysis done to reference B

Some variations are observed at the end of the open curve, when the valve becomes fully open, and at the end of the close curve, when the valve becomes fully closed, due to the mechanical stops existing in all of the references, and this part, which brings some fluctuation to the values, is to be disregarded. From this point onwards, trendlines can be drawn from the values after applying the standard deviation, and the type chosen was polynomial due to it being simpler to specify how to implement the control to the software supplier, which is mentioned later in this chapter. This so far is about how to achieve the equation limits, but it is also necessary to keep updating the information available and to monitor certain deviations by applying the EWMA chart. For obtaining the respective values, equation (1) is used, with the x_t being given by equation (2). Considering that α takes a value between 0 and 1, and the higher the alpha, the more sensitive it becomes to detecting changes, alpha will take the value 0.9, and it will consider the previous two samples.

$$EMWA_t = \alpha * x_t + (1 - \alpha) * (EMWA_{t-1}) \quad (1)$$

$$x_t = average\ value\ of\ the\ previous\ point\ calculated, with\ x_0 = 0 \quad (2)$$

The values of the EWMA chart limits are established by equations (3) and (4).

$$LSC_{EWMA} = \mu_x + 3 * \sigma_t \sqrt{\frac{\alpha}{2-\alpha}} \quad (3)$$

$$LIC_{EWMA} = \mu_x - 3 * \sigma_t \sqrt{\frac{\alpha}{2-\alpha}} \quad (4)$$

For the CUSUM chart to be used in the lower volume references, equation (5) represents the standard deviation to be calculated, while equation (6) is the *k* value to be calculated accordingly to have the chart centred.

$$\sigma_{CUSUM} = \frac{\bar{R}}{d2} \tag{5}$$

$$k = 0.5 * \sigma \tag{6}$$

The V-mask to be applied to the values in the chart is given by equations (7) and (8) as follows.

$$Upper\ CUSUM\ UC_i = Max(0, Uc_{i-1} + target\mu_0 - k) \tag{7}$$

$$Lower\ CUSUM\ LC_i = Min(0, LC_{i-1} + target\mu_0 + k) \tag{8}$$

These control charts are in place in this data acquisition phase to understand deviations upon updating the established control method polynomials. The procedure is, when the EWMA or CUSUM chart indicates a process is within control, to update the polynomials in the control method at the production line and, when doing so, to take sample data to update the EWMA or CUSUM chart. Differences smaller than hundredths of a unit in the average initially calculated are to be disregarded, so in these cases the polynomials are not updated. This makes it so that significant changes are followed accordingly, with the smaller changes being followed by the established control charts without the need to change the control method limits at the EOL every time there is production of a new batch.

4.2.3. Understanding the defects and updating the PFMEA

By the time of the statistical analysis, some product and process knowledge had been gathered, and the potential defects had been identified. One example of the defects identified can be given by the curve of one part of reference B, which had a segment gear with two broken teeth. Applying the trendlines obtained previously, its result can be seen in Figure 27.

Reference B will be used to illustrate a general view of the defects identified. In Figure 28, a description of the defects found as non-conformities through the hysteresis curve analysis can be seen. This Figure is represented in a general and simple way due to proprietary content. The identified defects centre around anomalies with the flap friction (the poppet for poppet valves) due to poor alignment with the shaft axis, with anomalies in the spring, as well as in the intermediate pin and in the gears of the part, all of which cause friction on the movement of the valve, hence compromising its correct functionality. All of these identified defects were determined by applying the trendlines as boundary limits to the data of the parts.

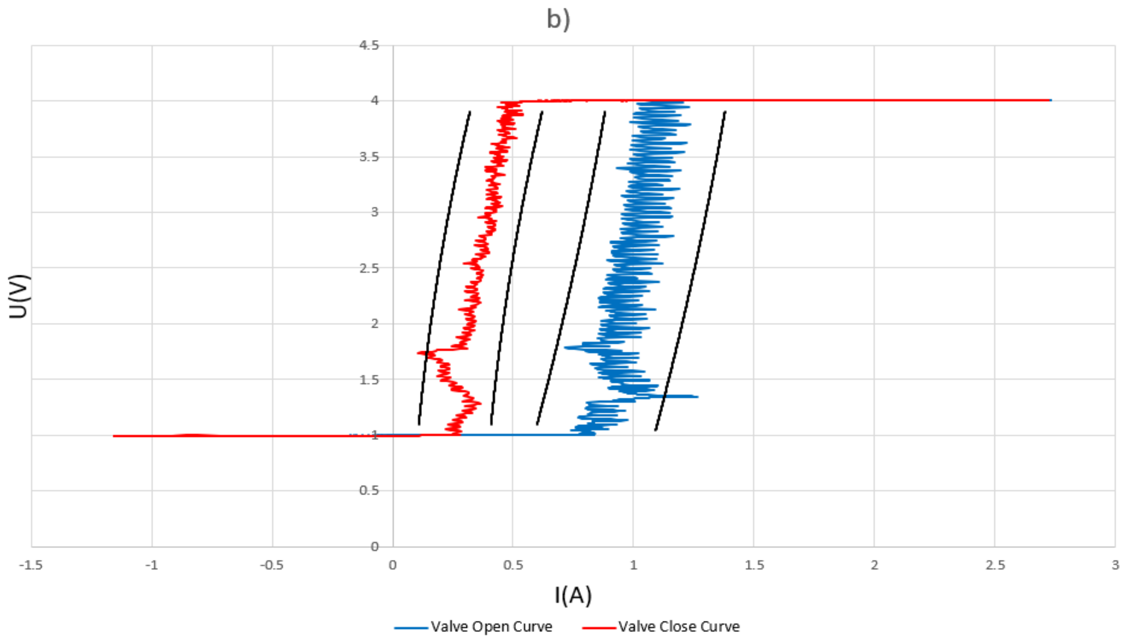

Figure 27 - Part of reference B with damage in one segment gear

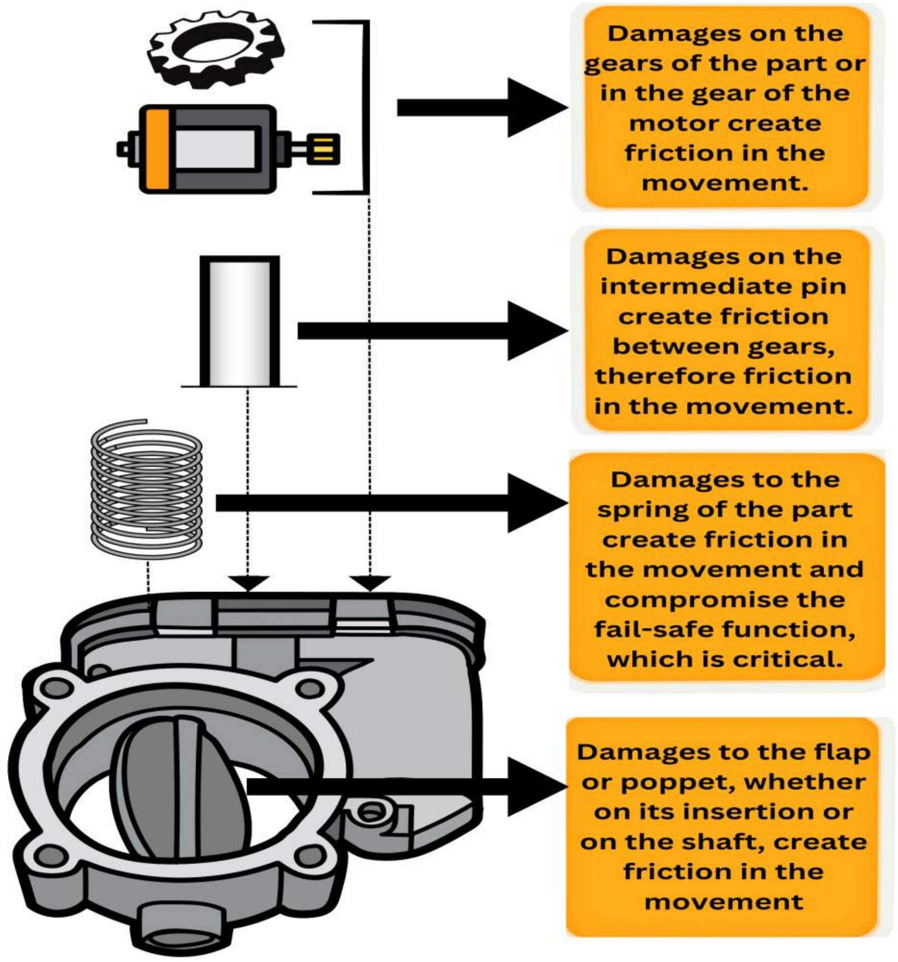

Figure 28 - Defects identified with the hysteresis curves for reference B

With the identification of these defects, the Process FMEA must now be updated with all the information gathered to this point. As mentioned in the previous chapter, the Process FMEA did not consider this control, so after assessing the situation together with the CFT, it was updated as displayed in Figure 29.

PROCESS			Potential Failure Mode	Potential Failure Effect(s)	Severity	Class	Potential causes/Failure mechanisms
Operation	Function	Requirement					
OP-EOL	**Valve Test: (Current Hysteresis)**		Damage Mechanical Parts	Loss of efficiency in the valve in the engine	7		Damaged spring, damaged gear segment, damaged intermediate pin, plate friction

CURRENT PROCESS				RPN	Recommended Action(s)	Responsibility & Target date
CONTROLS Prevention	Ocurrence	CONTROLS Detection	Detection			
Preventive Maintenance, Visual Inspection	4	Four-point Control	4	112	Develop Full Curve Control	Fábio Melo CW30

Figure 29 – Process FMEA update after assessing the initial situation

The four-point control mentioned previously is something that should be implemented immediately in the EOLs since it is achievable internally without additional steps.

4.2.4. Four-point Control

The control of four points, two in each curve, is something that is simple to understand. With a given sensor voltage value, the current must be within a defined interval. These intervals are defined by the trendline equation values obtained from the statistical analysis. Since it takes time for the software supplier to implement the full curve control as desired, this can be done as an immediate action to provide some control over the values. Reference B, that was used to describe the procedure so far and that was also used in Figure 28 to display the identified defects, is displayed in Figure 30 with an example of how the control of four points is applied. By defining voltage points of evaluation, the current values at those points are monitored. The chosen intervals were defined as control limits and were aligned with the existing internal specification for the reference, which had four points of control at the start of its project.

This cannot serve as a full control, firstly since the only inputs are the absolute values of voltage and current, and secondly, having a window too large would mean there is not an accurate control. And lastly, the software program is not optimised to work under a wide voltage interval, and it would raise the cycle time of the machine, which is undesirable.

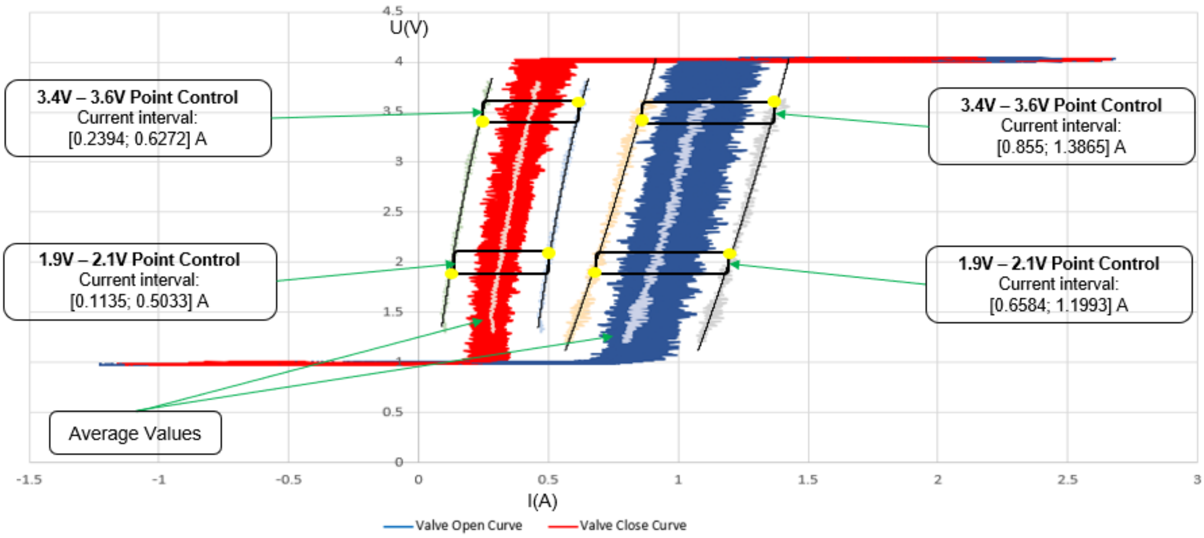

Figure 30 - Representation of a four-point control, two for each curve, for the reference B

4.2.5. Supplier Specifications

The communication with the software supplier was established, and a document was prepared with the necessary specifications for performing the desired implementation of full curve control. In Figure 31, there is a schematic of the thought process behind making the desired specifications. Using the polynomial trendlines, the coefficients given are used to establish the equations that generate the boundaries in the hysteresis curves. Considering the different zones to control, it was decided to enable the possibility of having two different polynomial equations with a lower degree per equation, since it would make it easier for the supplier to implement while having a lower cost compared to only having one polynomial equation that could go up to a fifth degree.

For each equation used, the start and stop points of its evaluation voltage interval are also determined. With these data inputs, the boarders are drawn in the EOL graph as well as in the data results stored by the program. There are also new variables introduced due to this implementation, namely the minimum value of the difference between the established boundary and the measured values. For an example, if one equation is considered to be the upper limit on one of the areas, having the minimum value as a positive one indicates that the measured value does not intercept the equation and it indicates conformity of the part tested in the hysteresis test, whereas if the value is negative, it means there was an interception and the measured value went over the established boarder equation, indicating a non-conformity in the part tested. These variables and results are saved locally in the EOL as well as in the database of the production line to be used for traceability.

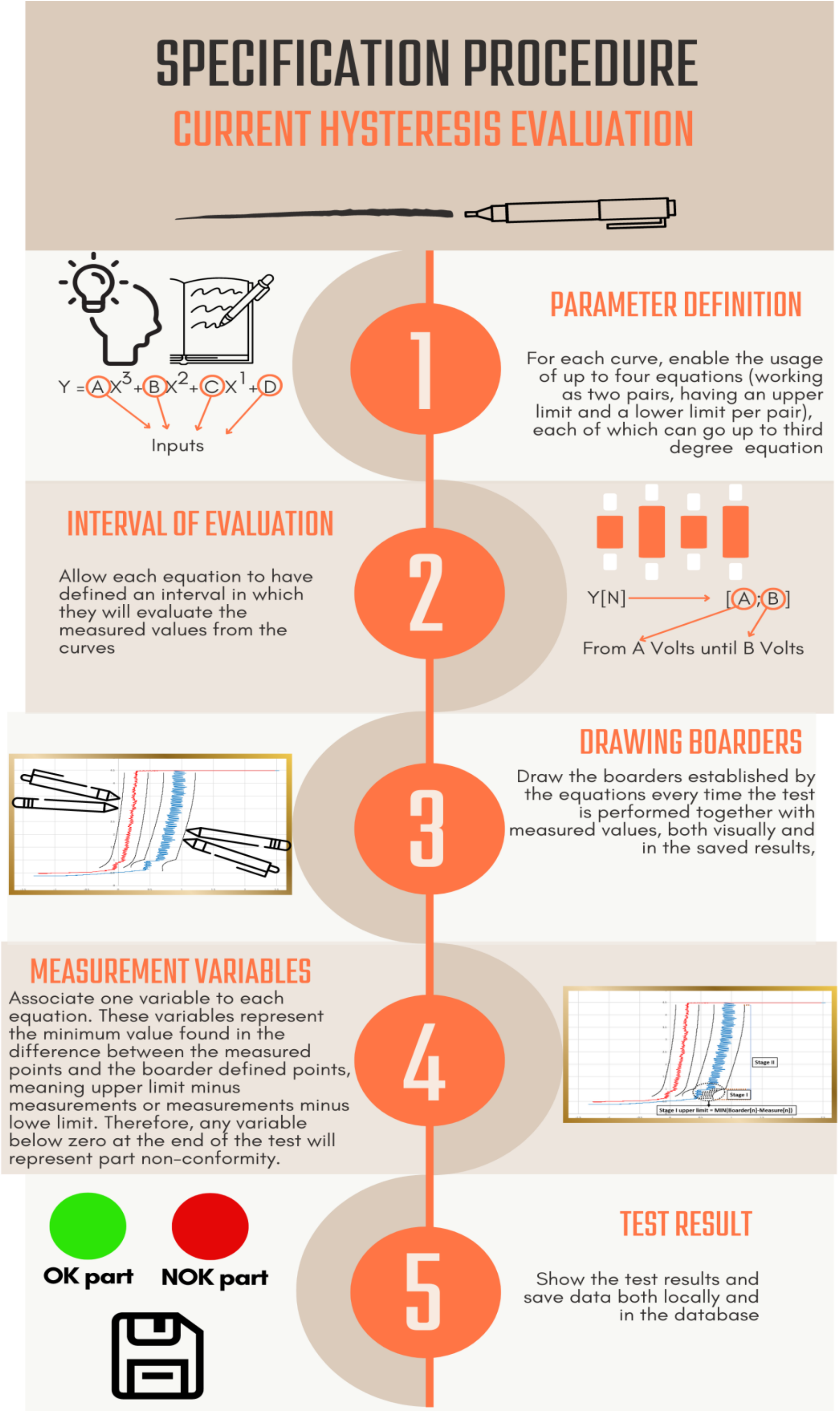

Figure 31 - Specifications for current hysteresis test

4.2.6. Implementation and Validation

For the software implementation part, the supplier first performed it in one of the EOLs of the production line that handled the group of poppet valves. Since the implementation also needed the changes in the database, it was done as a first step, and the second EOL (which handles the throttle valves) implementation was done on a separate date after the first. Displayed in Figure 32 is the output data for the first EOL post implementation for a part of the reference A, and in Figure 33 is the output data for the second EOL post implementation for a part of the reference B. The equations were tested in a shorter interval than intended for the full curve to validate the implementation, later being stretched to fit all values.

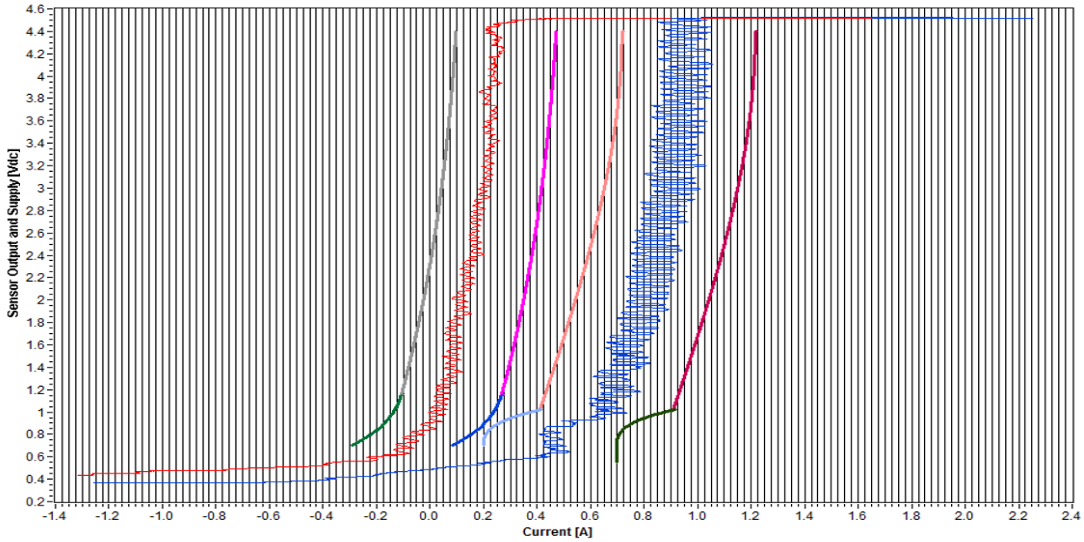

Figure 32 - Data output of current hysteresis in first EOL

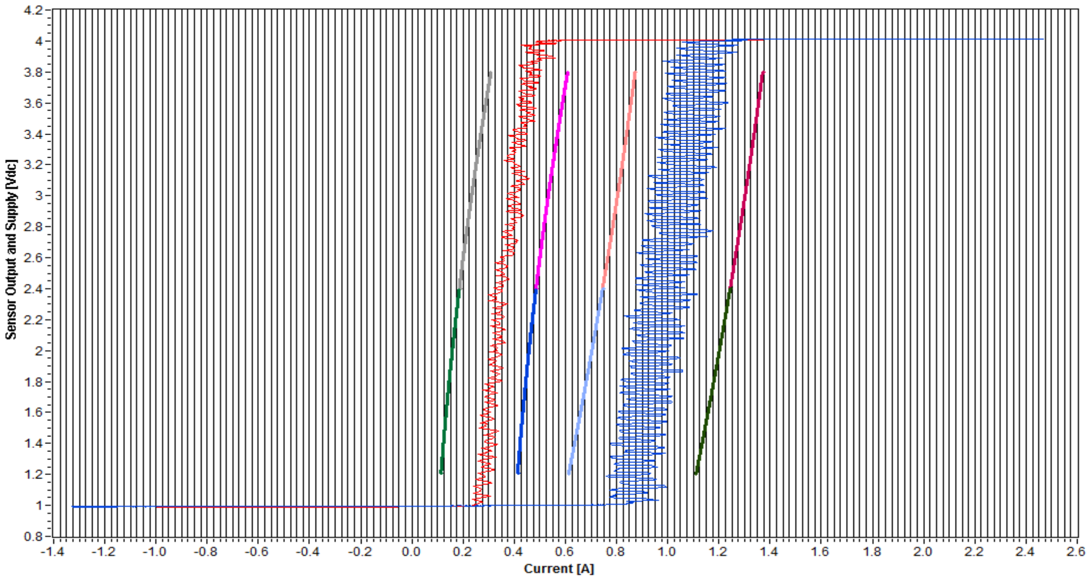

Figure 33 - Data output of current hysteresis control in second EOL

As it can be seen, for both cases, the measured values have upper and lower limits given by the boundary equations established from second- and third-degree polynomials. For the second EOL, there were added two pairs of boundary equations to each curve to test it and validate it, despite it not being strictly necessary since a pair of boundary equations, one upper limit and the other lower limit, would be enough.

The validation part was simple: thirty parts of one reference of poppet valves were tested in the first EOL, and thirty parts of one reference of throttle valves were tested in the second EOL. Of those thirty parts, five had the defects mentioned in the PFMEA displayed in Figure 29 as a way of proving that it detected the desired non-conformities. All the results went as expected, with the parts with defects being rejected in the EOL due to having values that went over the established boundaries. One example from reference B displayed in Figure 34, which had friction on the movement of the flap.

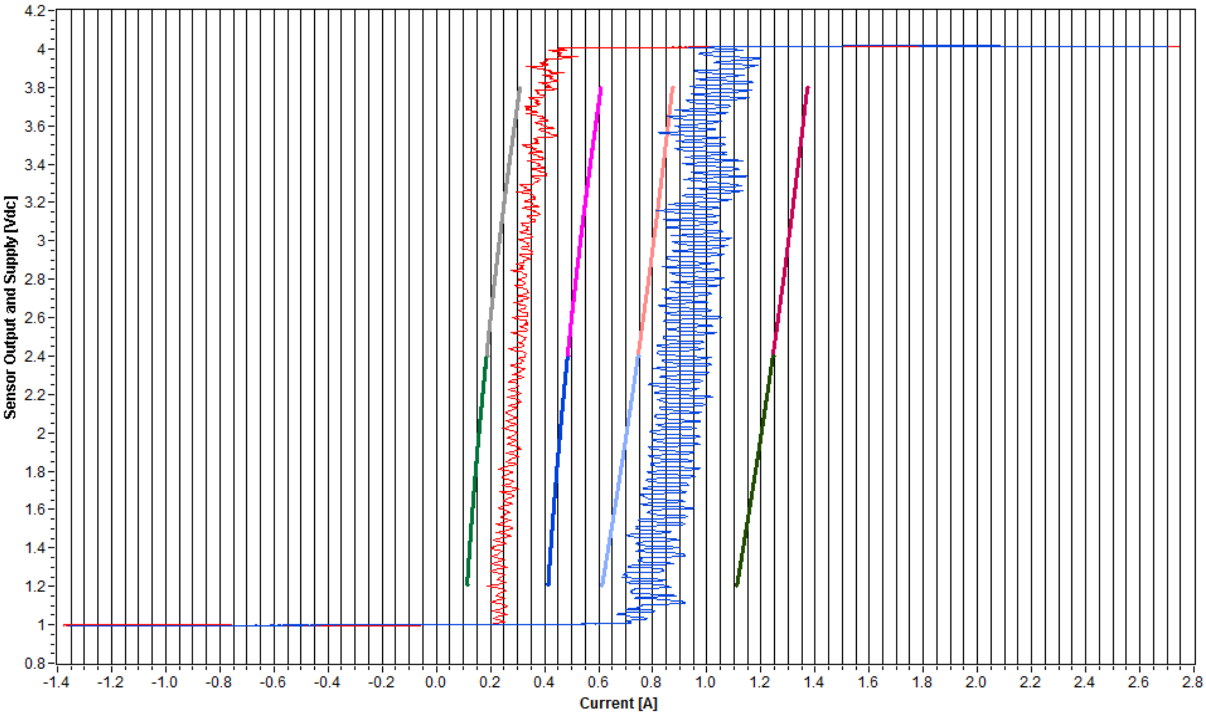

Figure 34 - NOK part at EOL from reference B

Proceeding towards the implementation, Figure 35 represents the example of reference A, where the variables recorded from the boundary equations are displayed in their rough values. In parallel, an Excel template was created with the data from the obtained polynomials for each of the references, to provide a manual alternative to checking the data prior to the implementation of the full curve control. This template was used to compare the data obtained from the test with the manual data obtained to see if the drawn boarder limits were correctly drawn, and the manual verification of these values from Figure 35 is displayed in Figure 36.

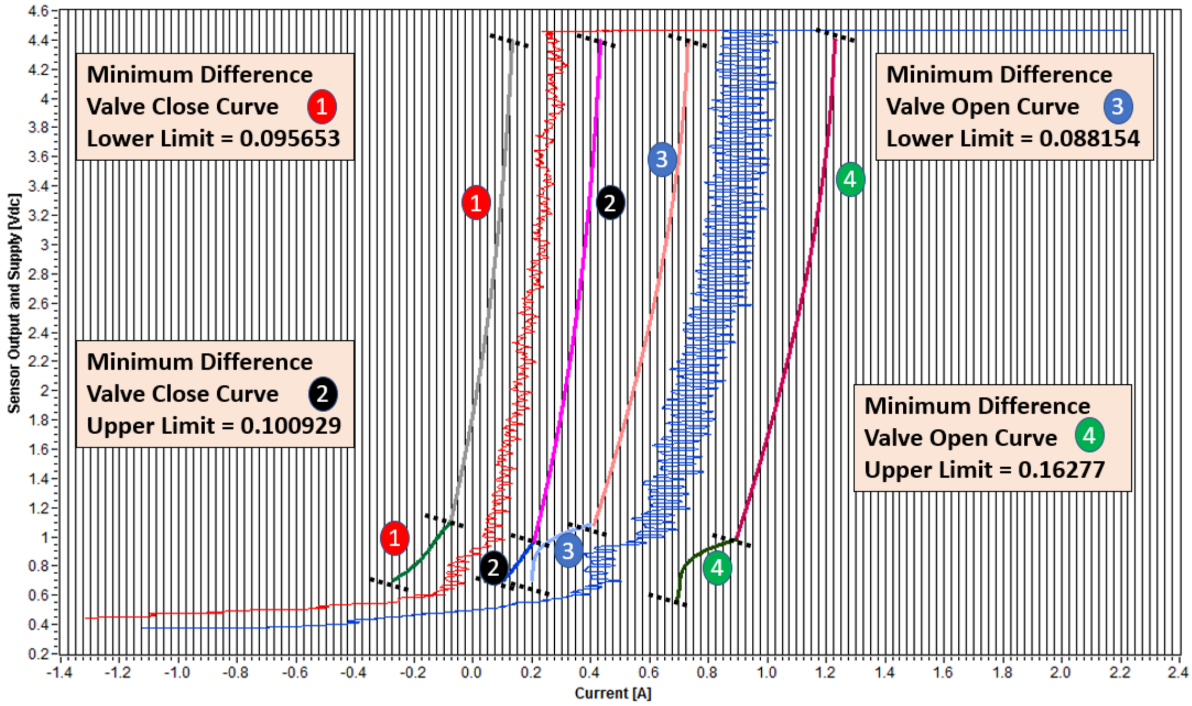

Figure 35 - Current Hysteresis Test Variables Measured in EOL

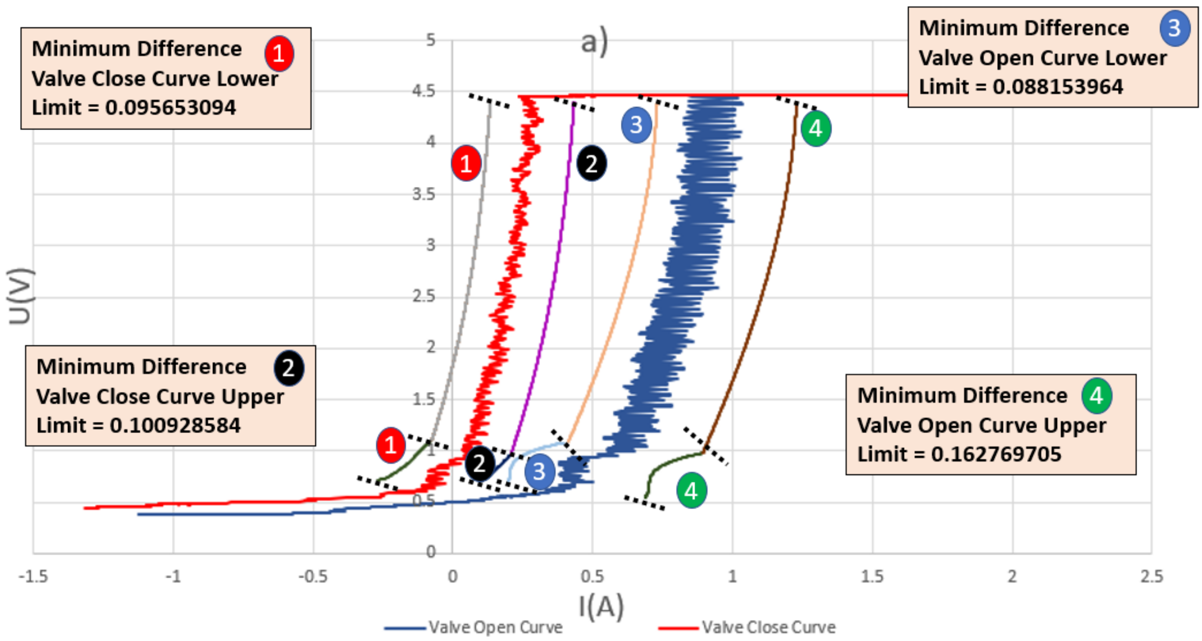

Figure 36 - Current Hysteresis Test Variables Manually Calculated

As it can be seen, the differences are a matter of rounding the values in the calculations, and because the database rounds the values up to a maximum of four decimal digits, the values are the same, so the implementation was successfully validated. As mentioned before, it is not mandatory to inform customers about the control, so it is only validated internally.

To complement the information, during the analysis of a valve from either a customer quality complaint or a warranty complaint, one of the performed tests is the current hysteresis test that is done in separate equipment from the production line, but the test itself is the same as the current hysteresis test in both EOLs. This test bench is displayed in Figure 37 below and features the same hardware used in the EOL of the production line.

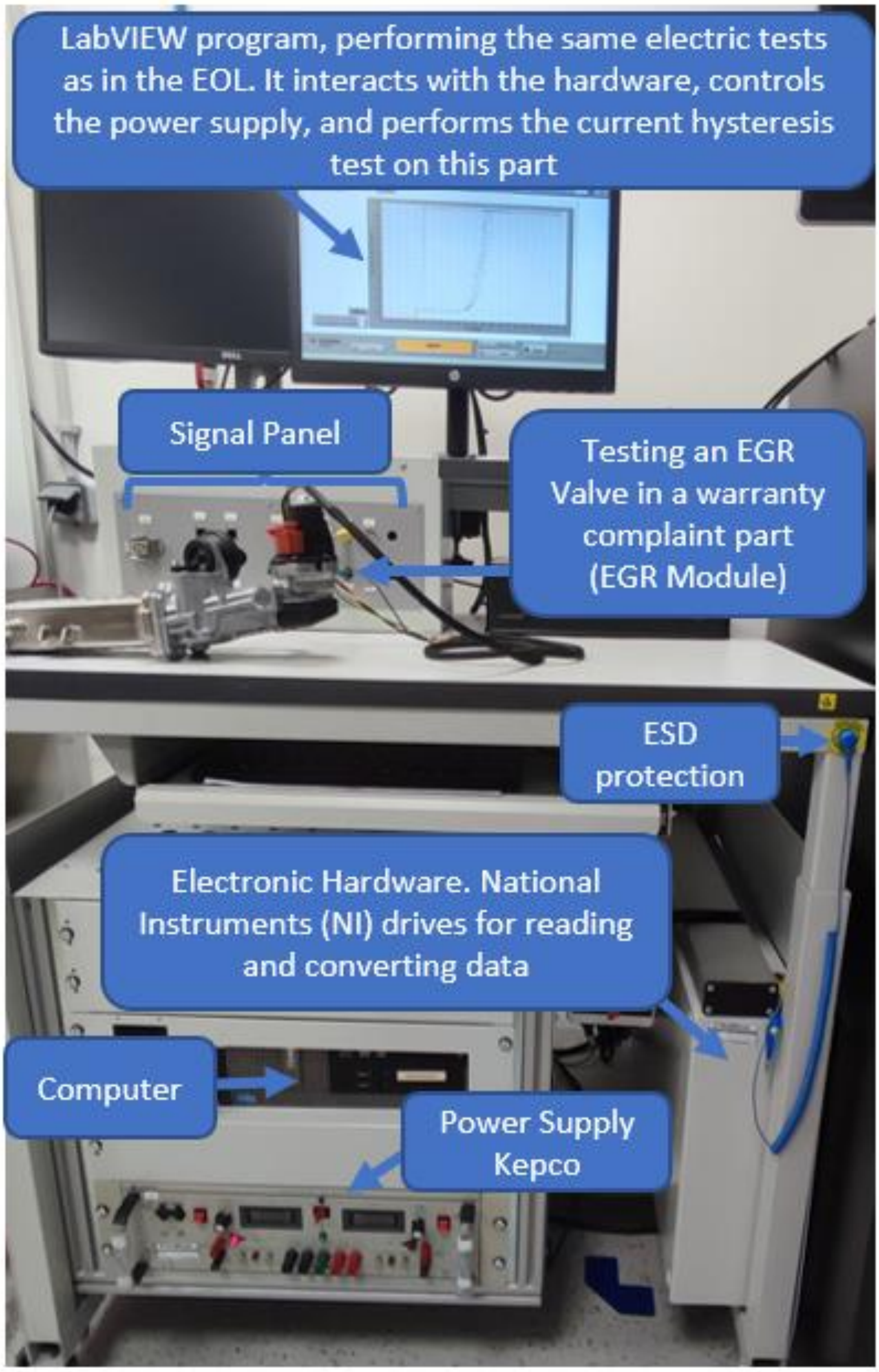

Figure 37 - Current Hysteresis Test performed in Test Bench

The Excel template that was previously prepared and used in Figure 36 is also used with the data generated from the test on this equipment to provide graphically the same result as the EOL post-implementation and support the analysis. However, there is quite a difference between parts of new and old condition when it comes to functionalities and values. As such, this template does not replace in any way the necessary analysis, but it provides support by establishing a criterion regarding product conformity.

4.2.7. Statistical Process Control

Post-implementation of the control method, it is necessary to monitor the values of the process. Statistical Process Control (SPC) charts are an effective method to be proactive about the slightest of changes, even if they are not impacting the quality of the product. Another relevant fact to be mentioned is that, although the current hysteresis test has its importance, it needs to be adjusted to the process setup, meaning that all factors that might slightly change the values must be taken into account when analysing data since the goal is also to remove or mitigate all false positive.

SPC can be defined as the usage of statistical techniques to monitor and control a process, allowing for the discovery of existing issues and the use of data analysis to find solutions. It is used to study the changes in the process over time, taking samples of the data generated from the process as it is displayed in chronological order. This was something that started to be used across the production line in general to have a better understanding of the process deviations and to support the proactive approach to finding the root cause of the problems.

Regarding the current hysteresis test performed in the EOLs, all result values are imported from the database of the production line and filled in an Excel file, which can be filtered by reference in order to retrieve a sample of twenty valves for each batch of production per reference. Then control charts are drawn for the variables, consisting of upper and lower limits, in order to monitor the process throughout its duration as desired. These lines can be adjusted throughout the process depending on the findings of the investigations and the actions taken. One example of the procedure taken can be seen in Figure 39 from reference A, where one of the SPC charts (using chart Xbar, s) relating to one of the variables from the test results is displayed. The points 10, 11, 14, and 15 are out of control limits, and one point is out of the 3σ interval. These process deviations were investigated to bring the process under control and keep it stable.

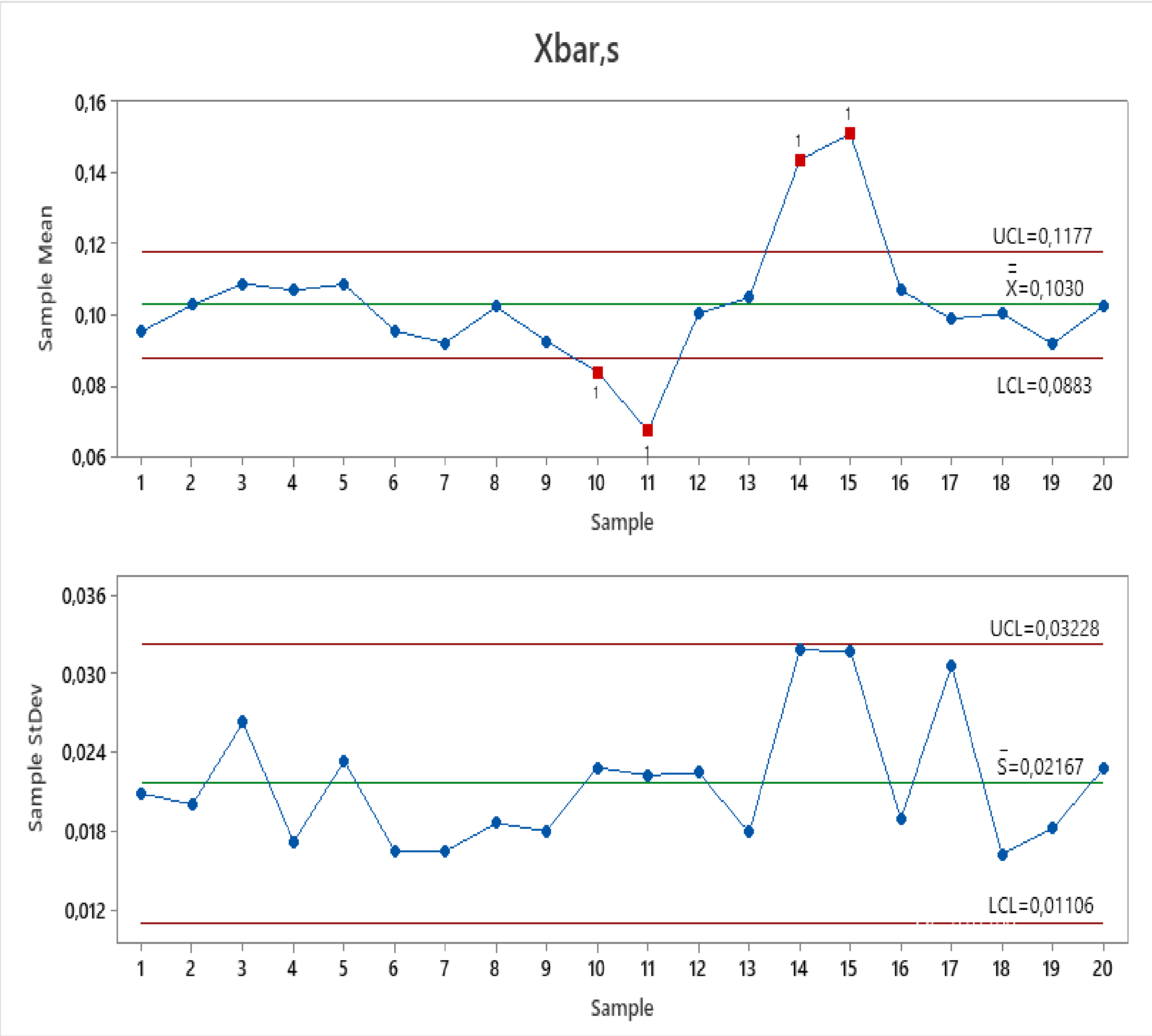

Figure 38 - SPC chart of one of the current hysteresis test variables

This monitoring of the variables of the test is not implicitly part of this dissertation topic, but to ensure that the developed and implemented control method keeps actively contributing to the product conformity, it needs to be assured that it will be efficient and optimised, therefore investigating process deviations. Parallel to this, it will also benefit the rest of the production line and team to move forward towards the continuous improvement of the product.

4.2.8. Documenting and updating PFMEA

Once the control method has been implemented, validated, and monitored, it is necessary to update the PFMEA with the corresponding values after the review with the rest of the CFT team. This update post-implementation is displayed in Table 3.

Table 3 - Updated PFMEA post-implementation of control method

ACTION RESULTS				
Actions Taken	**Severity**	**Occurrence**	**Detection**	**RPN**
Full curve control implemented and validated internally	7	4	2	56

The associated cost for this software implementation paid to the supplier for the implementation was approximately 4500 euros before VAT. The internal costs associated with the development and implementation were not quantified.

To consider for the results discussion, the implementation of the control of four points was done two months prior to the full curve control implementation, and since the date of implementation until the date of finishing this report was around a six-month period.

4.3. Discussing the Results

Understanding the data and identifying how it behaves was a crucial point in this dissertation for implementing the control. When there is a mechanical non-conformity, the current consumption of the motor either has a big delta variation in a short amount of time in its movement, or more current consumption in its open and close movements. Having this definition allowed for identifying the defects and specifying the necessary changes for the software implementation.

The validation part was done according to internal standards, and the support of the CFT was important to support root cause analysis and to be proactive when it comes to mitigating and preventing the mentioned defects.

Having done the analysis and development of the control method while updating the PFMEA established from the product, this itself will provide feedback in medium- to long-term regarding the effectiveness of the control method. However, the control does not replace preventive measures, as it is necessary to monitor the process, act preventively, and keep working towards the continuous improvement of the production line.

4.3.1. Production Line

Taking into consideration all the work done so far in this dissertation during the year 2022 as well as the involvement of the CFT in the production line, the value of the first rejection rate in the EOLs was 11.2% on average, a decrease of close to 40% when compared to the 2021 average value of close to 18%. Adding a new control to the production line raised the rejection rate during its introduction to the process, but through analysis of the data and working together with the CFT, it was possible to find the root causes of problems as well as smaller deviations. With the findings, actions to correct and mitigate the risks were implemented, optimising the process while working towards continuous improvement. This, added to the improvements made in the suppliers of the components, helped towards a decrease in the first rejection rate.

Another improvement that resulted from the continuous improvement and optimisation of the production process, combined with the implementation of the second EOL at the end of the second semester of 2021, was the increase of 23% in the total output of production, surpassing the initial expectations of up to a 20% increase.

4.3.2. Status of customers post-implementation

The impact of the implementation of the control method can be perceived by the amount of both customer quality and warrant complaints received. Comparing the year 2021, there was 0,052% (compared to the total output of the production line) of customer quality and warranty complaints, of which 37% were quality complaints and 63% warranty complaints, whereas in 2022 there were approximately 0,028% cases of customer quality and warranty complaints, of which 29% were quality complaint cases and 71% warranty complaint cases. Related to the variables this control intends to monitor are 17% of cases, which, apart from one, date back to a prior date of the implementation of the control method. The one posterior to it was essentially not detected due to the non-conformity in its hysteresis curves showing in another area outside of the four-point control, which the full curve control already in place would detect.

Chapter 5 - Conclusion

Having the opportunity to take part in a project in an industrial context with an international company proved challenging in many stages. From design to industrialization, the production process, quality control, and handling several different customers, among others, it involved the whole spectrum from product conception until the end customer, providing a valuable experience across all sectors of the automotive industry.

Regarding the references used, there is a lot of information related to the usage of the hysteresis concept for several different applications across a variety of industries, but this project is a solution for a very specific product in the automotive industry, with its own production process, and this fact turned this dissertation into something different from all the others already made.

The initial deadlines established had to be adjusted a few times due to several factors, mainly the unavailability of the software supplier and several other uncontrollable factors. Having the software supplier as the owner of the program that runs the production line limits its modifications, requiring their availability for it to be changed whenever it is needed, which impacts the response time. Still related to supplier issues, there were a few disruptions in the supply chain of the components that go into assembling the targeted products for this dissertation, which also caused a delay in gathering data as well as the validation phase. One last example of entropy is the fact that, since the software modification required a certain cost, it took additional time to justify and to have all the necessary approvals to issue the purchase order that was needed.

Moving on to the results part, the topic of this dissertation is something that needs monitoring in the medium term to fully understand the depth of its impact as well as the potential need to include or incorporate it in other projects, despite not being fully necessary to perform full curve control. Sometimes there are factors that need to be weighted, such as the associated costs and the time of implementation, to decide on the correct approach for future implementations. There are several different products, each of which has different customer specifications. It is vital to understand the customer needs and their impact on non-conforming parts to plan the necessary control for the project. In some cases, in the initial phase of the project, things do not go as planned, and later implementations such as this one proves to have a higher cost than if they had been contemplated in the design phase of the product. It was necessary to understand the impact of the defects in the parts that could be identified through this hysteresis concept and align with the CFT on the procedure to take for this specific product. In this case, at the time of finishing this dissertation, neither claims nor warranties with regards to the mechanical defects identified in the PFMEA from parts produced after the implementation were submitted, so as of now, the intended result of the project was achieved. Taken all of it into consideration, it can be concluded that the CFT and the FMEA method are essential parts of a project, especially at its design phase, in order to establish the cost and efficiency of the process carried out throughout its length. And also, to conclude that the short-term data indicates a positive impact of the control method, helping to decrease both the amount of company complaints and warranties as well as contributing towards the continuous improvement of the production line, which decreased in the rejection rate as well.

As for future work, the fact that no quality or warranty parts have been received related to the mentioned defects does not exclude the fact that it might be necessary to improve the software control for additional defects that might be identified in the future. Additionally, it might be an interesting idea to replicate the concept for other existing projects, depending on their needs.

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Appendix A

The data used to do the graph presented in Figure 38 is displayed below in Table 4.

Table 4 - Data Samples used for the Xbar, s chart

Sample 1 (29/03/2022)	Sample 2 (04/04/2022)	Sample 3 (15/04/2022)	Sample 4 (24/04/2022)	Sample 5 (10/05/2022)	Sample 6 (16/05/2022)	Sample 7 (26/05/2022)
0.0868	0.1173	0.0921	0.0971	0.1191	0.081	0.0803
0.0969	0.1221	0.0722	0.1063	0.1173	0.0962	0.0801
0.0949	0.1234	0.0732	0.1162	0.1112	0.1262	0.1071
0.1026	0.1152	0.0938	0.1387	0.093	0.0931	0.1021
0.1132	0.0942	0.1162	0.1179	0.095	0.0783	0.1263
0.1175	0.1011	0.0694	0.1201	0.1404	0.0978	0.0934
0.0461	0.0822	0.089	0.1212	0.113	0.0919	0.0868
0.1133	0.0522	0.0985	0.1051	0.1151	0.1034	0.0827
0.1271	0.1245	0.0901	0.1032	0.1182	0.0784	0.0978
0.091	0.113	0.1044	0.0981	0.0599	0.0932	0.0956
0.1011	0.0947	0.1011	0.0944	0.1157	0.0982	0.0974
0.0891	0.1389	0.1232	0.1221	0.0418	0.133	0.0965
0.0934	0.1129	0.1109	0.0895	0.0926	0.0979	0.098
0.0862	0.1078	0.0941	0.0663	0.1214	0.0998	0.1056
0.1393	0.0797	0.1611	0.0974	0.1176	0.1003	0.0856
0.0945	0.0827	0.1361	0.1093	0.1395	0.1038	0.1076
0.0734	0.1145	0.1333	0.079	0.1201	0.1098	0.0903
0.0682	0.0894	0.1371	0.1195	0.1196	0.0939	0.0412
0.0791	0.0933	0.1412	0.1275	0.1134	0.0754	0.0827
0.0981	0.1001	0.1426	0.1121	0.1115	0.0613	0.0889
Sample 8 (02/06/2022)	Sample 9 (07/06/2022)	Sample 10 (16/06/2022)	Sample 11 (27/06/2022)	Sample 12 (05/07/2022)	Sample 13 (14/07/2022)	Sample 14 (20/07/2022)
0.1071	0.1032	0.0721	0.058	0.0939	0.1011	0.1644
0.1122	0.0954	0.0752	0.0532	0.0319	0.1022	0.1534
0.1119	0.0921	0.0771	0.0651	0.1091	0.1045	0.1395
0.0978	0.1141	0.0718	0.0632	0.0759	0.0953	0.1256
0.1092	0.0898	0.0681	0.0351	0.0741	0.1089	0.0952
0.1052	0.1094	0.0732	0.0442	0.1052	0.1503	0.1728
0.0974	0.0866	0.0711	0.0532	0.1012	0.1013	0.1723
0.1087	0.0914	0.0813	0.0518	0.1007	0.1033	0.1673
0.1129	0.0862	0.1324	0.0857	0.1221	0.1023	0.0454
0.0458	0.0896	0.1501	0.0529	0.0807	0.1222	0.1589
0.1425	0.0824	0.0912	0.068	0.1028	0.0637	0.1528
0.0894	0.0472	0.1002	0.1342	0.1099	0.1326	0.1385
0.1118	0.1154	0.0821	0.0971	0.1099	0.1084	0.1494
0.1096	0.0993	0.073	0.0533	0.1067	0.1037	0.1086
0.1035	0.0812	0.0811	0.0672	0.1067	0.1021	0.1474
0.0896	0.0711	0.0714	0.0961	0.1078	0.1129	0.1522
0.0934	0.0865	0.0982	0.0631	0.1015	0.0733	0.1848

0.0957	0.0821	0.0871	0.064	0.1437	0.1046	0.1671
0.0838	0.1343	0.0813	0.0791	0.119	0.1096	0.1315
0.1219	0.0974	0.0461	0.0682	0.1091	0.0988	0.1452

Sample 15 (27/07/2022)	Sample 16 (03/08/2022)	Sample 17 (08/08/2022)	Sample 18 (15/08/2022)	Sample 19 (24/08/2022)	Sample 20 (07/09/2022)
0.1721	0.1068	0.0509	0.1036	0.0713	0.1059
0.1718	0.1079	0.1266	0.114	0.0886	0.1117
0.1576	0.1197	0.0815	0.1034	0.0979	0.1093
0.1455	0.1178	0.0662	0.1405	0.0963	0.0996
0.1778	0.1059	0.1355	0.0831	0.0909	0.1006
0.1542	0.1257	0.1166	0.1035	0.0948	0.1136
0.1343	0.1095	0.1237	0.1009	0.1007	0.1057
0.1984	0.1149	0.1101	0.1067	0.1025	0.1092
0.0664	0.1012	0.0992	0.1066	0.0823	0.0451
0.1516	0.148	0.0815	0.1007	0.0704	0.1073
0.1568	0.0974	0.1565	0.0828	0.0876	0.1078
0.1377	0.1336	0.0662	0.1227	0.0946	0.096
0.0769	0.0931	0.1281	0.0862	0.1018	0.0823
0.1495	0.1118	0.0591	0.0958	0.1312	0.1125
0.1746	0.0839	0.1047	0.1145	0.0704	0.1216
0.1591	0.1254	0.0534	0.0631	0.1064	0.0659
0.1455	0.0971	0.1069	0.0962	0.1038	0.164
0.1486	0.0696	0.0815	0.0924	0.1014	0.092
0.1884	0.094	0.0977	0.1038	0.1056	0.0991
0.1525	0.0776	0.1355	0.0886	0.0437	0.1009