Study of Automatic Validation of Technical Specifications
of Complex Products: Case Study applied to an EGR

João Abreu

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Escola de Engenharia

João Pedro Amorim Abreu

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- To my friends that made these past few years one of the best of my life.

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I declare that I have acted with integrity in the preparation of this academic work and confirm that I have not resorted to the practice of or any form of misuse or falsification of information or results in any of the stages leading to its preparation.

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ABSTRACT

This academic work consists in the study of mechanisms that can validate the technical specifications of a certain product, in this case, an EGR Module.

Initially, an analysis about the origin of these systems, their functionality and how they are produced was made. This part of the work gives most of the theoretical knowledge necessary to procced to the study of the main subject: Automatic Validation of Technical Specifications of Complex Products.

Then, a study of a specific EGR Module was carried out, going through every phase of its development, starting with Design Development, where the product was drawn, and several design alterations were made due to failures in the test benches and simulations.

The Process Development starts with the design freeze of the last design of the Design Development, the dimensioning of the tools specific for this product and with flow-chart of the process, which gives for the first time an overlook of the process itself. After this the production line starts to be designed to fulfill the demands of the client.

In this production line design, there is seen how it is possible to assure the quality of the product and which machines are fully responsible for controlling the specifications of the product. Finally, the production line is validated with multiple tests that measures how the measure process is exact, precise and feasible, being done MSAs, R@R, Capability Tests, etc.

Keywords

Design requirements; EGR; Inspection; Quality; Technical Specifications;

RESUMO

Este trabalho académico consiste no estudo de mecanismos que podem validar as especificações técnicas de um determinado produto, neste caso, um Módulo EGR.

Inicialmente, é feita uma análise sobre a origem destes sistemas, a sua funcionalidade e a forma como são produzidos. Esta parte do trabalho confere a maior parte dos conhecimentos teóricos necessários ao estudo do tema principal: a Validação Automática de Especificações Técnicas de Produtos Complexos.

Em seguida, é realizado um estudo de um Módulo EGR específico, passando por todas as fases do seu desenvolvimento, começando com o *Design Development*, onde o produto foi desenhado, e várias alterações de design foram feitas devido a falhas nos bancos de teste e simulações.

O *Process Development* começa com o *design freeze* do último *design* do *Design Development*, o dimensionamento das ferramentas específicas para este produto e com o *flow-chart* do processo, o que dá pela primeira uma imagem do próprio processo. Depois disso, a linha de produção começa a ser projetada para corresponder às exigências do cliente.

Neste desenho da linha de produção, verifica-se como é possível assegurar a qualidade do produto e quais as máquinas que são totalmente responsáveis pelo controlo das especificações do produto. Finalmente, a linha de produção é validada com múltiplos testes que medem como o processo de medida é exato, preciso e exequível, sendo feitos MSAs, R@R, Testes de Repetibilidade, etc.

Keywords

Especificações de Design; EGR; Especificações Técnicas; Inspeção; Qualidade;

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SYMBOLS LIST

Acronyms & Abbreviations

CO	Carbon Monoxide;
EGR	Exhaust Gas Recirculation;
DFMEA	Design Failure Mode and Effect Analysis;
HC	Hydrocarbon;
PDD	Product Design Development;
PFMEA	Process Failure Mode and Effect Analysis;
PM	Particle Matter;
PPAP	Production Part Approval Process;
PPD	Product Process Development;
NOK	Not Ok (non conformity);
NO_x	Nytrogen Oxide;

1. INTRODUCTION

The awareness for the current climate changes leads the society to study possible ways to reduce/eliminate the causes, but first it was necessary to identify them. The Greenhouse effect was considered the main explanation for the climate change and the thaw in the poles. Given this, the Man worked together to find, this time, the causes for this effect, realizing that the combustion of fossil fuels are the biggest contributor for the presence of gases in the atmosphere, responsible for the greenhouse effect. More than 25% of these gases, as is going to be analyzed further in this work, have their origin in the internal combustion engines [1]. The European Nations created and update standards for the emissions that the automotive constructors have to follow, in order to decrease the emission pollutants. Due these standards, various mechanisms were created with the goal of decreasing the emissions production, with special focus in one mechanism, the Exhaust Gases Recirculation (EGR).

BorgWarner was one of the pioneers in the development on clean and efficient future technologies for all types of propulsion, especially in the EGR Module. In this area, it has been in the vanguard, producing as distributing for renowned automotive brandes.

An EGR is a product very complex product, beginning in its design, that depends on innumerous factors: engine, performance, weight, etc. The project behind the development of an EGR module is long and meticulous, passing by different phases, with multiples tests and validations in each one. There are a continuous improvement of performance (due the update of the emissions standards) and awareness to the user safety, given the fact that this mechanism can affect the normal operation of the car, leading to problems that can be harmful to the user [2]. These factors compel the automotive suppliers to implement and have special attention on the quality control and assurance of the EGR modules.

The quality control and assurance are responsible for having a continuous and controlled manufacturing, making sure that every sample of the final product has a minimum grade of quality, fulfilling the specifications given by the client. The quality is assured by production cells and that analyzes each module during its assemble, with the goal of decreasing to the nullity the shipping of products with defects.

1.1. Motivation

The study of automatic validation of products is an area in continuous improvement, even if there are some guidelines and methods to being implemented, other ways to improve the quality of the product and its control are being studied and in continuous development.

EGR modules are complex products with a lot of failure modes, from their design (because of their functionality) until the process (a lot of parts with the need of being watertight) resulting in also complex ways to assure and control the quality.

1.2. Dissertation Objectives

The main objective is comprehending the specifications given by the client and implement in the production line, automatic quality controls that will control the compliance of that same specifications, assuring the quality in the final product, maintaining a reliable process with capability.

In the first part of the work, the goal is to understand the origin of the EGR module, its development and role in the car, passing by the origin of emissions and ways to reduce them. With this part, it will be possible to know more about how a project is implemented and developed in the automotive industry.

Secondly, study the development of the EGR module since the beginning of the project with the initial design phase until the last prototype model. In this part, it will be also possible to comprehend how meticulous are the tests to validate the designs. After this project phase, the process phase begins, the objective in this part is to analyze the implementation of the production line, its drawing, the processes, etc. Also, it is necessary to find a compromise between the design and the process, given the fact that innumerous complications appear in this phase due incongruences between the tools and the product (ex: the drill not reaching a screw to tighten due material interference).

As the name of this academic work implies, a study of the automatic control of technical specifications will be carried out, meaning that the process of automate the production line to verify the specifications of the product will be analyzed. This process involves analyzing the product minutely, understanding which specifications will be controlled, how it is going to be controlled (throughout machines/tools) and the outputs of this control. Basically, this study will enable the introduction of automatic control mechanisms.

1.3. Dissertation Structure

This academic work is divided in 6 chapters, being the objective of this structure to follow the project timeline of the Conception and Development of an EGR Module.

In the first chapter, an introduction to the subject, the objectives of it and the motivations behind it was made.

In the second chapter, there is all of the theoretical background that supports this work, starting with the study of the conception and development of a product, continuing with main types of production in automotive area. Then, the origin of the EGR module, starting with the internal combustion engines and its emissions is presented. After this is presented, the standards created to control these emissions and how it is possible to mitigate them. In this last part, a lot of mechanisms to control emissions are studied, being the EGR Module deeply analyzed.

The third chapter is about the design development of a specific EGR Module, being carried out a deep analysis in the design changes since the first version until the last one and why these changes happened.

The Process Development is analyzed in the fourth chapter. Starting with the quotation of machines, tooling design and the flow-chart of the process. In this part is analyzed the production line development and the lean thinking behind it, being shown how the layout of the production line changed due to capacity increase.

The climax of this work is reached in the fifth chapter, being analyzed which machines do the automatic validation of technical specifications and how the production line can assure the quality of the product. On the final of this chapter, part of the production line validation, with the respective results of multiples tests, can be seen.

In the sixth and last chapter, the possible conclusions of this work are shown and what can be done in the future about this subject.

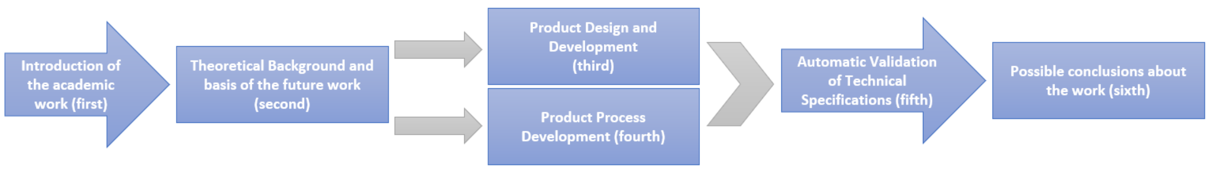


Figure 1.1 – Academic work organization.

2. Bibliographic Review

2.1. Introduction

The Bibliographic Review must give technical support to the work that it is being developed and introduce the theme that is going to be analyzed further in the project. In this chapter, there will be general contents like the conception and development of new products and more specific ones, such as how it works a combustion in an engine powered by fossil fuel, the effects of it, what is a EGR Module (Exhaust Gas Recirculation) and for what it is used. These questions are essential to understand what the project is about and give theoretical support for develop the work "Study of Automatic Validation of Technical Specifications of Complex Products".

2.2. Design and Development of a Product

Conception and Development of products, tools and productive processes it is a continuous and iterative process that requires a great amount of multidisciplinary knowledge [3]. It is an activity that includes processes, people, companies or organizations, having the compromise to fulfil multiple interests [4]. To make a good project, must follow all the phases of project, conception, and improvement. The planning of the product development is essential for the efficiency of the project because reunite and program every resource needed. With this kind of planning, it is possible to predict failures and warn mistakes. In that way, scheduling deadlines for the phases, avoids unwanted stoppages in the production line and organizes every step of the process, enabling the manufacturing phase[4].

2.2.1. Project Timeline

Usually, the project starts with an initial design of the product which aims to comply with the specifications required by the client, through multiple tests and validations. After the nomination to develop the project, it is necessary to make alterations of design multiple times, consequently new tests and validations have to be done in order to approve these designs. This process (Product Design and Development) is one of the longest in the project, ending when there is one complete validation of the product, complying with every specification required.

After that, the Product Process and Development phase starts, and the first thing to be done is the development of tooling and procure of tool suppliers, finding suppliers of materials that fits the specifications imposed by the company that is developing the project. Simultaneously the first assembly of the product in the production line is made, starting Off-tool (assembled with the same tools that will be used in the series production, but manually) and then Off-Process (completely automatized assembly of the product). Normally in this phase, diverse problems are found because of the manufacturing complexity, happening sometimes slightly design changes that will need new testing and validation. Because of this, usually there is more than one model in this phase. After doing the Process Validation Testing, the validation of the production line is achieved and the PPAP (Production Part Approval Process) is submitted

The conception and development of the product ends (if not consider the aftermarket) with the start of production.

2.2.2. Types of Production

There are various types of production, but in this work, only three will be analyzed: Production based on the product, based on the process and by cells.

2.2.2.1. Production focused in the Product

Production focused on the product is as the name implies. The design of production processes promotes the product, and the manufacturing departments are organized according to the type of product or service. The automobile industries are a good example of this, because usually they function in a continuous production also called “Production Line”. In this type of production, the materials flow through the production in a linear way, transforming raw material into components, that’ll be assemble and form the final product. One disadvantage is the high investment necessary given the need to build specific machine and tools to build the final product, reducing the flexibility and the variety of products possible[4].

2.2.2.2. Production focused in the Process

In this type of production, the organization of the departments instead of promoting the final product, it promotes the aggregation of production processes that use similar technologies. An example is grouping all the production operations that requires an oven in one place forming a kind of department, where does not matter the product, it needs to go to the oven, transported to that “division”. This intermittent process allows products to move from one department to the other in batches, usually determined by customer orders. There is a great advantage over the production capacity of small lots and a wide variety of products, increasing flexibility.

2.2.2.3. Production by cells

This type of production applies mainly in the processing of metals and it is based on a code system that identifies the parts produced at the factory, in particular about their physical characteristics. The code for identifying the parts varies from company to company [3], [4] and allows you to determine the flow in the production. Summarizing, it’s agglomerating similar components in one cell, aiming to reduce the investment in machinery in order to gain time in the production process.

In the project that this work will be analyzing, there is a mix of the two firsts types of production and some influences from the third one. In the assembling of the final product there is a production line, so the production is clearly focused on the final product, making sure that the subcomponents arrive to the line and step out of it a complete functional product. Nevertheless, there are some subcomponents that need to pass by an oven for a brazing welding. In this section of the company every part that has to go to the oven is agglomerated independently of the final product, being in this case production focused on the process.

Now that it was comprehended briefly “What is” and “How it’s made” the development of a product, in the next chapter will be studied the origin of engines, basically the genesis of the emissions, that consequently gives “birth” to the development of an EGR (Exhaust Gas Recirculation), case of study of this project.

2.3. Internal Combustion Engines

An engine is considered an internal combustion engine if it is part of a group of devices in which the reactants and products of the combustion serve as working fluid of the engine, transforming the chemical energy in mechanical engineering through the chemical reactions between the O_2 and the fuel (generally diesel or gasoline) Engines normally convert thermal energy into mechanical work and therefore they are called heat engines. This process occurs within the engine and is part of the thermodynamic cycle of the device, that consists in expansions, compressions and temperature changes of the mixture (air+fuel). While working, generates hot gaseous products of combustion, with the downside of producing gases harmful for the human (CO, NO_x, PM, HC). Internal-combustion engines are the most broadly applied and widely used power-generating devices currently in existence. Examples include gasoline engines, diesel engines, gas-turbine engines, and rocket-propulsion systems. Only the first two types have interest for the present work [5], [6]. The Figure 2.1 shows as normal internal combustion engine [7].

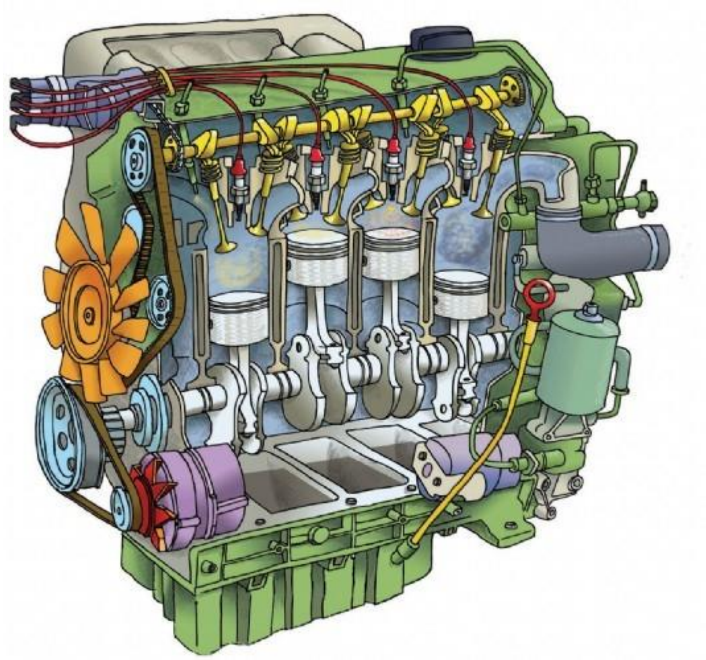


Figure 2.1 - Four Inline Cylinder Engine [7]

About the history of the Internal combustion engines, they are considered the heart of almost all vehicles used (even though more and more electrical vehicles are being produced) from cars and motorcycles on the road to planes in the sky and ships in the sea. This engine is the successor of old-fashioned steam engines or external combustion engines, being also more efficient [8].

In 1860, the history of internal combustion engines began because, Etienne Lenoir developed the first commercially successful internal combustion engine. A gas-fired internal combustion engine that is regarded as the first functional combustion engine. Functional because quite a few of these were produced and used all over Paris in several printing presses and looms [8].

Before him, some engineers and inventors start this work and try other things [8]:

- Almost fifty years before Lenoir, French engineers *Nicéphore Niépce* and *Claude* Niépce built an internal combustion engine fueled by a mixture of moss, coal dust, and resin that ran on controlled explosions;
- Shortly after, a hydrogen-oxygen-powered combustion engine invented by *Francois Issac De Rivaz*, using an electric spark as the ignition mechanism, installing his engine in a carriage, it became the world's first automobile powered by internal combustion;
- in 1823, Samuel Brown patented the first internal combustion engine that could be applied industrially, using atmospheric pressure to work;
- In 1826, Samuel Morey developed a compressionless Gas or Vapor Engine with a carburetor.
- In 1833, Lemuel Wellman Wright created a table-type double-acting gas engine with a water-jacketed cylinder;
- In 1838, William Barnett’s engine, was developed and it is believed to be the first engine that implemented in-cylinder compression;

In 1863, Lenoir installed this engine in a vehicle. He drove this vehicle for nine kilometers using a turpentine derivative as fuel; being the first vehicle to pack the liquid-fueled internal combustion engine. Unfortunately, Lenoir's vehicle could not serve the need for speed, with a two-stroke engine, capable of generating only 100 rpm and averaging a maximum speed of 6 km/h [8].

Even though Lenoir's engine was not very successful in the automotive industry, the reduced size and weight impressed many. A German Engineer, called Nicolaus August Otto, start the study of making trying to make this engine more efficient, exploring the potentiality of Ethyl Alcohol as fuel and installing four strokes, instead of two, to improve engine efficiency (give the that it had a previous compression before the expansion, upgrading a lot the engine efficiency) [8].

In 1872, twelve years after and a lot of rigorous experimentation and a number of failures, he succeeded in developing a functional four-stroke engine establishing the principles of intake, compression, combustion, and exhausts, something that are currently used in the majority of internal combustion engines [8]. The Figure 2.2 present this motor [9].

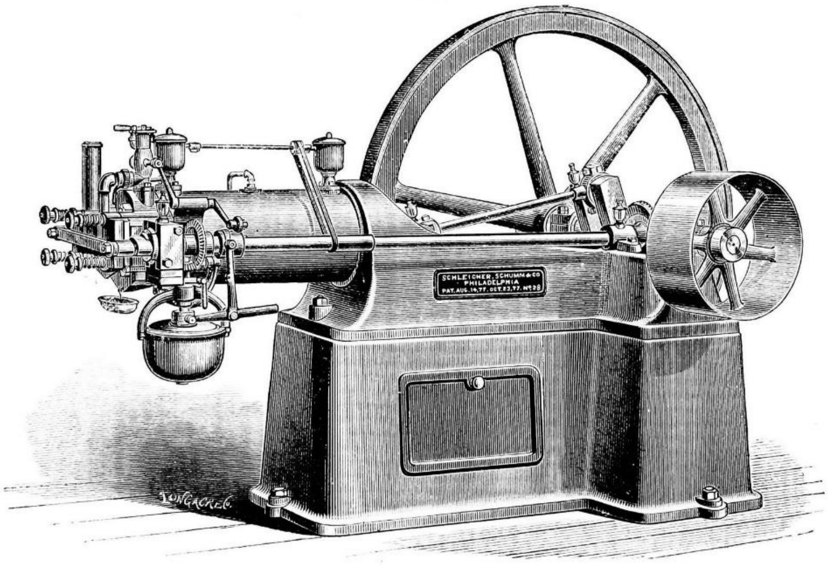


Figure 2.2 - The first 4 stroke petrol engine [9]

Despite the fact that Otto's engine was more powerful than the previous one, its weight became a concern for the automotive constructors. They were incredible powertrains to the industrial area, but for vehicle were still not appropriated. Gottlieb Daimler and Wilhelm Maybach started to optimize this engine, once associates of Otto, they start to do their own experiments, developing smaller, faster and more suitable for powering vehicles than Otto's engine [8].

Their first success came in 1883 when they developed a gasoline engine that could generate one hp at 650rpm. It was small and relatively light, making it ideal for use in vehicles[8].

In 1889, they created the first completely self-propelled vehicle with a 1.5hp motor, can be seen in the [10]. One year later, Daimler and Maybach increased the power of automobile engines to 35 hp, which were capable of a top speed of 90 km/h.

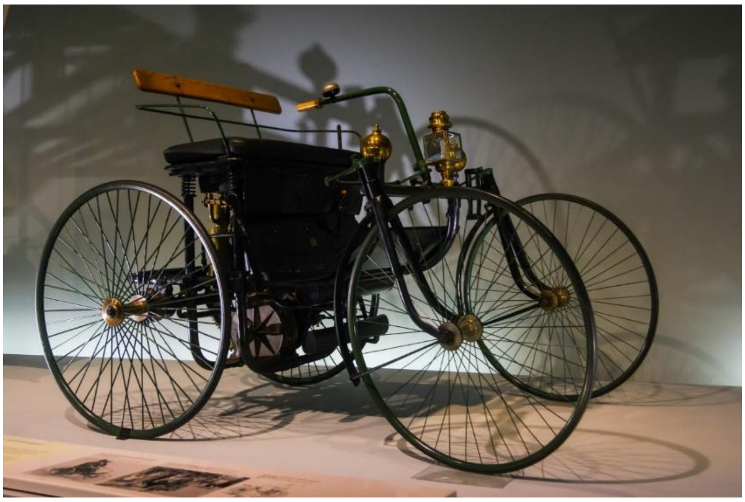


Figure 2.3 - 1889 Daimler motorized quadricycle (replica in the Mercedes Museum in Stuttgart) [10]

Following these groundbreaking inventions, the internal combustion engine has gone through several developments over the years. The establishment of several automobile companies played a significant role in it.

2.3.1. Gasoline Engines

The four-stroke cycle gasoline engines operate under an Otto Cycle (constant volume). Since ignition in these engines is due to a spark, they are also called spark ignition engines. The four different strokes are very similar to the Diesel Engine, the Figure 2.4 shows it [11][12]:

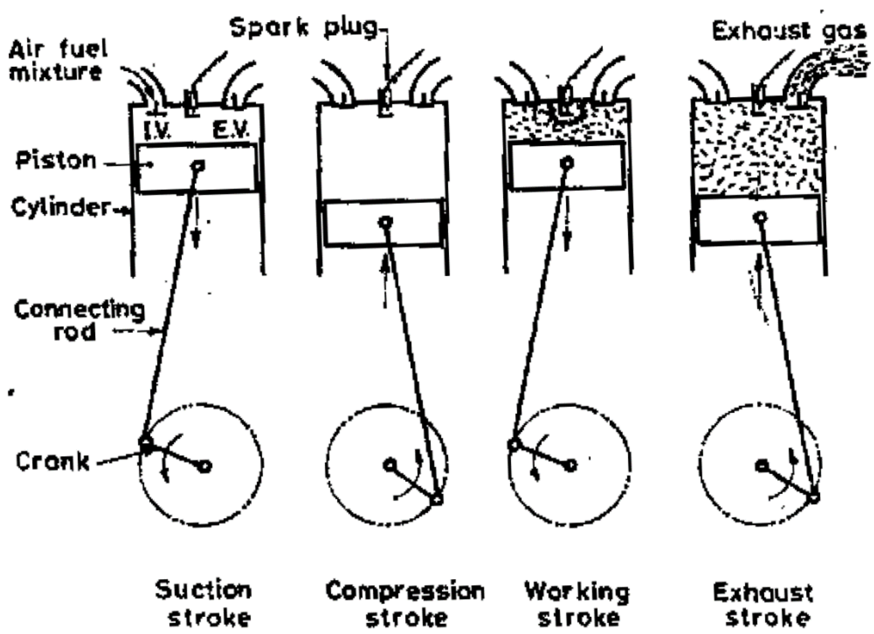


Figure 2.4 - Phases of a four-stroke gasoline cycle [11].

- Suction Stroke: During suction stroke, the piston is moved from the top dead centre to the bottom dead centre by the crank shaft. The crank shaft is revolved either by the momentum of the flywheel or by the electric starting motor. The inlet valve remains open, and the exhaust valve is closed during this stroke. The proportionate air-gasoline mixture is sucked into the cylinder due to the downward movement of the piston.
- Compression Stroke: During this phase, the piston moves from bottom dead centre to the top dead centre, thus compressing the mixture. Due this compression, the pressure and temperature increase and is shown by the line 1-2 on the theoretical Pressure/Volume diagram as seen in the Figure 2.4 . As soon as this stroke is finishing, a spark is created by a plug, which ignites the mixture. Theoretically this part takes place at constant volume as shown by the line 2-3. Both the inlet and exhaust valves remain closed during this stroke.
- Expansion Stroke: The expansion created by the combustion of the mixture exerts a pressure on the piston, moving from top dead point to bottom dead point and thus the work is obtained in this stroke. As the last stroke, in this one keeps the inlet and exhaust valves closed during this stroke. The expansion of the gas is shown by the curve 3-4.

- Exhaust Stroke: During the last stroke of the cycle, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escapes because of their own expansion. The drop in pressure at constant volume is represented by the line 4-1. The piston moves from bottom dead point to top dead point and pushes the remaining gases to the atmosphere. When the piston reaches the top dead point the exhaust valve closes and cycle is completed. The operations are repeated over and over again in running the engine. Thus a four stroke engine completes one working cycle, during this the crank rotate by two revolutions.

The theoretical thermodynamic cycle of the Otto Cycle is shown in the Figure 2.5 [11][12]:

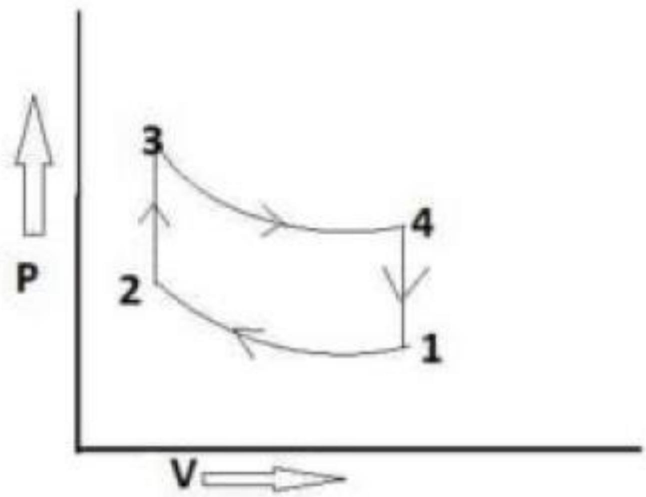


Figure 2.5 - Theoretical Cycle of four-strokes gasoline engine [11].

This cycle is characterized by two reversible adiabatic transfers. Heat is transfer during process 2-3 at constant volume and heat is rejected during the process 4-1 at constant volume. During adiabatic process 1-2 and 3- 4, no heat is supplied/rejected[12].

The real cycle of Otto, does not have processes at constant volume and have heat transfers with the exterior, not being adiabatic.

2.3.2. Diesel Engines

The four-stroke cycle diesel engine operates on diesel cycle. Since ignition in these engines is due to the temperature of the compressed air and not with a spark (Gasoline

Engines), they are also called compression ignition engines. The four strokes are as follow in the Figure 2.6 [11][12]:

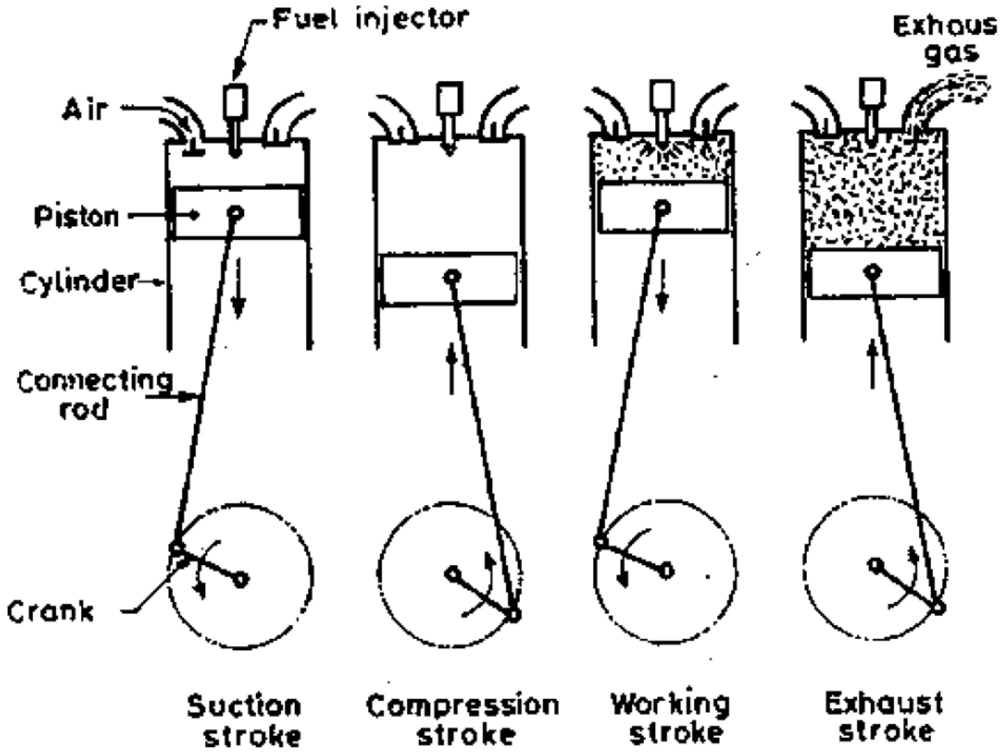


Figure 2.6 - Phases of a four-stroke diesel cycle [11].

- Suction Stroke: In this engine is only admitted air and the fuel is injected directly to the combustion chamber, being this the only difference to the Otto cycle;
- Compression Stroke: The air drawn at the atmospheric pressure during suction stroke is compressed to high pressure and temperature as piston moves from the bottom dead centre to top dead centre. This operation is represented by the curve 1-2 on the theoretical Pressure/Volume diagram. Injection/combustion is not instantaneous but occurs throughout phase 2-3 being this phase also of combustion at constant pressure, which is already part of the expansion time and already performs mechanical work.
- Working Stroke: The expansion of gases due to the heat of combustion exerts a pressure on the piston. Under this impulse, the piston moves from top dead point to the bottom dead point and thus work is obtained. Both the inlet and exhaust valves remain closed during this stroke. The expansion of the gas starts

in the point 2 and remains adiabatic during the period represented by the curve 3-4.

- Exhaust Stroke: Is identical to Otto Cycle.

The Figure 2.7 shows the theoretical thermodynamic cycle of the Diesel Cycle [11][12]:

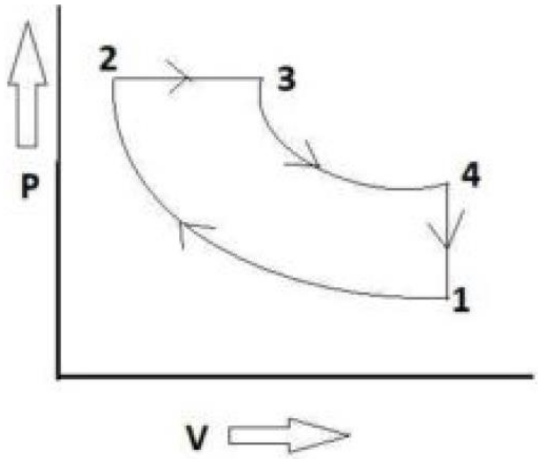


Figure 2.7 -Theoretical cycle of four-strokes diesel engine [11]

It consists of constant pressure and a constant volume, and two adiabatic processes. Heat is supplied during constant pressure process 2-3 and is rejected during constant volume process 4-1. During adiabatic process 1-2 and 3-4, no heat is supplied or rejected [12].

In reality, there is changes of heat between the cylinder's interior and the environment, thus there is not an adiabatic process in the cycle. 2-3 and 4-1 processes do not happen at constant pressure and volume, respectively.

2.4. Emissions

As it was possible to analyze in the chapter 2.2, after the combustion in a fossil fuel powered engine, is generated exhaust gases harmful for the human, being these partially eliminated by capable systems (EGR, CRT, etc). The principal exhaust gases are CO, NOx, HC and particles. According to *Público* [1], 25% of the emissions of gases that cause greenhouse effect are produced by engines powered by fossil fuels and it is estimated that more than 50% of NOx come from the automobile industry [13]. The EGR system was created mainly to deal with this last pollutant, having a good result in its mitigation. Nevertheless, it makes the combustion worse and slightly raise the other pollutants (HC and CO).

2.4.1. Types of Emissions

2.4.1.1. Carbon Monoxide

Carbon Monoxide is produced mainly if there is an incomplete combustion or not efficiently due low oxygen concentration in the cylinder. Usually, happens if the fuel mix is poor in oxygen and does not burn completely. This implicates that more atoms of carbon will react with oxygen, creating carbon monoxide (CO) instead of carbon dioxide (CO2) (a non-greenhouse effect gas) [13].

In the case of engines powered by gasoline, in order to have a good combustion, is necessary that the mixture (oxygen and fuel) comply a specific stoichiometry relation. When this proportion decreases, more CO is created because there is more fuel than it is possible to burn [13].

In engines powered by diesel, the mixture is heterogeneous, and the origin of CO is when the combustion ceases earlier than it should. This can happen because there isn't enough fuel but enough oxygen or the opposite, more fuel than oxygen, not completing the combustion being outside of the flammability limits [13].

2.4.1.2. Nitrogen Oxide

This gas has its origin when there is a combustion, and the nitrogen (inert gas) reacts with oxygen because of the high temperatures and pressure inside of the cylinder. The group of nitrogen oxides are called NO_x being the NO the majority of them in the engine.

NO_x are mostly produced when the engine is using all the power, meaning that the pressure and temperature are in their peak. Also, relatively high concentrations of this gas can appear in another conditions such as if the engine is overheating, the mixture (fuel+air) is poor and if the engine is overfed with air. The EGR was developed to reduce the emissions of this pollutant and it was successful because reduces the max. temperature reached (without increasing the O_2 concentration) and reduces the abundance of O_2 [13].

2.4.1.3. Hydrocarbon

There is a great amount of different hydrocarbon, and they can appear due many reasons. Carbonic Acids, Ethylene, Acetylene, Acetone, and other organic composts are types of HC that are product of incomplete combustion or dissociation , being in the presence of

NOx and solar light they are harmful, causing mucous membranes irritation and even cancer [13].

They can be considered also fuel that did not burn and are produced when there is not enough oxygen (more fuel than O_2) or if the mixture is poor and the fuel does not burn completely. Given this, it is possible to say that every engine produces HC, ones in more quantity than another, especially due to engine design [13].

2.4.1.4. Particle Matter

The Exhaust Gases are not only gas, there are also solid or liquid particles formed by carbon, organic components, Sulphur and traces of metallic components. Depending on the size, they are classified as big particles if they have a diameter between 2.5 and 10 micrometers, also called PM_{10}. Thin particles are smaller than 2.5 micrometer of diameter and have their own classification: between 2.5 and 1 micrometer are called $PM_{2,5}$, between 1 and 0,1 are PM_1 and smaller than 0.1 are $PM_{0,1}$ [13].

The smaller ones are more harmful because they can easily be inspired by humans.

2.4.2. Emissions Standards

There is a correlation between fuel consumption and gas emissions. Analyzing the two values, it is easily concluded that the more the vehicle burns fuel, a bigger number of contaminants it emits to the atmosphere. The value regulated by manufacturers is obtained through standard cycle of tests, obeying pre-established goals [14].

Given this, to reduce these emissions, standards that the automobile brands have to respect were created. The first standards appeared in the USA on the 70s. In Europe, the first standard given by the EU for the EU members was on 1988 (unofficial Euro 0) [15], and being constantly developed, became on 1992 the first EURO 1. The brands were forced to comply with the maximum limits of emission of each one of the gases, according to the type of vehicle and fuel.

Since 1988, the standards had been improving, imposing even more restrictions to the automobile industry when it comes to emissions, which made the companies pay more attention and invest more resources for controlling the emission of contaminants.

The Euro 0 began in 1988, since then, there were more 6 standards (Euro 1, 2, 3, 4, 5 and 6) for passenger vehicles and (Euro I, II, III, IV, V, VI) for transportation/heavy vehicles. The last standard to be implemented was the Euro 6/VI, announced in 2014 and been mandatory since 2015. The details of Euro 7, will be announced probably in 2022 and are likely to being compulsory from 2025, giving time for the automobile constructors to the implementation on their vehicles.

For example, in the Table 2.1 and Table 2.2 it is possible to see the standard to for passenger vehicles (gasoline and diesel) of vehicles that weight less than 1305kg (N1-I category in a European Standard) [13].

Name	***Date***	***CO(g/km)***	***NO_X(g/km)***	***HC+NO_X (g/km)***	***HC (g/km)***	***PM (g/km)***
Euro 1	1994	2.72	-	0.97	-	-
Euro 2	1998	2.2	-	0.5	-	-
Euro 3	2000	2.3	0.15	-	0.2	-
Euro 4	2005	1	0.05	-	0.1	-
Euro 5	2010	1	0.06	-	0.075	0.005
Euro 6	2015	1	0.06	-	0.075	0.005
Gasoline						

Table 2.1 - Standard to a Diesel Engine (N1-I category)

Name	***Date***	***CO (g/km)***	***NO_X(g/km)***	***HC+NO_X(g/km)***	***HC (g/km)***	***PM (g/km)***
Euro 1	1994	2.72	-	0.97	-	0.14
Euro 2	1998	1	-	0.9	-	0.1
Euro 3	2000	0.64	0.5	0.56	-	0.05
Euro 4	2005	0.5	0.25	0.3	-	0.025
Euro 5	2010	0.5	0.18	0.23	-	0.005
Euro 6	2015	0.5	0.08	0.17	-	0.005
Diesel						

Table 2.2 -Standard to a Gasoline Engine (N1-I category)

As it is possible to see in the table, it would take ten cars registered this year to match the level of pollutant emissions from a single vehicle that complied with the outdated Euro 1 standard.

Since 1993, there has been a cut of 82% in CO emissions in diesel engines and a 63% decrease in those values in petrol engines, which have also managed to correct the emission of particles into the atmosphere, with reductions in the order of 96%.

Also, in gasoline engines, since 2001, there has been an 84% reduction in the value of NOx, the most harmful for the human [14].

In the next chapter will be studied how it was possible to mitigate these emissions in the past and also presently. . Nowadays there are various technologies to reduce the contaminants, something that is discussed next.

2.4.3. Emissions Mitigation

There is not only one solution for reduce the emissions. Since the beginning of the identification of this problem, the automobile manufacturers adopted various strategies in order to decrease the amount of contaminant emissions. These strategies were for example work with the engine itself, improving the designs, using external systems like an EGR, a particle filter or a three-way catalyst. Some were more efficient than others, some relatively old and another still passing by a lot of studies because of the possibility of improving even more. In this work, for a better comprehension of the project will be analyzed only external systems that can be implemented in the engine.

2.4.3.1. Catalytic Systems

Catalytic Systems have the function to change the chemical structure composition of the exhaust gases trying to reduce the emission of contaminants. Catalysis is the name of the chemical principle that is used and basically consists in increasing the velocity of the chemical reaction, through the reduction of the energy to activate the combustion [13].

The composition of the catalyzer is a noble metal inside of a capsule at the ending of the exhaust manifold, having a lot of small chanels responsible to increase as much as possible the contact area. The gases are obliged to pass through to step out of the car, bridging in an increase of chemical reactions [13].

These chemical reactions can be separated in two groups: Oxidation and Reduction. In the first one, carbon monoxide (CO) and hydrocarbons (HC) react with oxygen (O_2) resulting in carbon dioxide (CO_2) and water (H_2O), and in the second one, the nitrogen oxides (NO_x) molecules lose part of their oxygen (O_2), transforming in nitrogen (N_2) and oxygen (O_2). The main goal of these reactions is transforming substances that are harmful in substances non-dangerous for the human. The problem remains in the fact that when one catalyzer is better for one type of reaction, is not good for the other one. Because of this there is a necessity to create a combination between both: Oxidant Catalyzer, Mixed Catalyzer and Selective Catalytic Reduction [13].

The first one, as the name indicates, has the function of oxidation, reacting with the CO, creating water and carbon monoxide. Usually, it is used coupled with an EGR system.

The second, can make the two reactions in two different phases. Firstly, the oxidation and then the reduction. Decreasing the number of contaminants (CO, HC and NO_x) expelled to the environment. These ones are more expensive but can control better the emissions and the quantity of fuel that is consumed, because only works perfectly in a proper stochiometric ratio.

The third one, is one of the most advanced catalyzers and it started to gain popularity when the Euro VI standard was announced. It consists in a gas reductor with ammoniac combined with a traditional oxidation catalyzer. Firstly, the traditional catalyzer does the normal transformation (referred up in the chapter), but it has a filter that collect part of the carbon particles, being eliminated afterwards. After that, the reduction is done, with the NO_x being converted into N_2 and O_2 . SCR has the advantage of using a urea solution, that is pulverized in the exhaust gases before the catalytic converter. This means that the urea reacts with the ammoniac transforming the NO_x.

In the Figure 2.8 is possible to see the interior of a catalyzer [16].

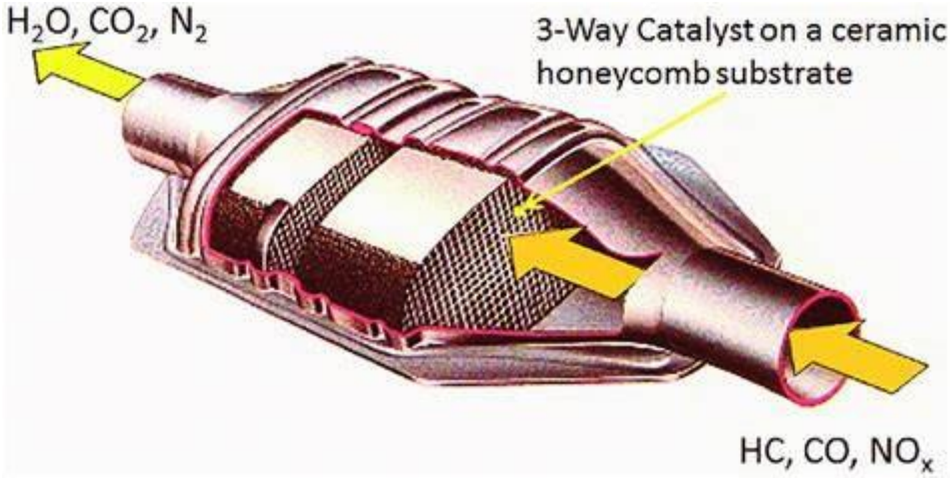


Figure 2.8 - Catalytic Converter [16]

2.4.3.2. NO_x TRAPS

Most of the times, the NO_x is not reduced as it should in the case of diesel motors, so to solve this problem was idealized an NO_x trap, being realized in two phases. The first one starts with the oxidation of the NO to NO_2 in the catalyzers, being retained by filters formed by specific metals oxides like barium. When the filter reaches its maximum capacity, is necessary to force a regeneration. [13].

This process can eliminate more than 90% of the NOX, but with the presence of the sulfur oxide in the fuel, the expected results are not reached because of the similarity of reactive characteristics of this oxide. To this, they stay trapped in the filter destined for the NOX, being necessary a regeneration more frequently than normal.

2.4.3.3. PARTICLES FILTER

DPF as known as Diesel particulate filter consists basically in a ceramic mesh that retains solids particles that are generated in the combustion. The design of this mesh is crucial for a good function of the DPF. Half of the tubes are open in one extremity and the other half in the opposite side. This makes the exhaust gas transiting from one tube for another through the ceramic mesh. The design of this mesh (thin and very small holes) makes the particles to stay retained while the gas continues its path to the exhaust tube [13]. The Figure 2.9 a scheme of how a DPF works [17].

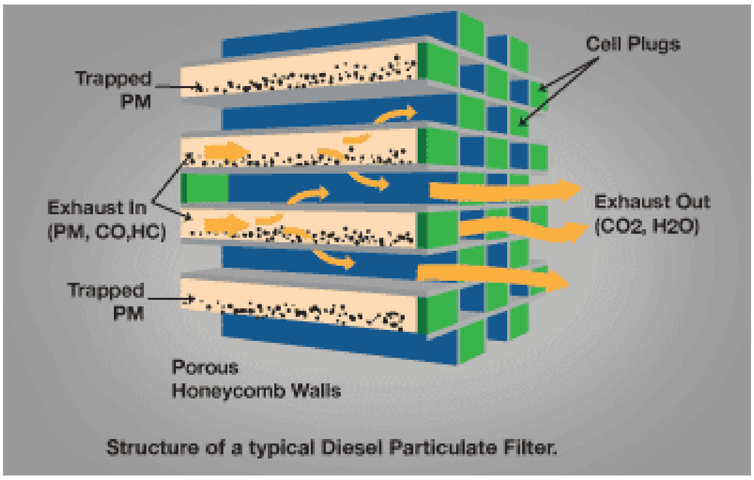


Figure 2.9 - How a particle filter works [17]

The particles created by a diesel engine should be, theoretically, zero, nevertheless there are some modes when there is more fuel injected than it should, not burning completely due to a deficient mixture. To eliminate these particles from the mesh of the filter is necessary to regenerate the filter, oxidating it. This happens in a natural way if there is enough oxygen and temperatures above 600ºC. This temperature is too high, and the exhaust gases usually arrive to this place between 300ºC and 400ºC [13].

The solution found is injecting occasionally more fuel than normal, increasing the temperature of the exhaust gases, achieving the ideal conditions for the spontaneous combustion of these particles.

Some of the vehicles do this automatically when it detects that the filter is reaching the maximum capacity. Other constructors, introduce a catalyzer that makes the spontaneous combustion temperature decrease, regenerating the filter softly and less harmful for the exhaust system.

2.4.3.4. Continuously Regenerating Trap

Known as Continuously Regenerating Trap (CRT) is an anticontamination system that combines a platinum catalyzer followed of a particles filter. The CRT have two phases of working, firstly the catalyzer oxidates NO_x od the exhaust gases converting them in NO_2 which is going to react with the solid particles around 250ºC, regenerating the particles filter, expelling reminiscences of NO. Being this last product and the presence of sulfur the biggest disadvantage of the process. A CRT can be seen in the Figure 2.10 [18].

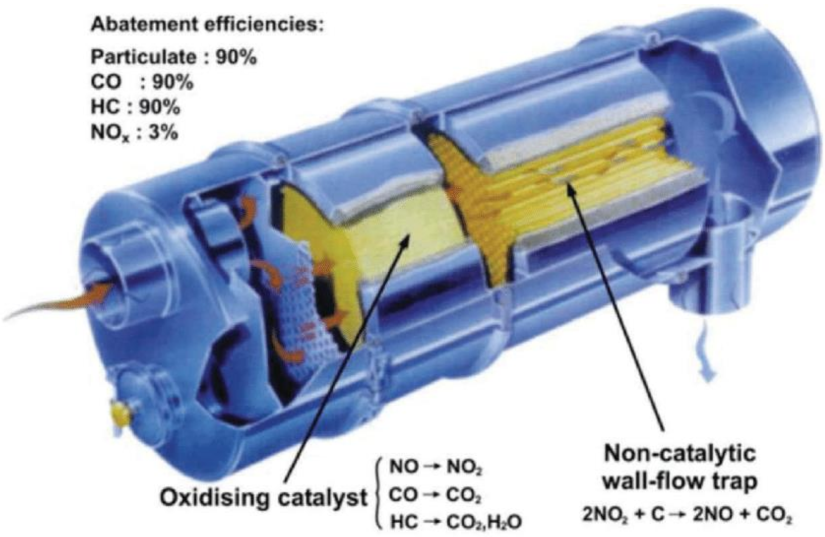


Figure 2.10 - Example of a Continuously Regenerating Trap [18]

2.4.3.5. EXHAUST GAS RECIRCULATION

Exhaust Gas Recirculation (EGR) is the most important system for controlling NOX produced by the internal combustion engines. This system will be analyzed and studied in the next chapter more elaborately, given the fact that the whole project is related with this component. It will be important study how an EGR works and how is composed in order to understand how it is possible to guarantee the quality of the module itself [13]. The simplest EGR system can be seen in the Figure 2.11 [19].

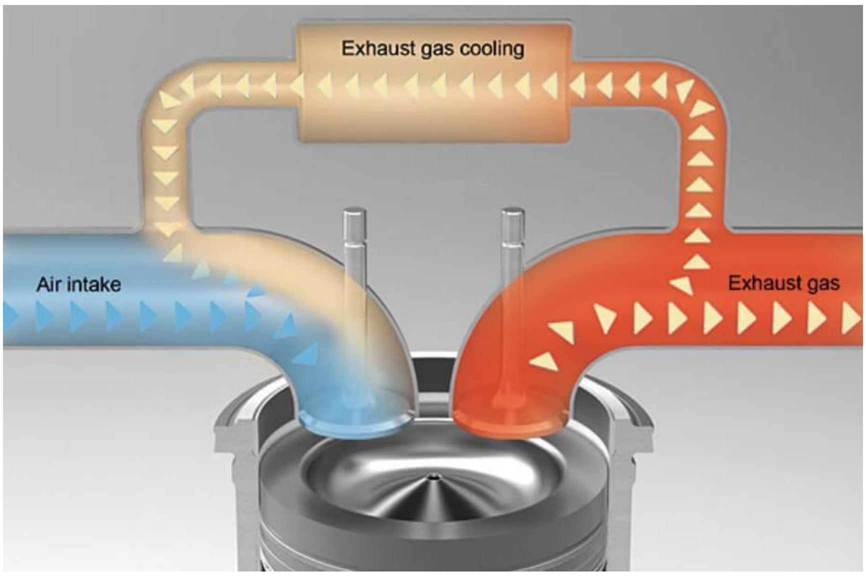


Figure 2.11 – A simple EGR system used in origin of these type of systems [19]

2.5. EXHAUST GAS RECIRCULATION MODULES

2.5.1. ORIGIN AND DEFINITION

Exhaust gas recirculation (EGR) was first introduced on vehicles in the 70s in USA and it consisted in a tube that directly connected the exhaust manifold to the intake manifold. The Euro standards appeared and with them more restrictions, which means that there was a need to improve the EGR systems. Now it is used on all diesel-powered vehicle as a main system to reduce the level or nitrogen oxides (NO_x) [20].

This process leads to a significant reduction in NO_x emissions because it reduces the two elements underlying its production: oxygen in excess and combustion temperature. Consists in reintroducing the exhaust gas in the combustion chamber, reducing the temperature of it reducing the formation of nitrogen oxide in almost 60% [13].

The principle is very simple, the exhaust gases are poor in oxygen, so if they are sent again to the combustion chamber, less space for fresh air there will be, and less oxygen will be available for the combustion. This causes a less pollutant and cooler combustion, decreasing the temperature and pressure. There is a limit of exhaust gas that can be reintroduced – 35% - if surpass this value, an incomplete combustion or no ignition can happen [20].

It's possible to define this quantity with following equation:

$$EGR(\%) = \frac{\dot{\mathrm{m}}_{EGR}}{\dot{\mathrm{m}}_{Intake}} \times 100 \tag{2.1}$$

Being the $\dot{\mathrm{m}}_{EGR}$ the flow of gas recirculated and $\dot{\mathrm{m}}_{Intake}$ the total flow of gas that enters in the chamber [13].

The proportion of gas that is recirculated it'll depend on the load that and the rotations of the engine and in normal conditions it stays between 5% and 30%. The EGR system only works when the engine is at the working temperature and it is disactivated if the temperature is not reached or if is required maximum engine power [21].

Some EGR systems have a cooler that cools down the gas that will be reintroduced, improving the efficiency of the process, given the fact that the combustion occurs at lower temperatures being possible to reduce the NO_X.

In order to find the exact proportion of recirculated gas that the engine needs every moment, there is an Engine Control Unity that take into account, every variable that has influence using sensors, measuring things like: Engine Rotations, temperature, intake gas and fuel present in the combustion chamber, quality of oxygen [21].

Although the reduction of NOX, this system is far away from perfect. The increase of CO and the dirtiness of the combustion chamber are the biggest disadvantages, being possible reduce the CO by using a catalyzer after the EGR module, something that is always used [21].

2.5.2. Components

An EGR system can have different types, thing that will be discussed in the next subchapter. For now, will be analyzed which components can be used of an EGR and what is their function in the system.

2.5.2.1. EGR Valve

The main function of an EGR valve is to allow or block the exhaust gases to flow from the exhaust manifold into the intake manifold. In the past they used to be pneumatic, but nowadays electrical valves take the lead because of their quality when compared with the pneumatic ones. They are faster, more precise control, which fits stricter emissions standards, the disadvantages are being more expensive and operation mode more complex [13], [22], [23].

Modern EGR valves usually have these elements: Valve (opening/closing variable); actuator (provides force to open/close the valve); valve body (holds the valve, actuator, return spring and other mechanical components); position sensor (transmits information about the position of the valve); case (contains all of the last elements) [23]. An EGR valve for example can be seen in the Figure 2.12 [24].

Figure 2.12 - EGR Valve [24]

2.5.2.2. EGR Cooler

The EGR cooler is responsible for lowering the temperature of the exhaust gas before it is introduced into the fresh air charge stream. It is constituted for 2 independents watertight systems – gas and fluid (water, coolant, etc), between them there is the desirable heat transfer that lowers the temperature of the exhaust gas. These systems can function in a parallel flow way or counter-flow, depending on the specification required. The cooler can be I or U type, depending on the shape of the gas passage through the cooler. In the case of a U-shaped EGR cooler, the inlet and outlet flanges are combined into a single unit at one end of the cooler [13], [22], [23].

The lower the temperature, the higher the density, the better the efficiency in reducing the NOx emissions. Cooling the exhaust gas prior to mixing with the intake air lowers the combustion temperatures. Cooled EGR was introduced in order to achieve Euro 4 and Euro 5 NOx limits [22], [25] .

2.5.2.3. Intake Throttle Valves

EGR systems may have intake throttle valves. The purpose of the throttle is to create a pressure difference between the exhaust and intake manifold (when closed) and to regulate the exhaust gases to flow into the cylinders. Most of the EGR throttle valves are traditional 'butterfly' valves and are controlled electronically the ECU (electronic control unit) [23]. There is an example below in the Figure 2.13 [26].

Figure 2.13 - Intake Throttle Valves [26]

2.5.2.4. Bypass System

Most EGR systems have a by-pass valve integrated with the EGR cooler. When the engine is cold, the exhaust gas is circulated directly into the engine. The EGR cooler has a very high heat exchange efficiency, and, without by-pass, the recirculated gases would be very cold and delay the warm-up of the oxidation catalyst, which would lead to excessive emissions of HC and CO. The solution is therefore to bypass the EGR cooler until the oxidation catalyst reaches nominal working temperature. These systems permit different modes of function depending on the load that the engine is working. Nowadays, the most advanced EGR module have 3 modes. High Performance, Low Performance and Bypass mode [13], [23].

This valve, presented in the Figure 2.14, also is important for the engine reach a good operation temperature, if the temperature is low, the valve is going to activate recirculating the exhaust gases directly to the intake manifold, do not passing by the cooler, increasing in this way, quickly the engine temperature.

Figure 2.14 - A traditional Bypass Valve [23]

2.5.2.5. OTHER COMPONENTS

By other components, it included everything that usually makes part on an EGR Module.

Firstly, the structure itself, every module has at least one casting, Figure 2.15 [22], responsible for connecting the components analyzed in the last subchapters- Depending on the specifications, another casting could be introduced, in that way the inlet and outlet casting will have different functions.

Figure 2.15 - A both inlet and outlet casting of an EGR module [22]

The module that will be studied in this project has two castings, attached to the inlet casting are the EGR tube, EGR valve and by-pass valve. In the case of the outlet casting, contains the by-pass valve and it is the way out of the gas. Further in the project this will be analyzed more deeply.

Coolant tubes are also components that are important, given the fact that the coolant cannot lose more than a certain amount of pressure. Because of this, the design must be carefully studied.

The EGR tube, Figure 2.16 [28],responsible for directing the hot gas to the EGR module.

Figure 2.16 - EGR tube, connecting the exhaust manifold and the EGR module [28]

2.5.3. Architectures

Depending on whether the exhaust gas is recirculated before or after the turbocharger, there are two main types of EGR systems: High Pressure and Low Pressure. But there are some EGR modules that are Hybrid (both high and low pressure).

In the next subchapters will be presented these types.

2.5.3.1. High Pressure

High pressure EGR, is referred to the “classic” EGR architecture. This architecture is the most widespread and has been used on diesel engines since Euro 2 pollutant emission limits. In a high pressure EGR system, the exhaust gas is taken before the turbine and reintroduced into the intake manifold after the compressor, thus in the high-pressure zone of both exhaust and intake manifolds [20], [21], [23].

A high pressure EGR system is able to provide high EGR rates due to low volume, high dynamics of the EGR gas circuit. This allows fast adjustments of the EGR rate function of the operating point of the engine. Also, because the exhaust gas is mixed with the intake air after the compressor, there is no impact of the particulate matter on the compressor wheel. For this reason, the reliability of the turbocharger is not affected and can operate with nominal performance through its entire service life. However, the EGR cooler must withstand the damaging effects of the high pressure and high temperature of the exhaust gases [21].

2.5.3.2. Low Pressure

With the implementation of new standards for emissions (Euro standards) a significant drop has imposed and an increase of the EGR rates was necessary, being introduced the low pressure EGR systems.

In a low pressure EGR system, the exhaust gas is taken after the turbine and reintroduced into the intake manifold before the compressor, thus in the low-pressure zone of both exhaust and intake manifolds [20], [21].

In a low pressure EGR architecture, the EGR valve is positioned after the diesel particulate filter (DPF). This way the soot does not end up in the EGR valve, cooler or turbocharger. Another advantage is the lower temperature of the exhaust gases which reduces the thermal stress on the EGR components (valve, cooler, throttle). Due to lower temperatures, a low pressure EGR system is more efficient in reducing NOx emissions, compared with a high pressure EGR system [21].

The main disadvantage of the low pressure EGR system is the higher inertia of the exhaust gases, when the regime changes. All the ducts and components are relatively far from the engine and cannot respond quickly in a change of the EGR rate. For this reason, the EGR rates of a low pressure EGR are lower, compared to a high pressure EGR, in order to avoid excessive exhaust gas recirculated back into the engine [21].

2.5.3.3. Hybrid EGR System

Hybrid (combined) EGR system integrates both high pressure EGR and low pressure EGR on the same engine. This type of EGR architecture is also called dual loop EGR system. The advantage of this architecture is that combines the benefit of both low and high pressure EGR systems, switching between them depending on the operating point of the engine (speed and torque). The hybrid (combined) EGR allows the turbocharger to operate in a region of high efficiency at any operating point of the internal combustion engine [21].

The disadvantage of dual loop EGR is the additional cost, complexity and space requirement, given by the high number of components and potential issues with controlling the EGR rate depending on the engine operating point. The control algorithm becomes quite difficult since several actuators (high/low pressure EGR valve, intake/exhaust throttle and turbine vanes/waste gate) need to be controlled to get the required amount of air and exhaust gas into the cylinders.

2.5.4. Design of an EGR

There are a lot of variables when it's necessary to design an EGR module. The costumer asks for specifications that the developer have to attend. Height, length, efficiency, different working modes, watertight, airtight, and many more. These are all specifications that are previously requested, and the R&D Engineers/Applications Engineer/Product Engineer will have into account since the first drafts /designs. In the prototype phase every specification is tested and validated. After validating the design, the prototype phase is over and start the series phase, where the modules start to be product in a production line, firstly off-toll and finally off-process. For that it'll be necessary testing and validating the process, but that will be analyzed the 2.5.4.1 subchapter. In the following one, will be presented how the design and validation design is made. Beginning with the usual type of specifications that are requested and after the type of tests that are made, most of the times, to an EGR module.

Firstly, the product to be developed is presented and with it the intended specifications. For as EGR module, usually there are a certain number of parameters that are common to every module [20], [22]:

- Timespan of the product (more than a given amount of cycles);
- Limited occurrence of quality issues;
- Limited leakage ERG Module (both, water and gas side);
- Function and limited leakage EGR Valve;
- Certain geometry interfaces/function surfaces;
- Function in a certain span of pressure and inclination;
- Should handle a span of temperatures;
- The exhaust gas has to decrease to a minimum temperature;
- Limited weight;

These specifications are the guideline for designing the product. Being crucial that every aspect is taken in consideration. After that, the DFMEA is started. DFMEA, acronym for Design Failure Mode and Effects Analysis, is a methodical approach used for identifying potential risks introduced in a new or changed design of a product/service [29]–[31].

The Design FMEA initially identifies design functions, failure modes and their effects on the customer with corresponding severity ranking/danger of the effect. Then, causes and their mechanisms of the failure mode are identified. High probability causes, indicated by the occurrence ranking, may drive action to prevent or reduce the cause's impact on the failure mode. The detection ranking highlights the ability of specific tests to confirm that the failure mode/causes are eliminated, the Risk Priority Number is a calculation that results from DFMEA, having in consideration, the severity of the failure effect, the frequency of failure occurrence and the detectability/preventability [29]–[31].

DFMEA is an indispensable product engineering tool for ensuring companies produce reliable products and services that satisfy customers in today's competitive business landscape.

There are other tools used in the development of a product, such as STAMP (Systems-Theoretic Accident Model and Processes) and CAST (Casual Analysis Systems-Theoretic), nevertheless, in this project was used the DFMEA and the PFMEA (analyzed further in the work). These methods have the same objective of analyzing the product development possible failures and avoid/overcome them.

As previously mentioned, companies run DFMEA to reduce their number of design defects. Ideally, the process helps companies prevent any design-related problems from occurring at all. Anything that hinders a product from operating correctly is considered to be a "defect." Risk is the substitute for failure on new/changed designs. It is a good practice to identify risks on a program as early as possible. Early risk identification provides the greatest opportunity for verified mitigation prior to program launch. Risks are identified on designs, which if left unattended, could result in failure [29]–[31].

The result? The consistent production, manufacturing, and output of high-quality deliverables. Companies involved in manufacturing, high-end technology, service delivery, and construction industries are the most likely to use DFMEA.

2.5.4.1. Testing and Validation

In order to validate the design, its necessary to proceed with the testing of the specifications previously spoken, that will validate the product. Normally the tests made to an EGR module are [22]:

- Module Leak Test: consists in testing the leakage in the water and gas systems, to be validated (OK part) the module shouldn't have more leak than the specification;

- Efficiency Test: depending on the type of EGR module, the efficiency test is responsible for validate the product in terms of efficiency. If it was more than one mode of operating, each one will be tested individually. Basically, to be an OK part, in this test, the temperature of gas in the outlet housing has to be no more than the specified;

- Vibration Durability: Normally the acceptance criteria are no failure or leakage after a certain amount of time being tested. As the name indicates, this test consists in exciting a frequency range, spending a certain amount of time at each frequency;

- Resonance Fatigue: If there is found a natural frequency in a span of frequency that could be critical, this test has to be performed and to be validate, should not be any leakage or failure after a certain number of cycles;

- Frequency Sweep Test: This test is made before the resonance fatigue, in order to find the natural frequencies of the module. Being analyzed if they are below a certain frequency;

- Pressure Drop Test: In this test is analyzed the amount of pressure drop. If it was more than one mode of operating, each one will be tested individually. Basically, to be an OK part, in this test, the temperature of gas in the outlet housing has to be no more than the specified, and the pressure targeted has to be reached;

- Alternating Temperature and Alternating Pressure Test: these tests consist in alternating the temperature and the pressure periodically. The acceptance criteria is no leakage or failure after a certain number of cycles;

- Thermoshock: this one is the most severe one, consists in variating the temperature (both gas and coolant) repeatedly during a great number of hours. Like these, the EGR module is taken to the extreme, and it's possible to see the result of non-likely situations;
- Icing Test: consists in testing the EGR valve, when frozen during a certain time. If it works after that, it is an OK part;

The tests that are made will obviously depend on the type of EGR module and its main purpose. Given this, a lot of other tests can be added to the referred below.

2.5.5. PROCESS

The process development of an EGR module follow the normal production standards, with special incidence on the quality of the final product, due user safety. Guarantying the quality of the final product will mitigate the probability of a malfunctional product going to the market.

Normally, the process development starts with the design freeze of the last prototype version, because after this phase, in general, the designs will not be changed in a point that will interfere in the process. The tools are designed and ordered, being a long phase until the delivered of it. Slight changes can be made in the design to facilitate the production of it.

While the tool procurement, the production line layout is also developed, this process requires a lot of logistics in order to design line capable of produce the number of products demanded by the client. Usually there are 2 phases for this development, initially, the production line is simpler, with less tools and less demand, nevertheless in an advanced phase of the production, new and more machines could be added to fulfil the goals of production and optimize to the maximum the production line capacity [22].

Like the design of the EGR module, the process is also tested and validated using different methods to do it, these tests are going to be analyzed in the next chapter. Furthermore, is possible to preview some failures of the production in the PFMEA (Process Failure Mode and Effects Analysis).

PFMEA, is a qualitative tool used for the intention of preventing failures in the manufacturing and making process. Being used by manufacturing and process engineers to identify and analyze potential failures in a process. Conducting PFMEA allows teams to prepare and build process safeguards that reduce or prevent the occurrence of operational downtime, injury or accident, costly repairs, and reworks in the business. So, it is conducted when a production line created or optimized with new tools, technology, or processes [32], [33].

The theory behind PFMEA is the same as DFMEA. Firstly, there are a process review identifying potential failure modes, then listed consonant their severity, occurrence and detection, giving a certain RPN (a score that classifies the potential failure based on a matrix). Like this, depending on the classification, the potential failure will have an action that reduce the RPN, reducing the probability of happening [32], [33].

Thus, both DFMEA and PFMEA are essential for a good specifications control. In these methods are considered a wide range of failure modes, which help to understand the behavior of the product, both in design and process. Knowing the failure modes and effect analysis, is possible to predict how sometimes a failure will imply in the quality control. These studies will provide a great knowledge about the product and the process and how a failure can be identified and therefore how avoidable a mislead can be.

2.5.5.1. Testing and Validation

In order to validate the process some tests are made. These will depend on the product and the production line analyzed, but in general, the tests are:

- Measurement Systems Analysis (MSA): Measurement Systems Analysis (MSA) is a tool for analyzing the variation present in each type of inspection, measurement, and test equipment, analyzing the quality of the measurement system. It allows us to make sure that the variation in our measurement is minimal compared to the variation in our process, determining how much the variation within the measurement process contributes to overall process variability [34].

- Run@Rate: all field of industries have quality and capacity requirements, and these demands must be accomplished. During a Run at Rate audit (Run@Rate), the supplier proves and demonstrates that its manufacturing process is capable to produce parts according to customer requirements at the quoted production rate. The Run at Rate is performed by the supplier, based on the request of the customer's Supplier Quality Department (SQD). In most of the cases Run at Rate is launched because of a new production initiation, a major process change, or a production relocation (moving to other site or facility), which are all PPAP-mandatory changes [35], [36].

- Capability Test: The process capability is the measurement of the capability of the process performed when there are some noise factors and process inputs impacting the process due to which the output of the process could not be in target line and might get deviated from the target. Defined as a statistical measure of the inherent process variability of a given characteristic. You can use a process-capability study to assess the ability of a process to meet specifications [37], [38].
- Tooling Dimensional Report: this is a test done to every tool in the production line. It is measured in the CMM to confirm that the tools fulfil the specifications requested and are capable of assemble the parts of the product.
- Cleanness Report: this test is a compromise between the Design and the Process. In the automotive industry, every system that has flow (gas, fuel, coolant, lubrification) have to pass in a cleanness test. Basically, this test consists in analyzing if there are more particles in the flow systems than it is specified, measuring the height and number of it.

After a good performance in these tests, the production line and the process are validated and the product can start the production in series. This does not mean that the production line keeps the same until the end of the project, there is always a continuous work to increase the performance of the process.

2.6. Quality Control & Assurance

Nowadays automobiles are more reliable than ever before. The reason behind it is the continuous effort of car manufacturers to master the quality control in automobile field. In any industry, quality control is a process used to ensure that the final product is free from failures, operational issues and other possible problems. In automotive manufacturing, that means automotive components go through rigorous testing to make sure they're well-engineered and harmless [39].

As it was possible to see the past chapters, the quality control process starts long before the first production models of components. When an automotive company releases a new product, they build prototypes, which are tested to evidence mechanical problems and other details that could be improved. Once the prototype phase it is over, the design goes into production, where quality control continues on the production line.

Quality assurance (QA) and quality control (QC) are two terms that are often used interchangeably. Although similar, there are distinct differences between the two concepts [40], [41].

Quality assurance and quality control are two aspects of quality management. Typically, QA activities and responsibilities cover virtually all the quality system in one fashion or another, while QC is a subset of the QA activities. Also, elements in the quality system might not be specifically covered by QA/QC activities and responsibilities but may involve QA and QC. Figure 2.17 shows ISO 9000 definitions from ISO 9000:2015: Quality management systems - Fundamentals and Vocabulary [42].

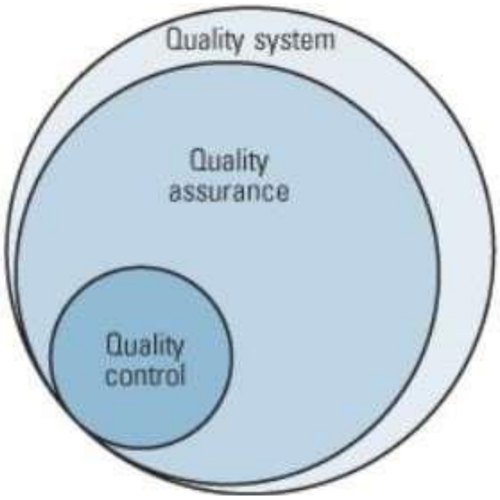


Figure 2.17 - Quality Management System

So basically, Quality Assurance can be defined as "part of quality management focused on providing confidence that quality requirements will be fulfilled." The confidence provided by quality assurance is twofold—internally to management and externally to customers. An alternate definition is "all the planned and systematic activities implemented within the quality system that can be demonstrated to provide confidence that a product or service will fulfill requirements for quality” [40], [41].

Quality control can be defined as "part of quality management focused on fulfilling quality requirements." While quality assurance relates to how a process is performed or how a product is made, quality control is more the inspection aspect of quality management. An alternate definition is "the operational techniques and activities used to fulfill requirements for quality” [40], [41].

Thus, in the next chapter, based on the theoretical knowledge learned in this chapter, it will be presented the development of an EGR Module, with special interest in the automatic validation of its specifications, during the assembled of the final product.

3. Product Design and Development: EGR Module

3.1. Introduction

The project of the EGR Module under surveillance in this document began in 2017, with the client reaching BorgWarner with a proposal to develop it. Firstly, it's made an initial design to be approved by the client in order to win the initial product quotation. This 0.0 version/initial design was submitted to initial tests and its results were the base to the constructions of the first prototypes that were also tested, and its validation presented to the client. After this, the costumer itself test the prototypes with his own tests and give the last validation necessary to go to the next phase.

Secondly, the project starts officially and with it the prototype phase, usually the longest phase of a project. During this, there were 7 versions of prototypes, and multiple tests to validate this design. In each version there were various changes that needed to be tested, understanding if the new design was or not efficient. The tests were made by the costumer and internally, having in this way different inputs and more scrutiny of the designs.

The PDD ends with the last design freeze, prototype construction, testing and respective validation, that in this project was the seventh version of design.

3.2. Initial Design Phase

As it was already referred, the initial design is the start point of the project. First of all, the costumer sent the specifications to the dimensioning of the EGR module, and a first design is made to do further tests. Normally these tests are functional ones, in order to verify if the design works virtually.

This EGR module was to be assembled to a 4-inline diesel engine and had to operate in 3 modes (Bypass, High-Pressure, Low-Pressure) as is possible to see in the Figure 3.1.

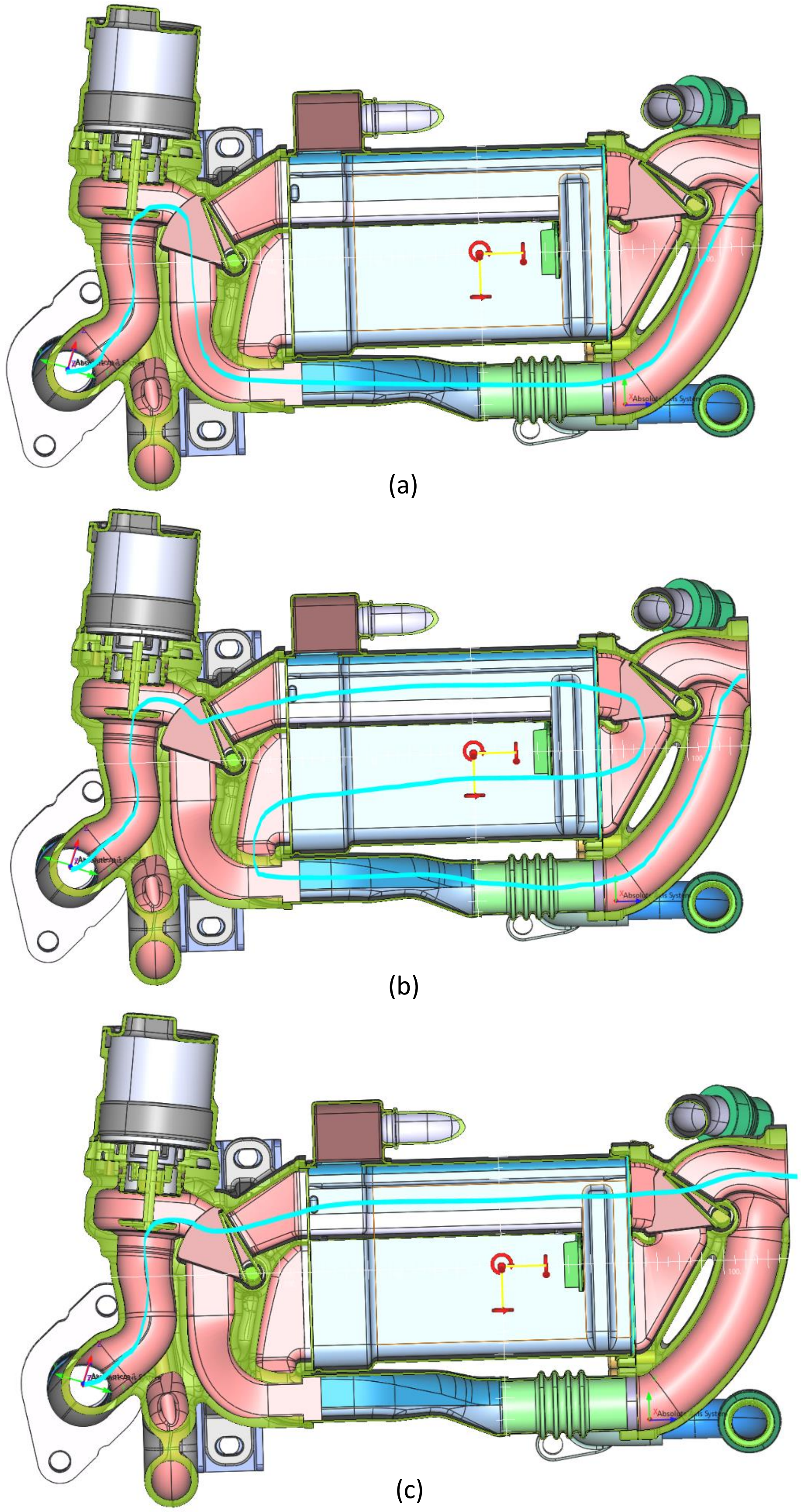


Figure 3.1 - Modes of a EGR Module ((a) bypass mode, (b) high-pressure mode and (c) low-pressure mode)

This design was product of a panoply of specifications given by the client, that would be presented below.

In terms of lifetime, the product had to be designed in such a way as to ensure that full functional capability is assured for at least 12 years or at least 300 000 km. The development object shall be designed for operation of a minimum ambient air pressure of 580 hPa, corresponding to 4300 m above the sea and a maximum ambient pressure of 1070 hPa, corresponding to 400 below the sea level.

The development object was designed for operation at the ambient temperature of -40ºC to 70ºC, with a possible start at -30ºC. At the flange surface for the intake system, the development object was designed at least for -30°C up to 350°C, with a possibility of short-term at 450ºC (50h accumulated over lifetime). When exceeding these max permissible operating temperatures of adjacent components due to radiant heat of the development object it was necessary to came up with protection measures on the development subject. The neighbor components were design to handle certain temperatures:

- cylinder head cover: 220°C duration / 240ºC short-term
- Design cover: 120°C duration / 165°C short-term
- coolant pump: 135°C / 165°C for a short time
- air intake manifold: 190°C duration / 240°C short-term
- sensors: 130°C duration / 165°C short-term
- engine harness: 150°C duration / 175°C short-term

In terms of coolant, it was designed to operating in a temperature span between -40ºC and 125ºC. Could be raise to 160ºC in case of an emergency for less than 15min. It operated in a permanent pressure of 5 bar and a maximum of 7 bar.

The maximum weight of the EGR module it had to be less than 4500g, including the EGR Valve weighting less than 460g.

The leakage is also something that have a specification, and if surpasses a certain amount, the sample is consider NOK. In this way, there is limits for the leakage rate in the two circuits: coolant and gas.

In the coolant side, in the whole EGR module the leak must be bellow 4cm^3/min at 2,5 bar. The gas side had a permitted leak of less than 600 cm^3/min at 600mbar in the EGR module and <4000 cm^3/min at 6000mbar in the EGR valve. Also, the EGR valve shaft has a permitted leak of 30 cm^3/min at 600mbar.

The surface of a component that could came into contact with water, or exposed to warm humid air, it was designed in way that eliminated the possibility of condensation forming inside the component.

In the electronical side was designed to be short-circuit proof against 0V and 5V and the sensor protected against pole-interchange proof up to 300mA and 7V for 60 seconds.

The main goal of an EGR module is to cool down the exhaust gases, and there was a specification for the efficiency of the cooling process, depending on the mode that is operating.

Some notes that are important to retain due this cooling performance.

- The outlet temperature in the bypass mode must lie above the limit temperature curve;
- The outlet temperature in the cooling mode "high power stage" must lie below the limit temperature curve;
- The temperature may drop by 10° degrees Celsius in the bypass mode over lifetime;
- The temperature must not rise more than 20° degrees Celsius in the cooling mode over lifetime;
- Measurement condition: AGR valve completely open;

Thus, throughout this part of the project, is possible to see the amount of specifications do came up with this kind of complex products, in order to reduce the extension of this work only a few numbers of variables will be analyzed deeply:

- Cooler Leakage Rate (each circuit);
- Inlet Subassembly Leakage Rate (each mode);
- Outlet Subassembly Leakage Rate (each mode);
- Module Leakage Rate (each mode and circuit);

- Module Geometry;

In order to fulfill the customer specifications, a complex design was made, having 3 main groups: cooler, inlet casting and outlet casting.

The Inlet casting was the structure where the heated gas enters. Attached to it was the EGR valve, the EGR tube and the bypass tube (Figure 3.2). The bypass valve was inside of the casting, and it was responsible to change the module operating mode. It has 2 fluid systems completely separated from each other - the gas and coolant circuit - in this case they have the same flow direction (both enter in the inlet casting and flow to the outlet casting direction).

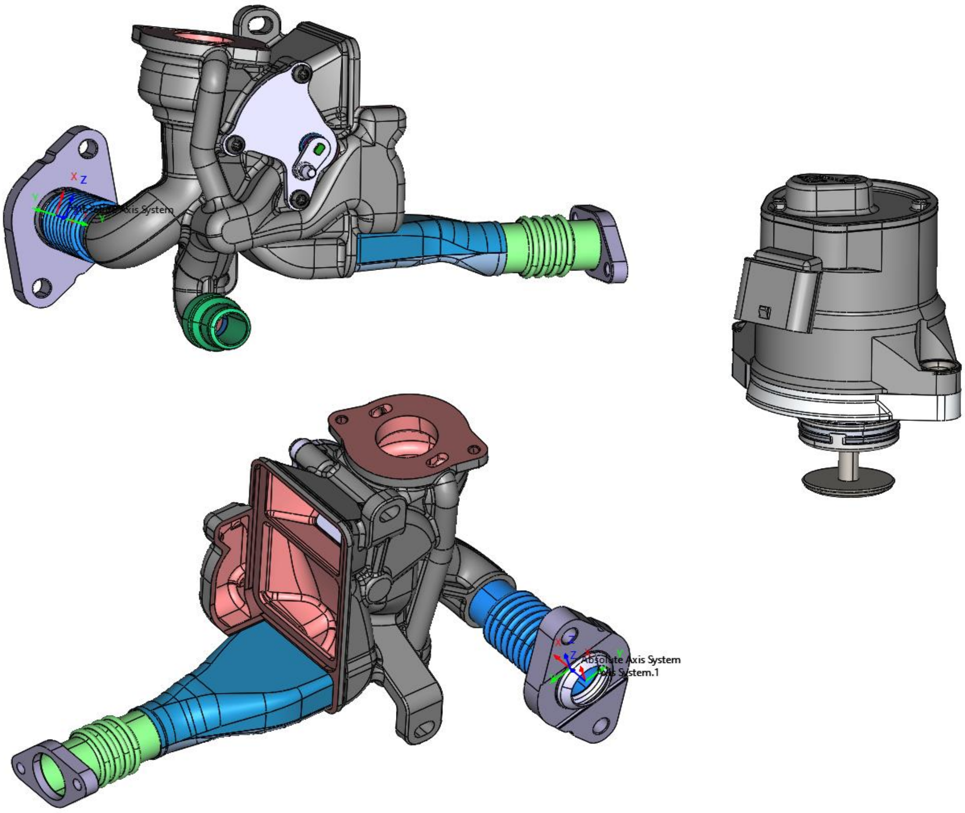


Figure 3.2 - Inlet Casting, EGR Valve and Bypass Tube

After the inlet casting there is the component responsible for decrease the temperature of the exhaust gas: the cooler.

The cooler (Figure 3.3) designed has the peculiarity of having a technology developed in BorgWarner, the hybrid tube. This technology is very interesting because increase exponentially the heat transfer between the gas and the coolant. Depending on the EGR module mode, the gas can go for 2 different paths, if its low performance mode, it only passes by the cooler one time and go out by outlet casting. If it is high performance mode, the gas pass 2 times in cooler, passing by the low performance first and then by the high performance one, going out finally by the outlet casting. The goal of these modes is, as it was possible to read in the bibliographic review, to have an adaptative EGR module, that will be more efficient or less, depending on the engine requisition. In the cooler is also present the exit of the coolant and the bypass actuators support.

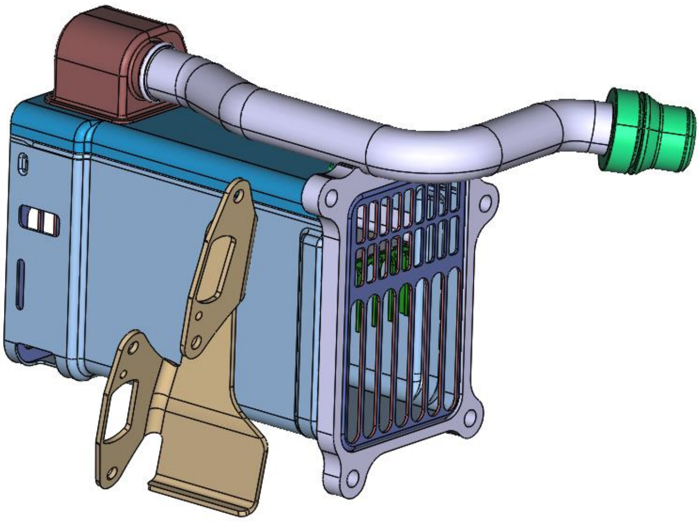


Figure 3.3 - EGR Cooler

The end part of this module is the Outlet Casting (Figure 3.4. In this part there is the 2nd bypass valve and it is attached to the intake manifold, being the part where the gas already cool downed go out of the module.

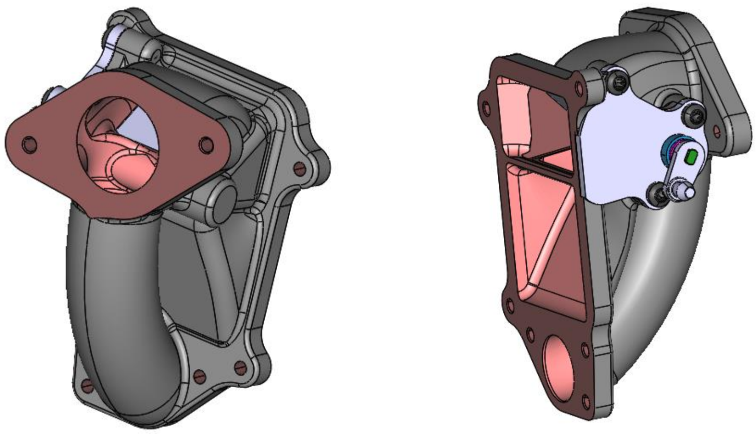


Figure 3.4 - Outlet Casting

The final initial design looked like this when it was submitted to the first test – a CFD – being able to understand the performance of the EGR Module (Figure 3.5).

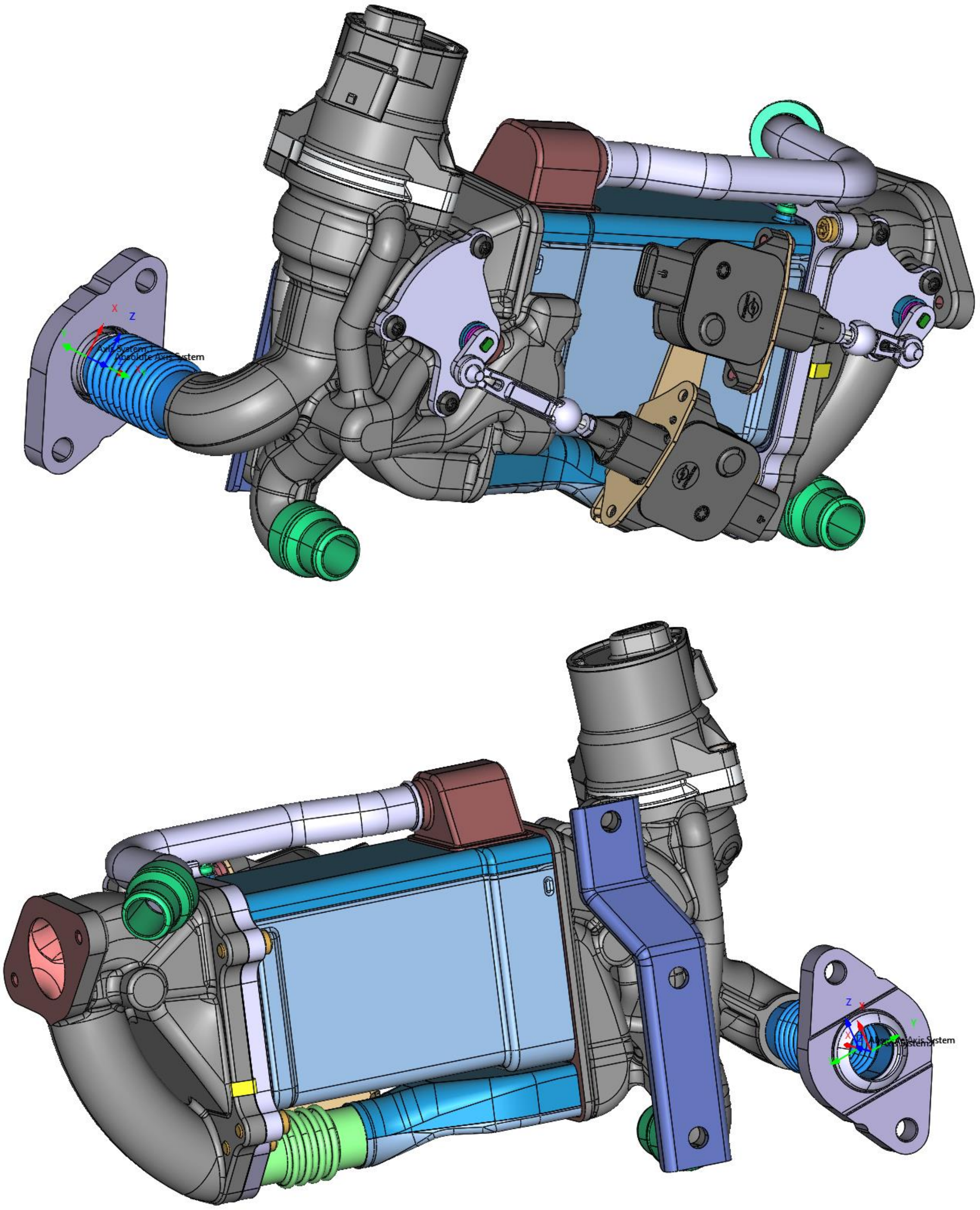


Figure 3.5 - First Design of the EGR Module

The CFD inputs had the objective of:

- Check temperature distribution on shaft assembly;
- Check temperature distribution on valve housing;
- Check temperature distribution on inlet housing;

These were the critical parts in the module, being the reason why they were tested first.

The inputs of the CFD analysis (Figure 3.6) were:

- Thermal conditions:
  - Gas side: 50 kg/h at 820ºC & 1.2 bar-a
  - Coolant side: 750 L/h at 50ºC & 2.2 bar-a

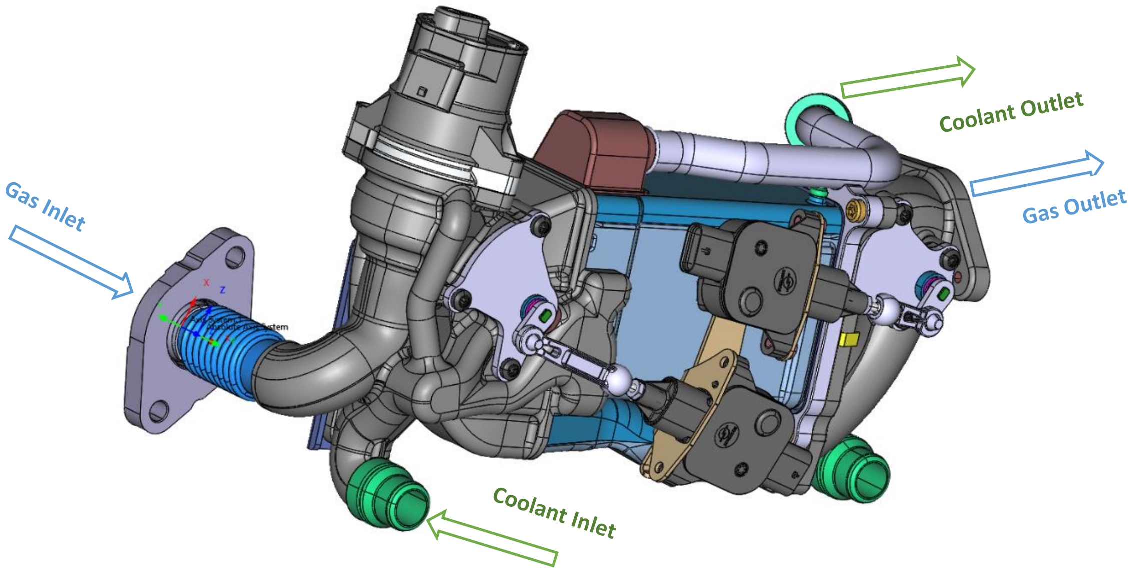


Figure 3.6 - Flow directions of the two circuits (gas and coolant)

The results of this CFD (Figure 3.7, Figure 3.8 and Figure 3.9) is showed below done by the Test Engineer:

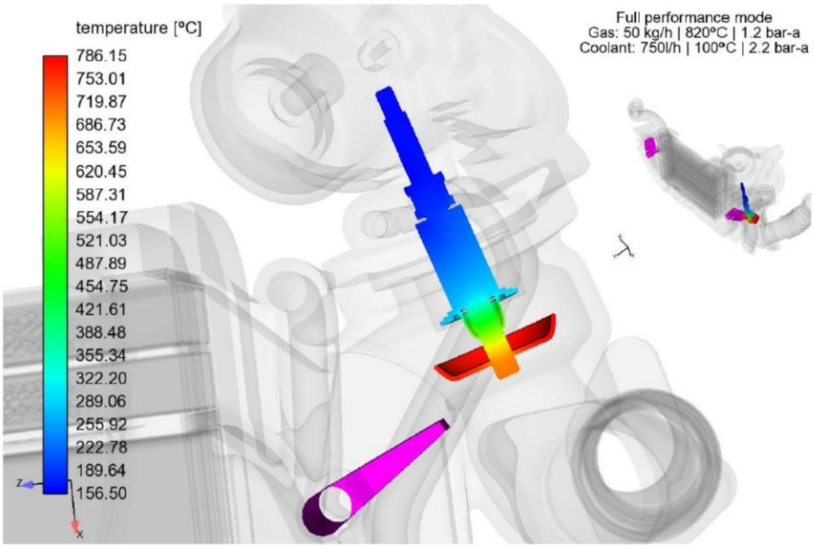


Figure 3.7 - EGR valve Poppet

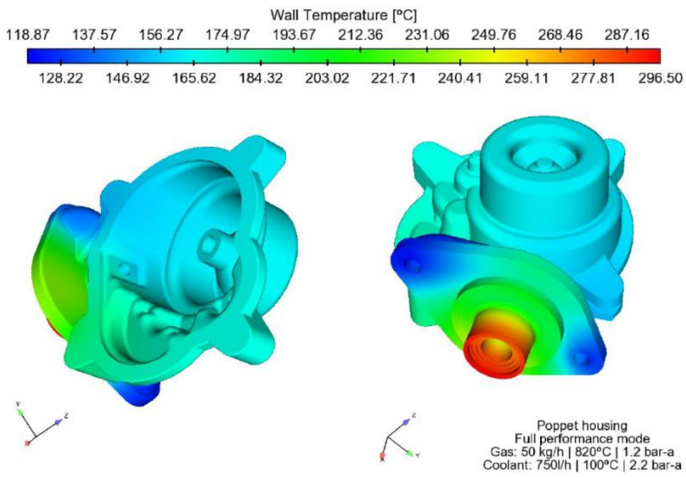


Figure 3.8 - Outlet Casting

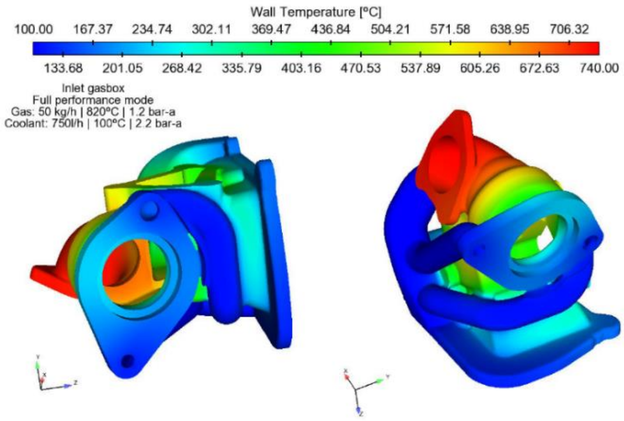


Figure 3.9 - Inlet Casting

The temperature in the poppet of the EGR (bottom part of the shaft) valve was the higher encountered in the simulation, concluding that it was necessary to cool down this part of the valve internally. The valve housing suffered the same problem and it was to be cool downed, at this temperature, the electronical part of the valve will collapse. The inlet housing registered a maximum temperature of 740ºC, which means that there is a heat transfer between the gas and the EGR Tube before arriving to the inlet housing. Some chanels will to be done for the cooling system, in order to decrease the temperature in these 3 parts of the module. Nevertheless, it was possible to conclude that this design had potential, it was not perfect, needed changes, but it was a possible solution for the client.

Being this simulation done, a certain number of samples were produced – as prototypes - assembled and shipped to further tests in the client. But first, BorgWarner did its internal testing, validating the initial design.

After the client tests and respective validation, there was the nomination of BW to develop and produce the EGR module. With this nomination the Initial Design Phase ended, starting the Prototype Phase, where the product was fully developed and tested.

3.3. PROTOTYPE PHASE

In the last chapter it was possible to understand how the project started, and now, on this one, it will be presented how the next phase procced. – Prototype Phase. The Initial Design Phase ended with the first validation of an CFD and further building and testing of the physical samples. Thus, after the nomination for the project, the Applications Engineering Department started to work to correct the previous design. The validation of that design, served only to understand the performance and potential of an EGR module from BorgWarner, and like that, a lot of changes were done, the first design can be seen below in the Figure 3.10 and Figure 3.11:

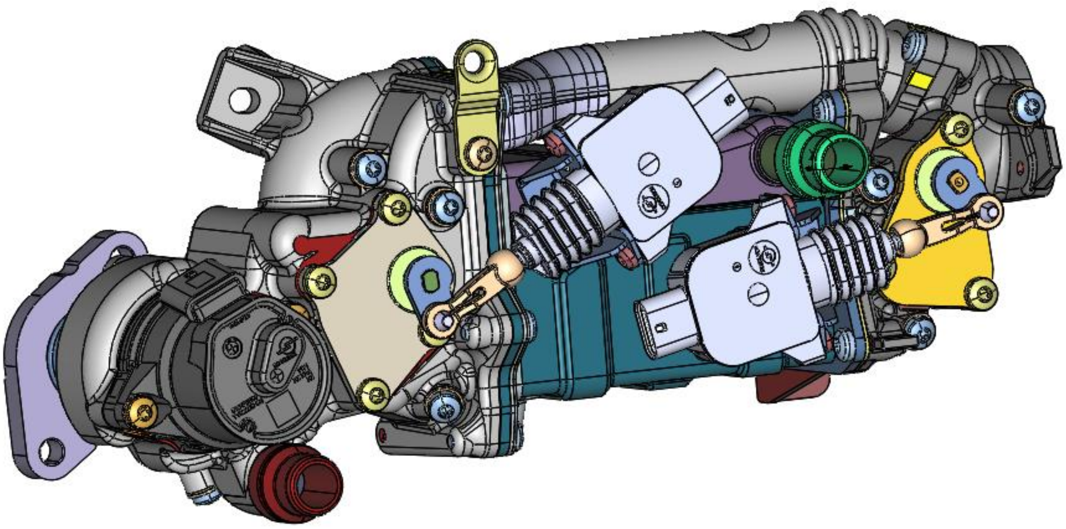


Figure 3.10 - EGR Module in the first version of the prototype phase (actuators side)

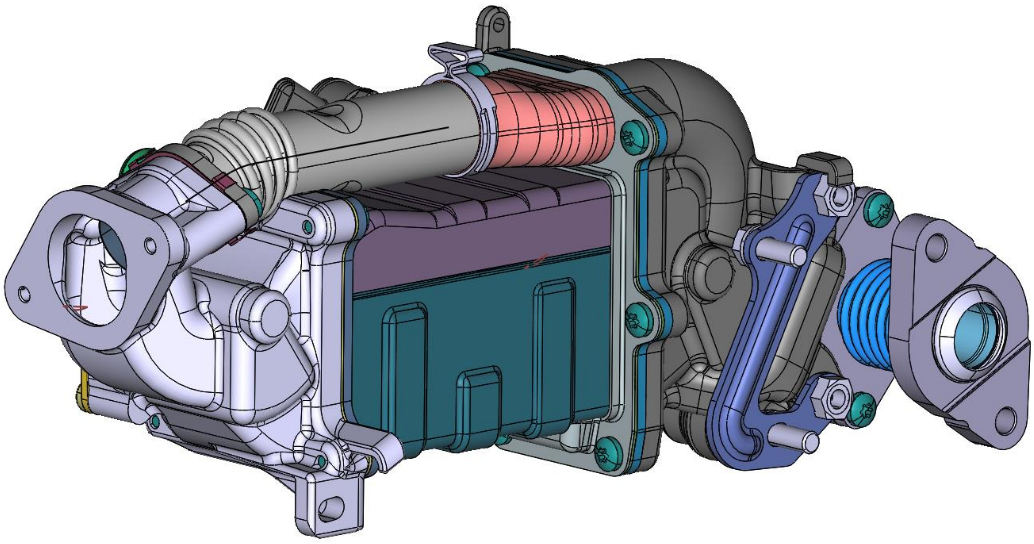


Figure 3.11 - EGR Module in the first version of the prototype phase ("back side")

This was the first design of the prototype phase, and it is possible to see significant differences comparing it to the initial design. The major differences were:

- Inlet Casting with the EGR valve and EGR tube position changed due packaging restrictions and the need to simplify the geometry.
- Bypass tube position, changed from being below the cooler to be above it. This change lead also to changes in gas paths in the castings.
- The outercases of the cooler also changed, both shape and height.
- The coolant tubes changed position and height.
- Position of the actuators also changed, operating in the opposite way.

In general, almost every component in the module was modified. This change had the objective to optimize the performance and geometry.

After this, there was an agreement between the developer team and the client to freeze the design, thus the first suppliers are contacted to give quotations about the parts to be assembled. After an exhaustive process of suppliers selection various components are ordered and finally assembled in the prototype laboratory. These freshly assembled EGR module were submitted to internal tests, according with the Design Verification Plan and Report (DVP&R), and to delivered to the client to perform own tests.

The DVP&R contemplates the majority of tests that are referred in the design subchapter. The prototype version has to be successful in every of it to be validated, thus, if the sample fail at one test, it was to be teared down to analyze the cause of failure and it was to be redesign in the future, beginning the 2nd version of module of the Prototype Phase.

One important thing to have on mind, many failure modes and possible errors are foreseen in the DFMEA, that is done simultaneously with the prototype phase and can last more than one version of prototype. Thus, before analyzing the tests done to this first prototype, it will be analyzed the major Failures Modes and Errors, that will predict the problems the design may present in the future.

In the bibliographic review, was seen that the in the DFMEA, the failure modes are classified quantitively (severity, occurrence and detectivity). The main ones are going to be presented below:

- Component breakage
- Component disassembly
- Component untightened
- Component and out of tolerance
- Coolant Leakage
- EGR modes nor available
- Gas Blocked/
- Gas flow unrequested/requested but not flow
- Gas leakage
- Gas Temperature drop
- Increase in Pressure Drop
- Leakage between EGR modes
- Leakage between circuits

Having this knowledge à priori, made it possible to predict the behavior of the EGR module to the tests.

Thus, this first design was submitted to the new simulation and tests referred in the 2.5.4.1. subchapter being successful at: module leak test, efficiency test in each mode; gas pressure drop in each mode; coolant pressure drop. There were four tests postponed (corrosion resistance; alternating temperature test gas side; thermoshock; frequency sweep test), for the next design version, given the failure of the EGR module in three tests: alternating pressure test gas side, alternating pressure test coolant side and bypass actuation over temperature.

Two full assembly EGR Modules (1st version of prototype) were tested with the goal of measure the resistance of the coolant and gas circuit when submitted to alternating pressure according in a test bench (Figure 3.12).

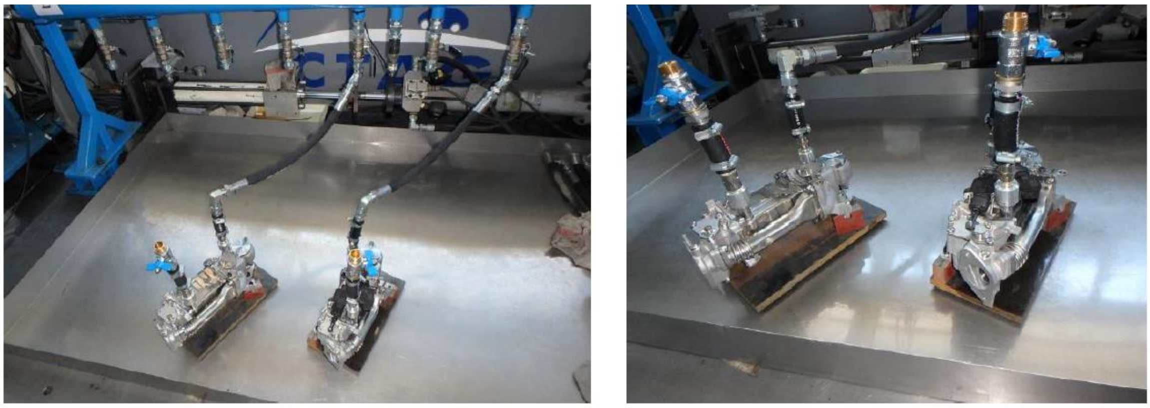


Figure 3.12 - Bench test

Unfortunately, the coolant side could not handle the pressure variation and both parts presented leak signs (Figure 3.13).

Figure 3.13 – Leaky Zones

In a test of 100 000 cycles, the first part failed after 37 000 and the second after 74 000. In the third test the failure was located between the crank and the bush.

The simulation was a CFD of both circuits (Figure 3.14), but the most influent result was in the coolant circuit. The results shown that the coolant outlet was submitted to high pressures in this part, needing some improvements.

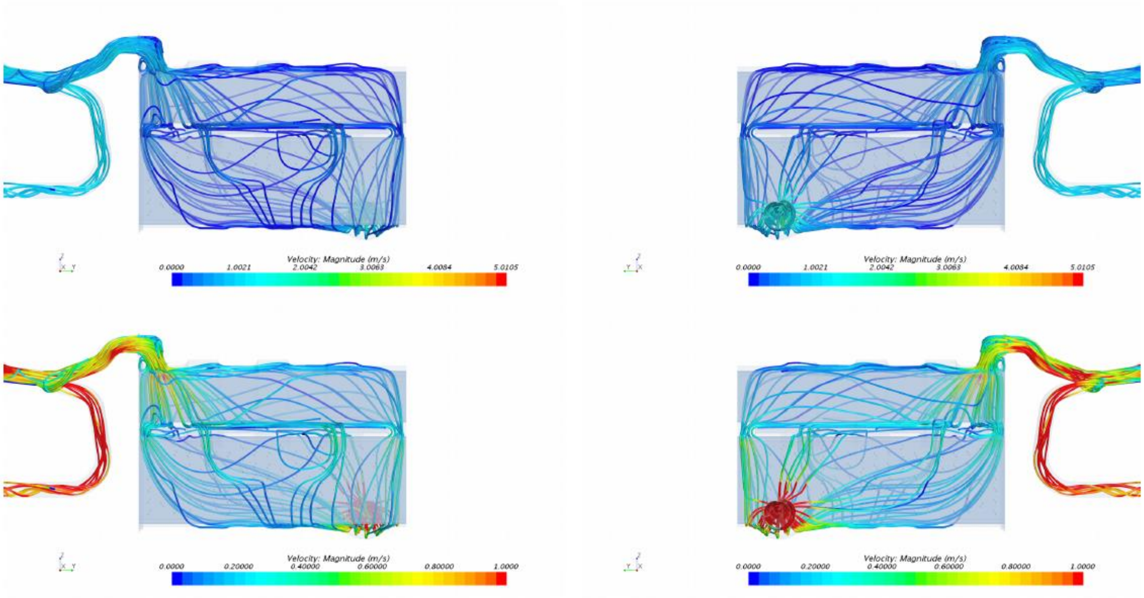


Figure 3.14 - CFD to evaluate the performance

The second design had a lot of modifications, with the goal of improving the performance of the EGR module and to validate the design. The main changes were:

- In the inlet casting (Figure 3.15 and Figure 3.16):
    - the material was changed from aluminum to SS, mostly because thermal proprieties: stainless steel is more resistant to higher temperatures (melting point is 1450ºC compared with the 600ºC of the aluminum), and is a lot less thermal conductive (SS has 20W/(mK) and the aluminum 150W/(mK); [43]
    - the refrigeration on the EGR poppet removed, due design simplification;
    - the inserted bypass tube was removed, due the change of material (more resistance to heat, there is no need to have this component);

- the coolant channel section increased, in order to improve the cooling performance without compromising the circuit (more pressure distribute in bigger section);

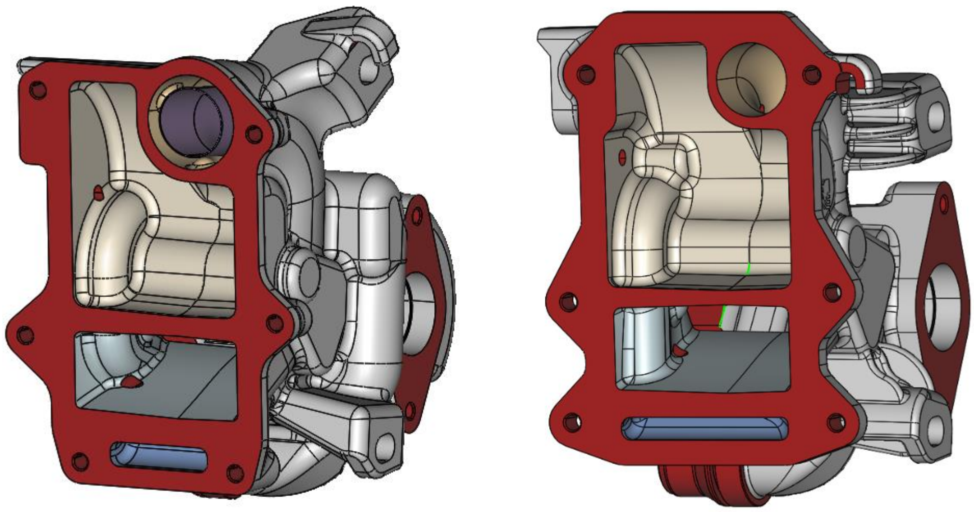


Figure 3.15 - Changes in the Inlet Casting (Inside View)

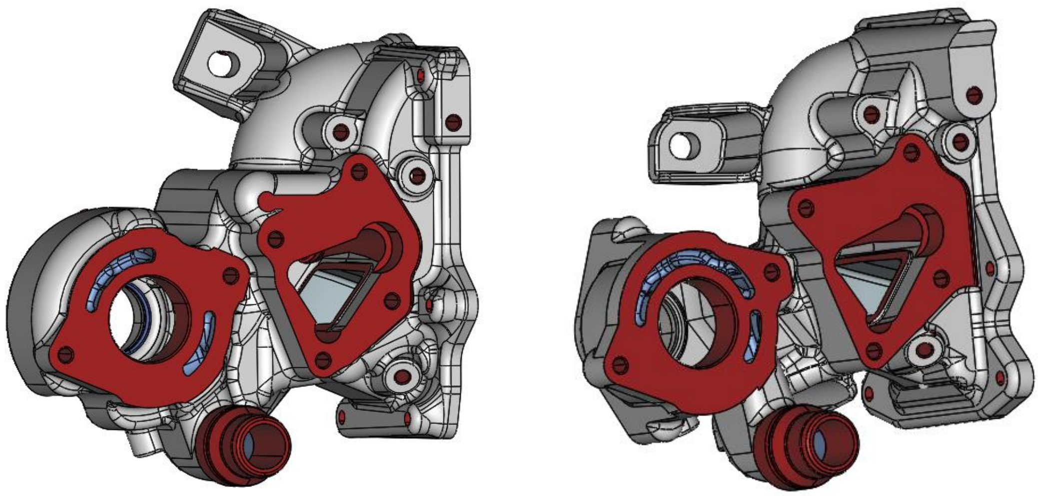


Figure 3.16 - Changes in the Inlet Casting (Outside View)

- In the cooler (Figure 3.17 and Figure 3.18):
  - coolant sealing components changed, due structural resistance improvement.

- flanges thickness increased from 4mm to 8mm, to be able to deal with the variation of pressure in both coolant and gas circuit.
- the big half of the case changed upside down, trying to overcome the failure that appear in the tests analyzed above. Adding the ribs design changed, with these two changes it was expected to improve the structural resistance of the outercase and the success in the next round of testing;
- it was added the coolant connection on the outercase, targeting the improvement of coolant flow, thus upgrading the cooling performance, not compromising the integrity of the cooler;
- the outer coolant tube position changed, in order to make easier the coolant outlet (as it was seen in the CFD).

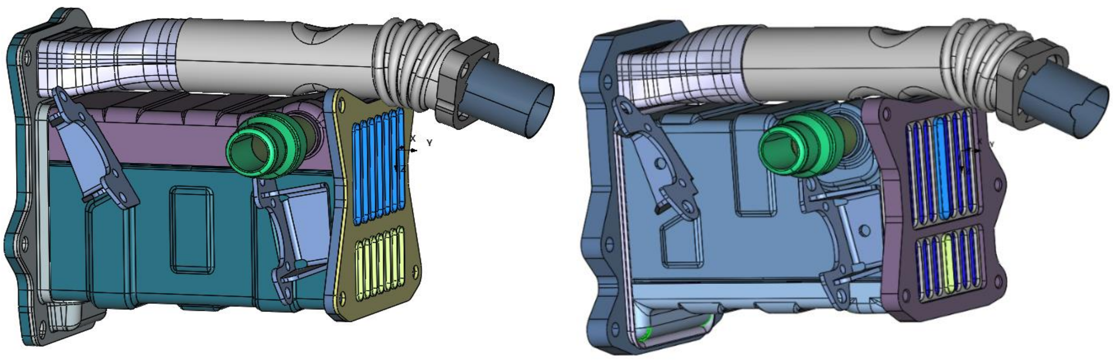


Figure 3.17 - Changes in the Cooler

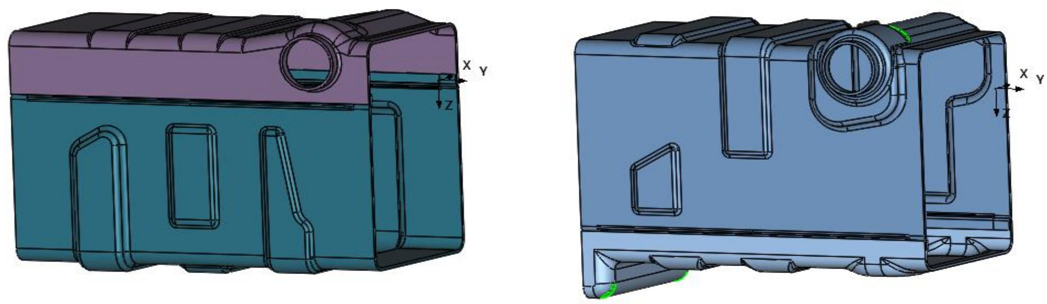


Figure 3.18 - Changes in the Outercases

- In the bypass tube (Figure 3.19):

- there was added a pokayoke on the flange to reduce the possibility of assembling the flange incorrectly;
- the gasbox geometry was changed to improve the flow of gas through it;

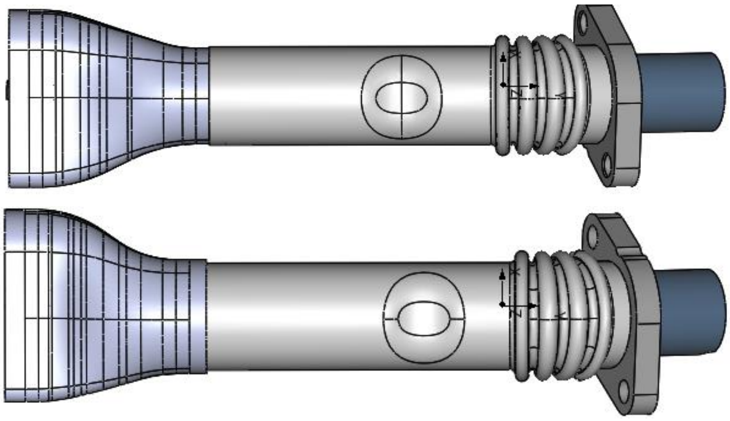


Figure 3.19 - Changes in the Bypass tube

Thus, the final design of the second version was quite different as it is possible to see in the Figure 3.20.

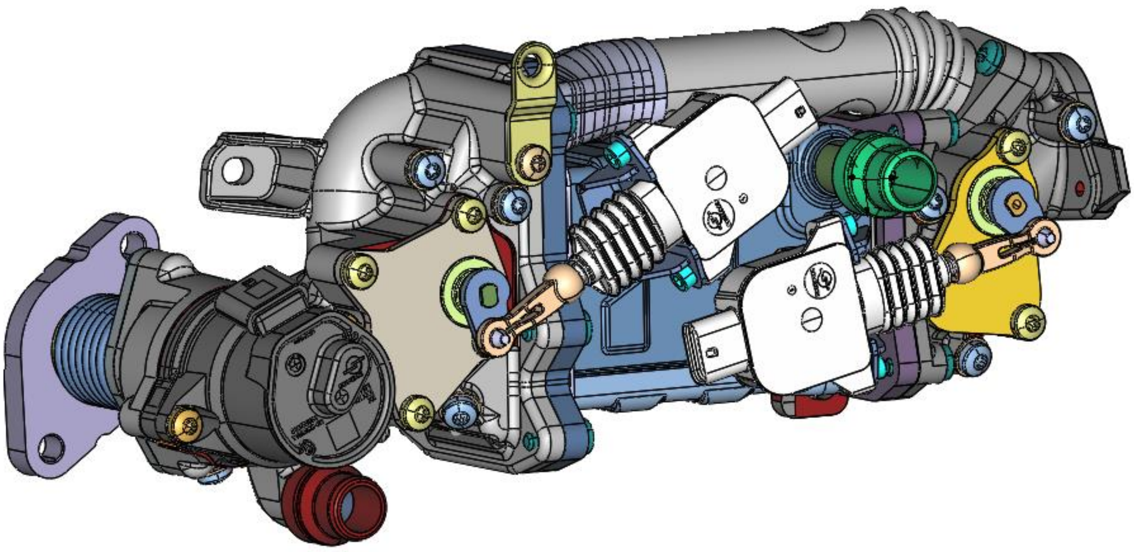


Figure 3.20 - Second Version of the prototype phase

The second version of prototypes was remade, the design was changed, new simulations were made, the client had to approve the design changes, there was the design freeze and only then were built in the prototype laboratory. As usual, they were submitted to the same tests done on the first version, being introduced even more tests: boiling test; resonance fatigue test; vibration durability test; bypass actuation durability.

This time, the EGR module had more success, passing in fifteen out of nineteen tests, with only one fail and three postponed to the next design version. The design passed on the module leak test, efficiency test in each mode; gas pressure drop in each mode; coolant pressure drop, corrosion test; boiling test; alternating pressure test on the gas side; thermoshock accelerated, frequency sweep test; bypass actuation over temperature and bypass actuation durability.

The three tests that were postponed (Alternating temperature test gas side; resonance fatigue test; vibration durability test) due no data available to have reference values and inputs for the tests, being rescheduled to be done on the third design version.

The only test that failed (Figure 3.21) was the alternating pressure test coolant side. This time, there were assembled 5 parts to the test bench and all of them had leakage due component breakage.

Figure 3.21 - Bench test

In these five parts, all of them failed, four in the same area (Figure 3.23) and only one in the cooler flange (Figure 3.22).

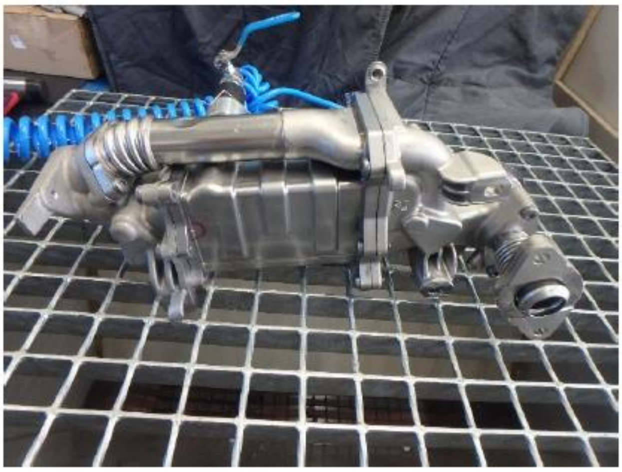


Figure 3.22 - Leakage zone (in red)

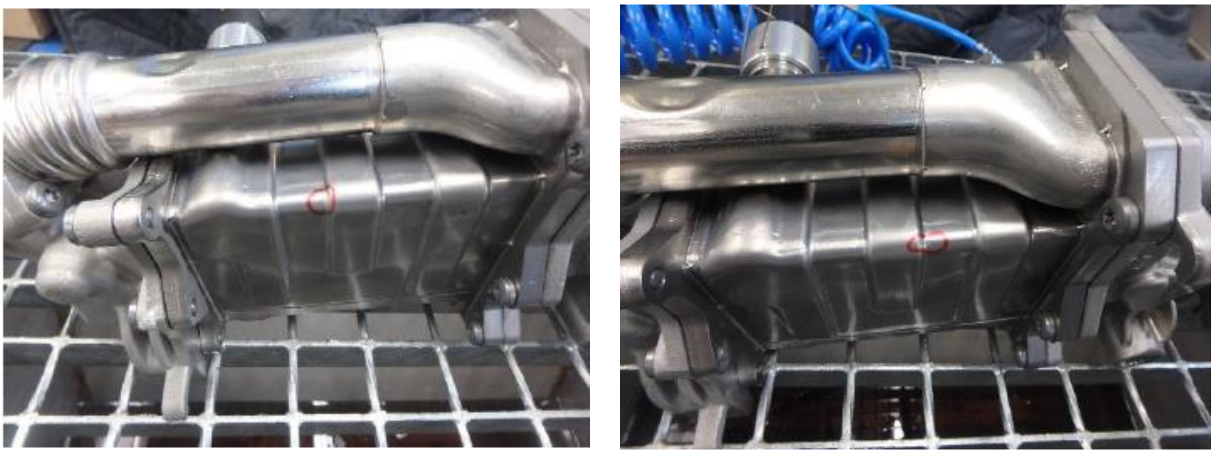
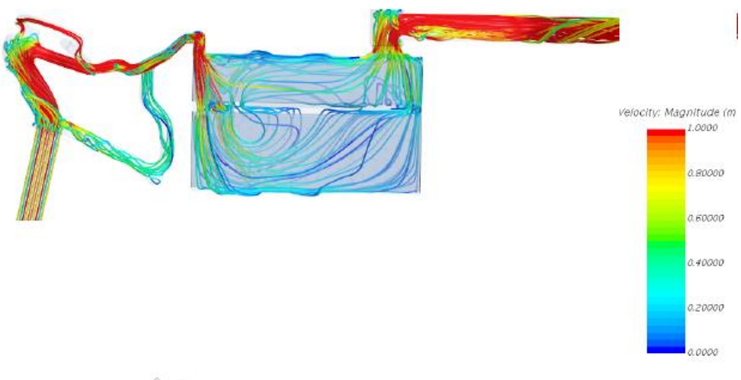


Figure 3.23 - Leakage zones in the outercase

As it is possible to see, the first image corresponds to the breakage in the flange, this happened after 33 000 cycles. The next two photos are modules that broke in the same rib but in different sides. There was 4 that broke in this area, two after 33 000 cycles, one after 37 000 and the other after 18 000.

The CFD simulation (Figure 3.24) can corroborate these results and explain why.



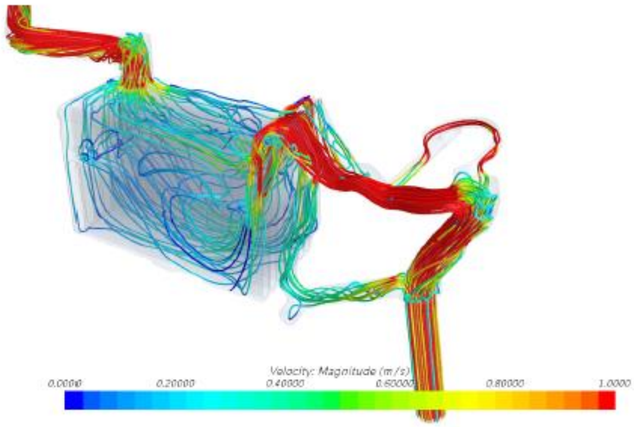


Figure 3.24 - CFD results that explain the breakage of material

The pressure of the coolant was more than the outercase and the area near the flange could handle, being necessary to redesign something in order to solve this breakage of material.

This phase is cyclic, given the fact that this process is repeated until the design if fully validated (the module is redesign, both parts reach an agreement, there is a design freeze, new parts are assembled, tests are made both in BorgWarner and client, depending on the results/client exigencies, a new redesign has to be made or the design is validated), with an agreement between BorgWarner and the client. Thus, in this work, was only presented the first two designs of the project, for example purposes, and it will be analyzed the last design, before the next project phase, for understand how the prototype phase culminate.

This prototype phase had seven design versions, until the final validation. In the sixth version, most of the structural changes were already validated, being the seventh version pretty similar to sixth, in this way, the validation of this last version was partially done in the penultimate design.

In the versions before the sixth (3rd, 4th and 5th) there were made key changes, like the changing of outlet coolant connection position and the design of the outercase, improving the structural resistance, solving the material breakage encounter in the first and second version.

Thus, from the sixth to the seventh design version, was changed:

- the inlet casting suffer slightly changes (Figure 3.25 and Figure 3.26):

- sensor holes were removed;
- Added material to improve the feeding;
- Machining the surface of the bolt seats;
- Bypass cover threads increased from 15,5mm to 20mm;

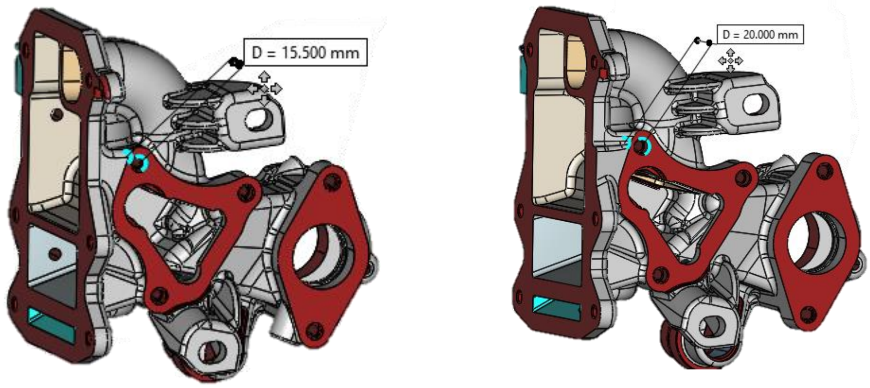


Figure 3.25 - Changes in the Inlet casting from the 6th to the 7th version (Inside View)

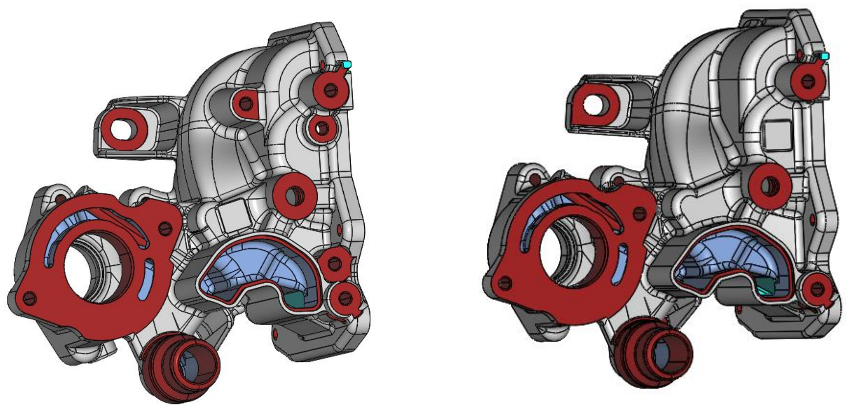


Figure 3.26 - Changes in the Inlet casting from the 6th to the 7th version (Outside View)

- The flange of the bypass tube (Figure 3.27):
  - The position of the inner supports changed;
  - Added chamfers on the tubes seat for assembly improvement;
  - Process change from laser cut to fine blanking;

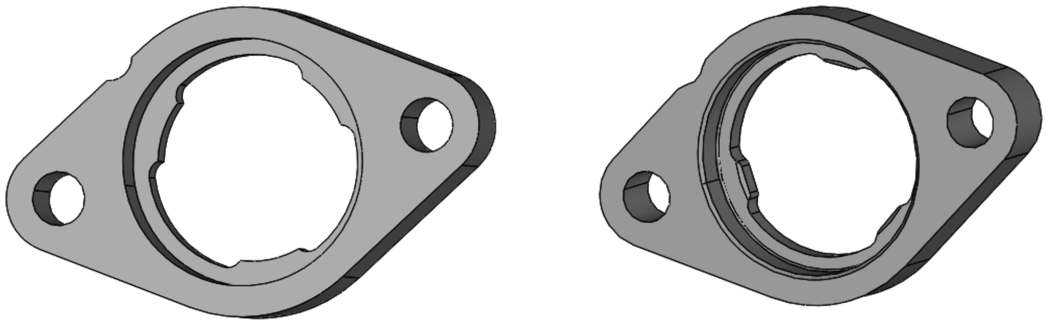
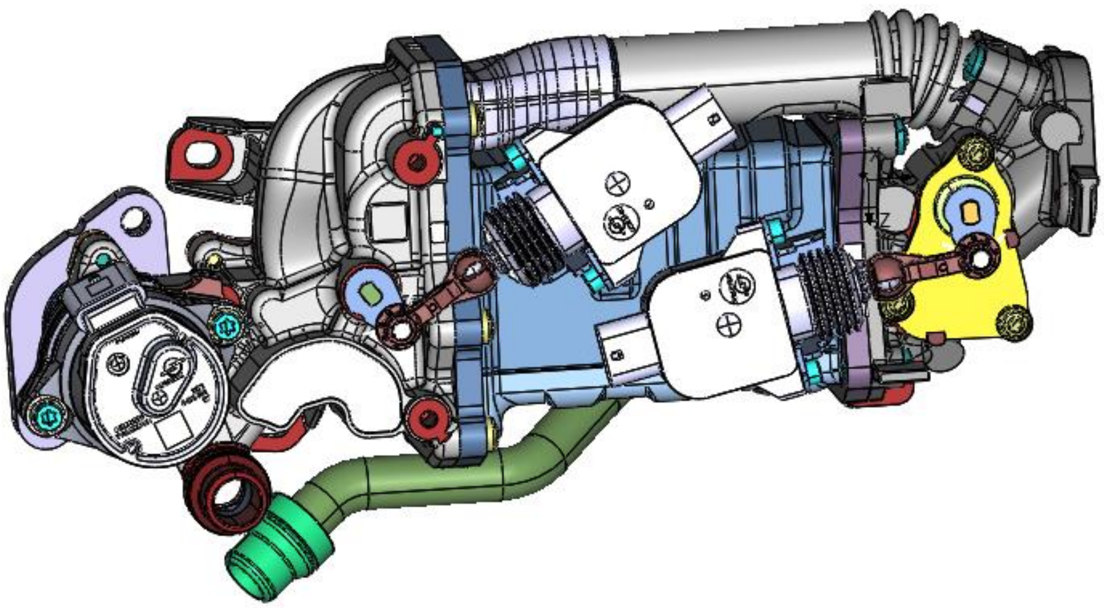


Figure 3.27 - Flange modifications

There changes were very insignificant compared with the functionality of the module. Thus, the design verification plan and report were reduced from 19 tests to 3: Thermoshock, alternating temperature bypass tube and bolted joints. The other 16 tests did not require new validation, given the previous testing and validation in the sixth version.

In the Figure 3.28 below it is possible to see final version of the EGR module.



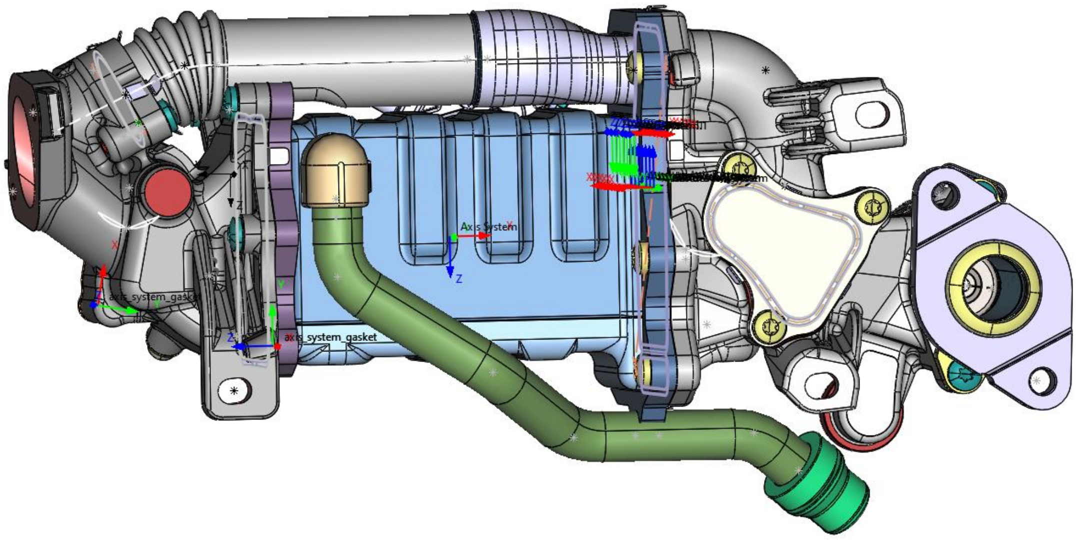


Figure 3.28 - EGR Module in the end of the Prototype Phase

4. Product Process and Development: EGR Module

4.1. Introduction

Product Process and Development (PPD) is, as the name indicates, the process development of a certain product, in this case an EGR Module.

In this phase of the project, the manufacturing team worked to create a process where the performance and quality are foundations. Starting with a meticulous analyzed of each part of the product, with the goal to develop tools/machines to create and/or assemble these parts.

There was also a study to find a compromise between the efficiency and resources to design the production line layout, being this possible based on the flow chart and applying lean thinking (a methodology applied to industries and organizations being also a mindset focusing in two main pillars: Continuous Improvement and Respect for the People). The layout designed is also changeable depending on the customer demands, disponible resources and other factors.

In this chapter, will be analyzed the PPD in general, with special interest in the machines/tool responsible by the quality control of the product (it will be presented an example), production line layout and the knowledge behind it and the flow chart of the product (how many operations until the final product is assembled).

4.2. Product Line Development

About this subject, a study of how a production line is developed was conducted. The initial phase of this part of the project is similar to the beginning of the product design and development. There is a quotation for the process of the project, submitted to the costumer, being the kick-off for this phase.

This quotation has every manufacturing operation and every parameter associated to it. The parameters consider in this quotation are:

- The machine cost per part produced;
- Number raw material to make a part;

- Number of operators needed by each operation;
- How many pieces can the machine produce per hour;
- The duration of the operation;
- The machine use per day;
- Total cost for the tool
- Total cost for the machine

For example, in the operation of the final geometry control:

- The machine cost per part produced: 0,12€
- Raw material needed to build a part: 1,00 unity
- Number of operators needed by each operation: 1,00
- How many pieces can the machine produce per hour: 75,00
- The duration of the operation: 56.47sec
- The machine use per day: 17,16h
- Total cost for the tool: 7 000,00€
- Total cost for the machine: 15 000,00€

After finishing this method to every operation, there will be a final cost for the project process, being subjected to validation by the costumer. Thus, being approved, is developed a flow-chart of the whole process, being divided in eight phases, with some of them manufactured at the same time with this, is possible to start idealize the production line. The base for the flow chart is the design done in the last project phase, analyzing and studying each part of the product, it is obtained a certain operation that will transform a raw material or a sub part, in a new part or subassembly. After this study, a flow chart with all operations necessary to obtain the final product is created, being one of the kick start for the process development.

In the flow-chart of the EGR Module analyzed, hybrid tubes manufacturing (Figure 4.1), EGR cooler subassemblies (Figure 4.2) and the tubes manufacturing (Figure 4.3), are built at the same time.

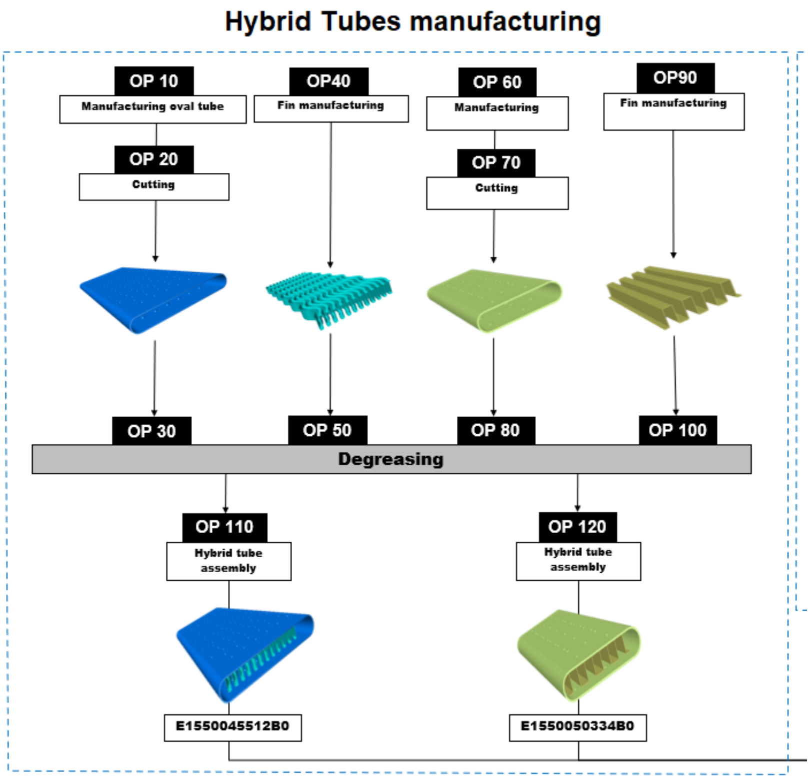


Figure 4.1 - Flow Chart – Hybrid tubes

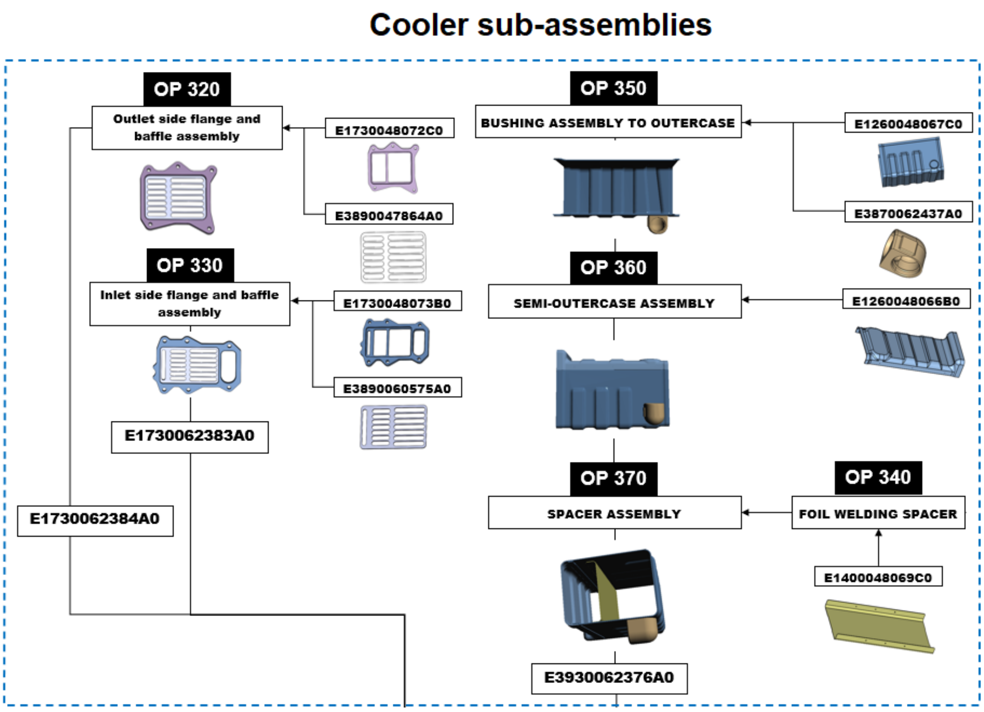


Figure 4.2 - Flow Chart – Cooler Sub-components

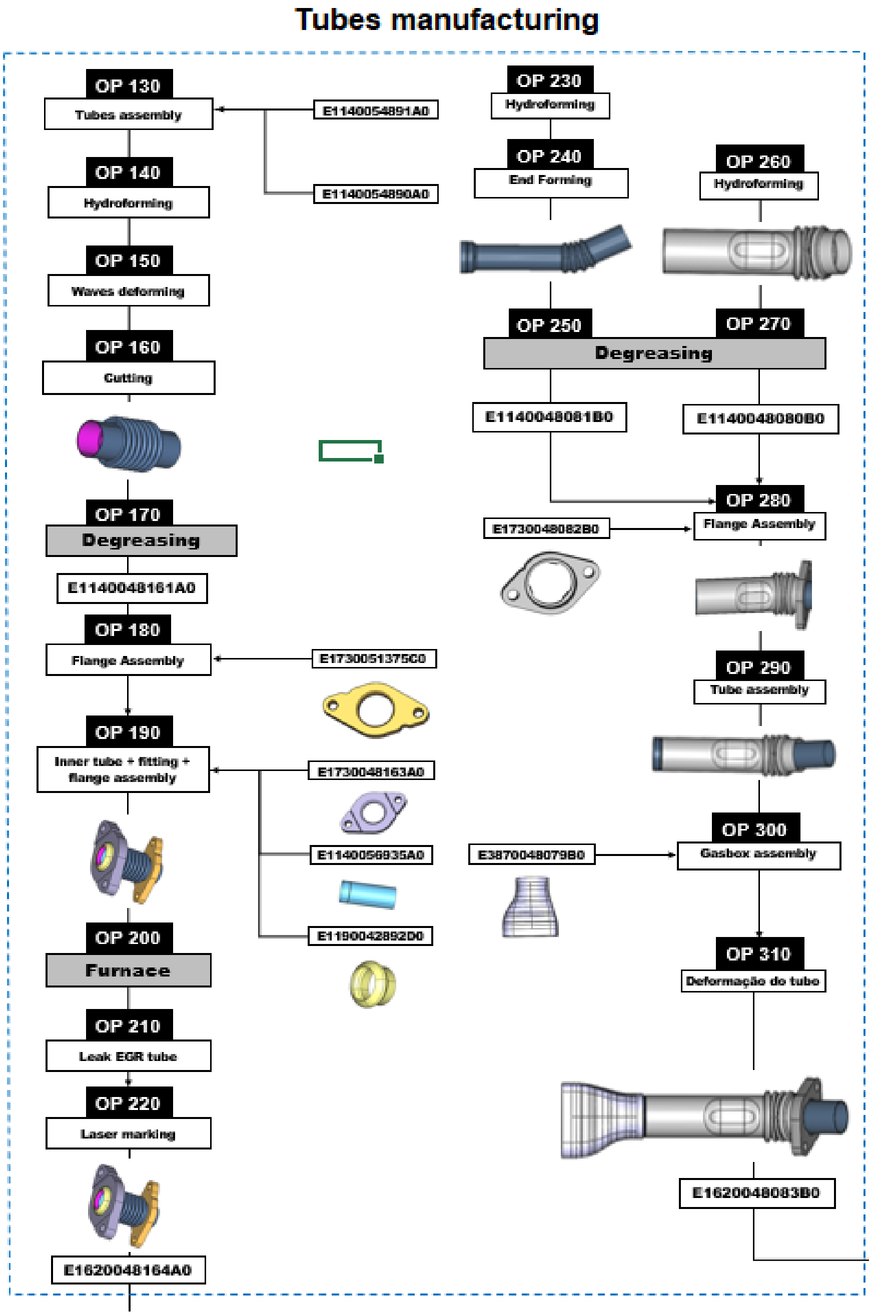


Figure 4.3 - Flow Chart – Tubes Manufacturing

After the OP220, the EGR tube goes to be assembled with the inlet casting while the Bypass tube (OP310) goes to be assembled with the EGR cooler (Figure 4.4), along with the cooler sub-assemblies and the hybrid tubes (320, 330, 370 and 110, 120, respectively).

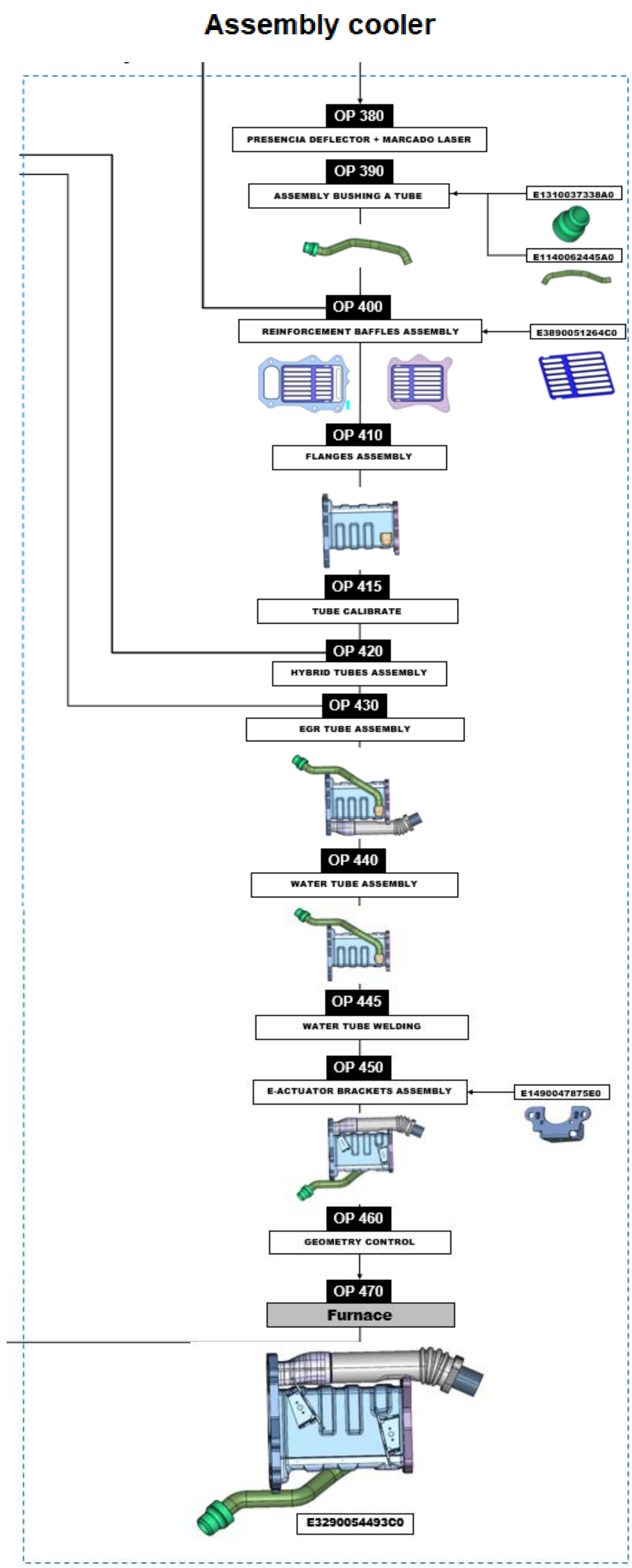


Figure 4.4 - Flow Chart - Cooler Assembly

Meanwhile, there is also three another operation being assembled while the cooler is manufactured (casting subassemblies (Figure 4.5), Inlet Casting (Figure 4.6) and Outlet Casting ()).

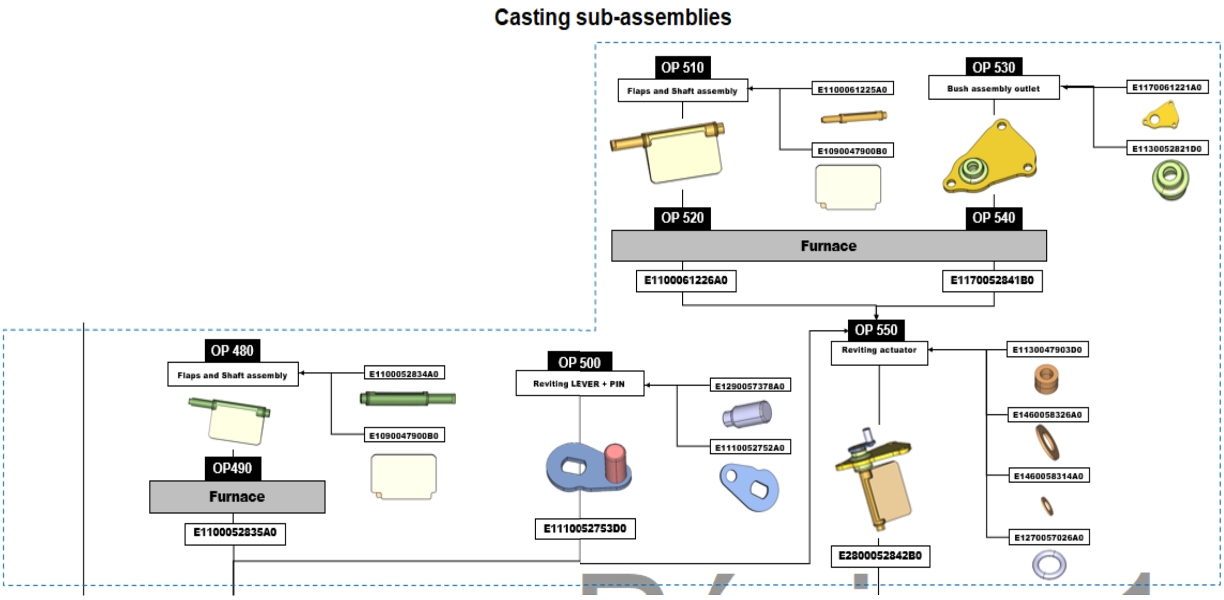


Figure 4.5 - Flow Chart - Casting Sub-components

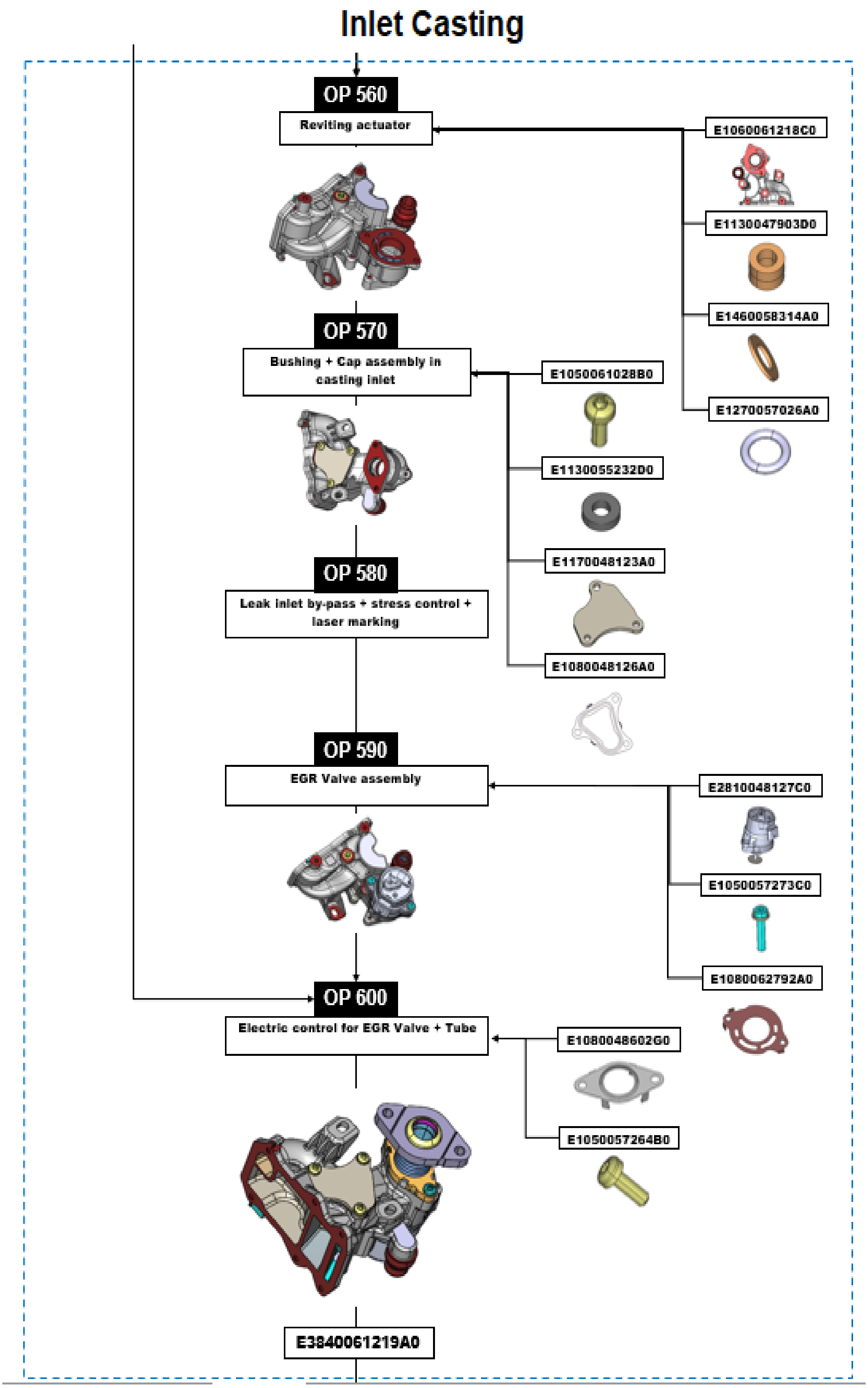


Figure 4.6 - Flow Chart -Inlet Casting

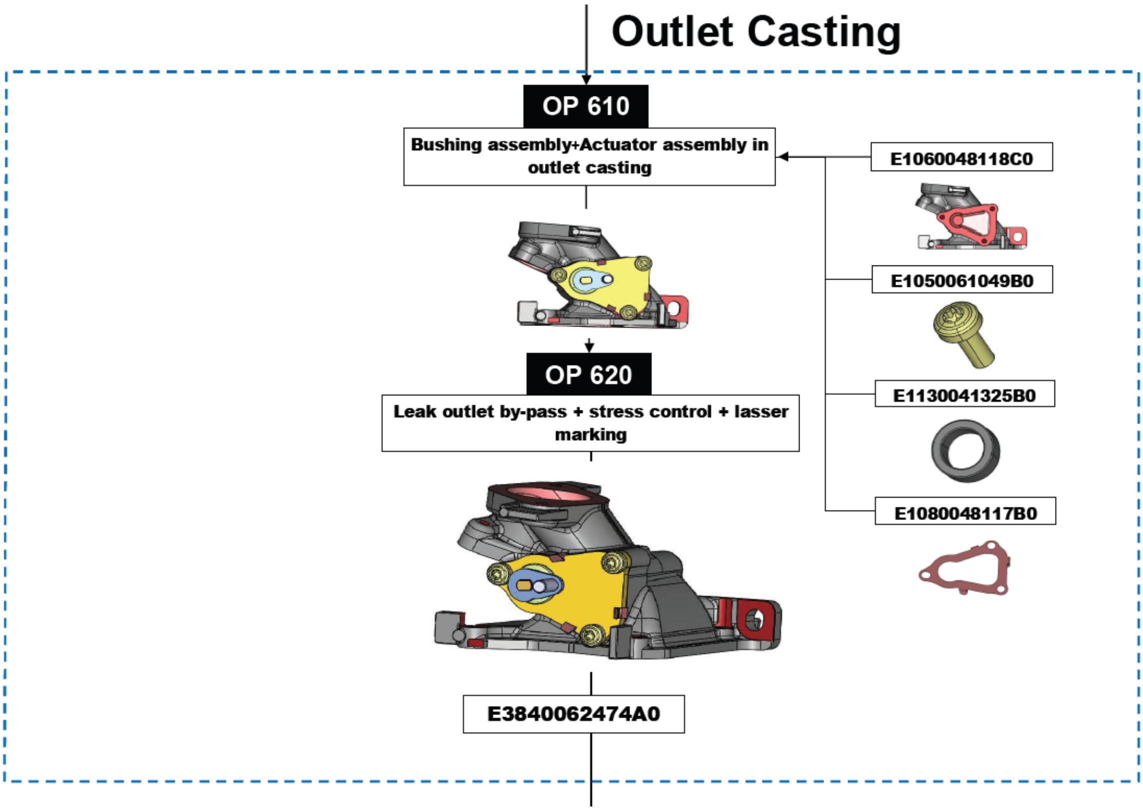


Figure 4.7 - Flow Chart - Outlet Casting

Thus, the sub-parts done in OP420, OP600 and OP620 are assembled to create the final product (Figure 4.8).

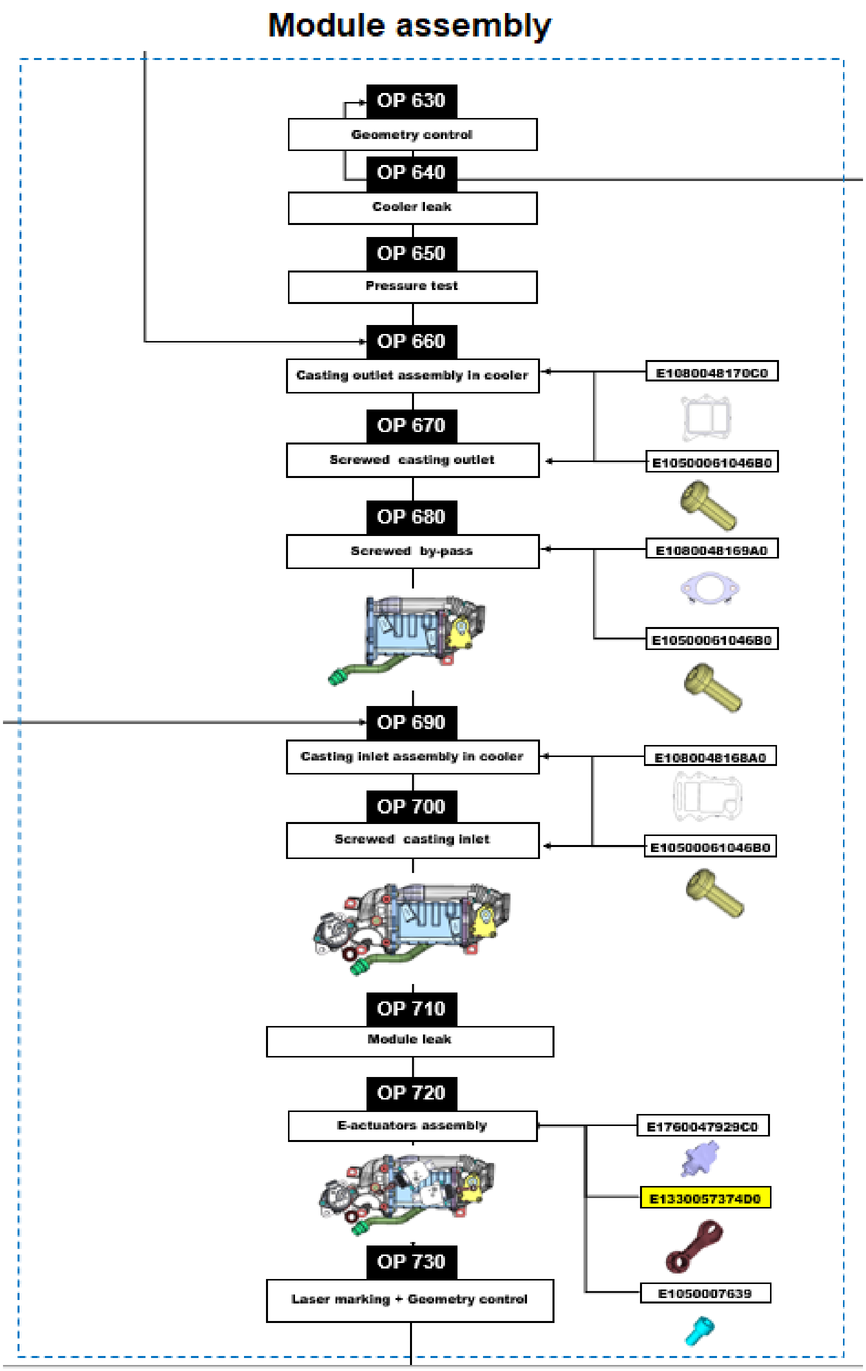


Figure 4.8 - Flow Chart - Module Assembly

In the next chapter (Quality Control & Assurance) it will be analyzed some machines/tools/operations that contribute or have the function to control and assure the quality of the product, so it is important to be aware of the operation code (OPXXX).

Being the flow chart complete, it is approved, and the tooling part of the project starts. In this phase, the manufacturing engineers design the tools to assemble to the machines in order to build the parts. Each tooling is associated with a product or similar products if it shares some parts.

Below it is shown one of the tools and machine (for example terms) responsible for controlling the fulfilment of customer specifications. In this case is the leakage rate of the EGR Module. In this machine (Figure 4.9), there are two screens giving the operator the results of the leak test, made automatically by the tool, fully designed only for this specific "EGR module" product.

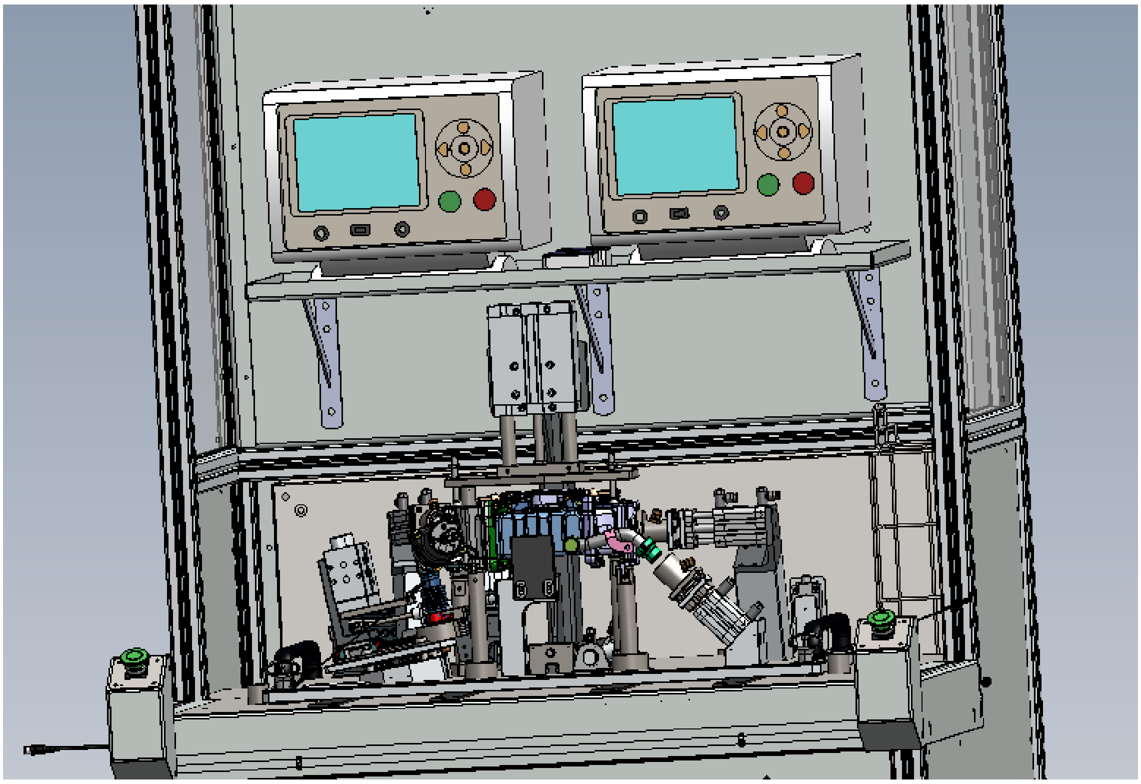


Figure 4.9 - Machine thar measure the Leak Rate of the Module

The tool itself can be seen in more detail in the Figure 4.10 below. There is one important feature about these tool/machine. After the leak test, being an OK part, a DMC (datamatrix) (red circle) is read and these results are associated to this specific sample. This DMC is the identification of the EGR module sample guaranteeing a traceability of the product in the future in case of any problem.

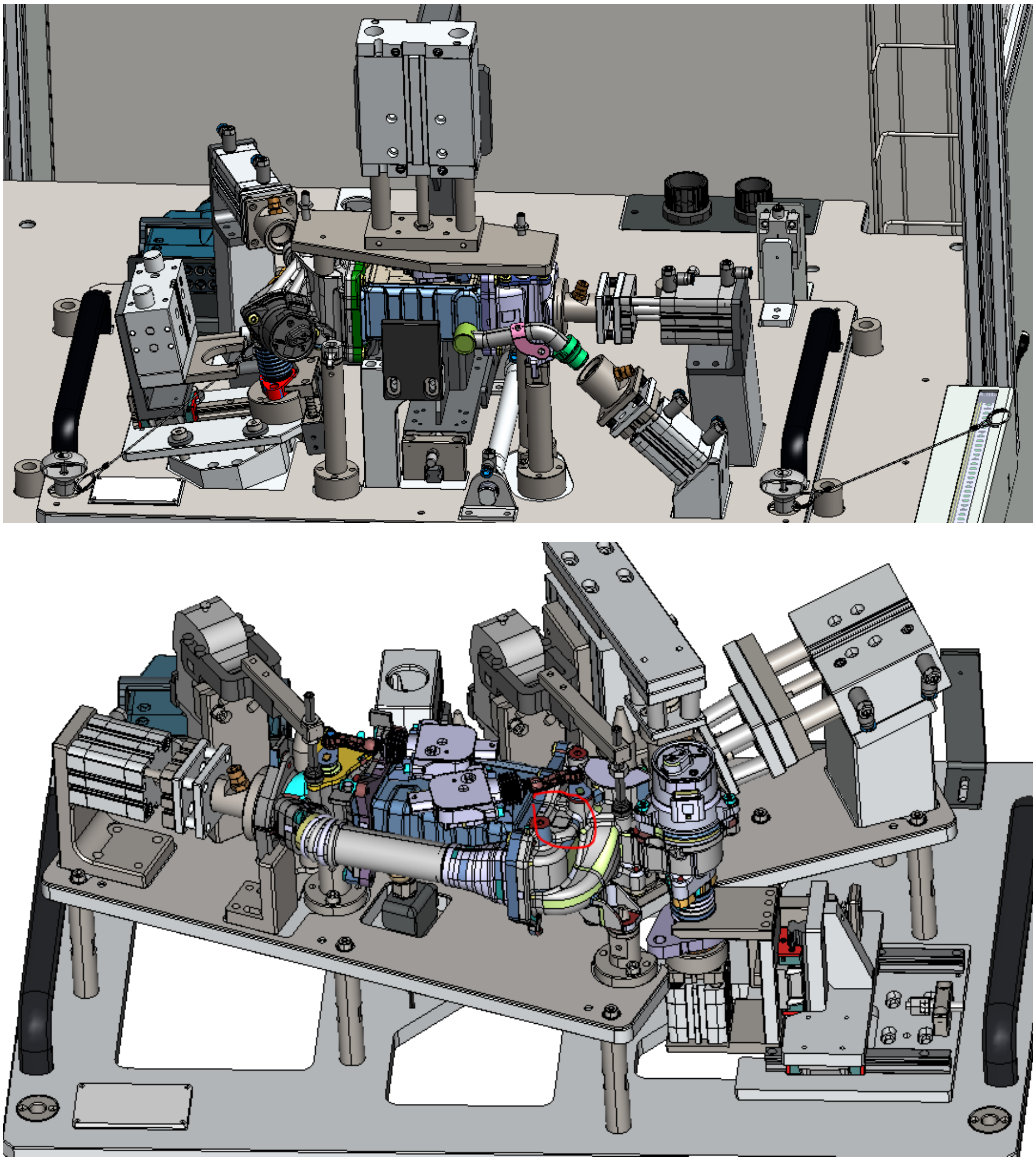


Figure 4.10 - Tooling for this EGR Module model – Datamatrix in the red circle

There is presented one tool/machine of many more of this project. This example is important to understand how complex are these tooling systems and why the production line was designed in a certain way (restrictions or design constraints) in the beginning of the project and now, why and how it changed to the new layout.

First of all, the cooler, hybrid tubes and tubes are assembled in different production lines apart from the module assembly line, mostly because these subparts are shared with other products, being supplied to the main assembly lines by the logistics department. In the figure below, it is possible to see the first layout of the module assembly production line.

One of the methods to design a production line layout is the Lean Design, which has 6 foundations: Safety, Ergonomics, Flexibility, Efficiency, Flow and Investment. Inside these parameters there are multiple characteristics that define if a process is more or less safe, ergonomic... The production line is evaluated to verify if it has these characteristics, resulting in a score (percentage 0-100%) in each foundation. The objective of the Lean Design is to have 100% in each pillar and therefore having a process completely Lean.

This layout (Figure 4.11) was designed to have a cycle time of 80sec with 8 operators working at same time. The outlet and inlet casting assemble worked in two different sections that co-flow to the other part of the final assembly line, where the cooler (already assembled in other production lines and transported by the logistics department) waits to assemble the full module.

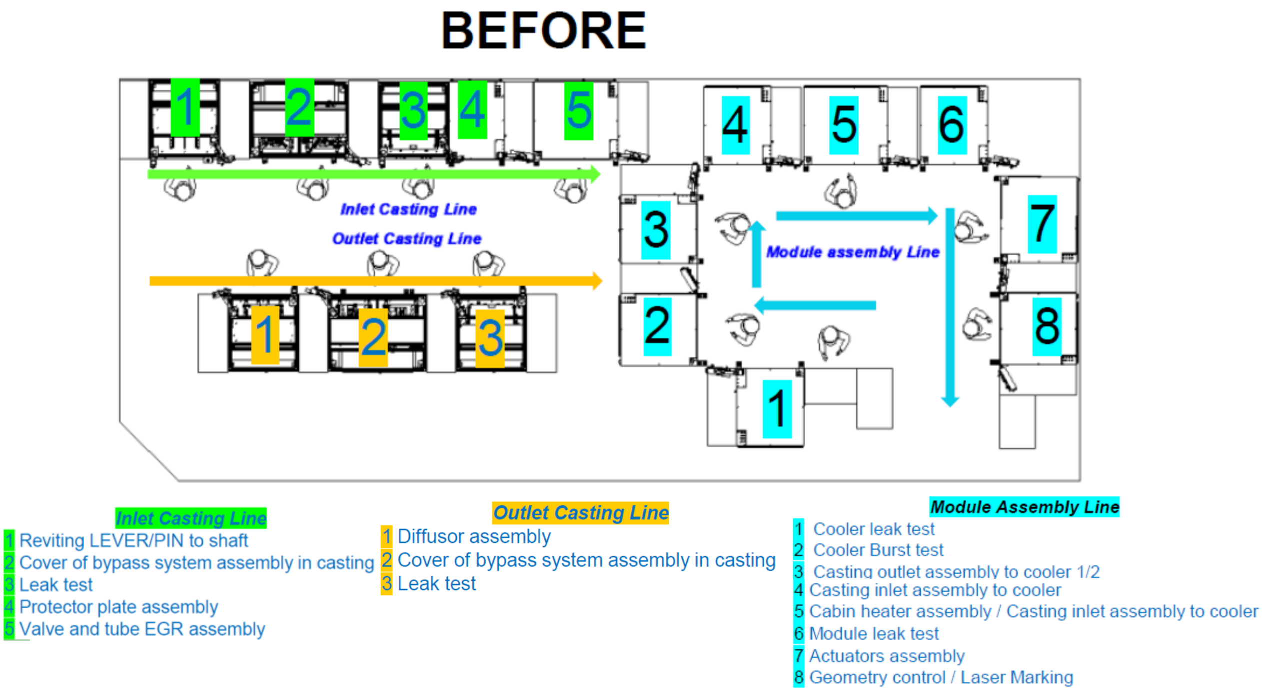


Figure 4.11 - Production Lines Layout Before Upgrade

In terms of Lean design, the first layout had some problems, obtaining a score of 75,0%. Complying at the fullest with the Safety, Ergonomics and Investment factors. In these, all the main characteristic were fulfilled, such as “Operator at workstation is safe”, “Operator at workstation is comfortable / ergonomic” and ”Equipment, packaging, Storage racks and material handling devices are re-usable and reconfigurable”. The other 3 foundations were also evaluated but did not have the desired result: Flexibility with 75%, Efficiency with 78% and Flow with 60%.

These lowest scores are due the default of main characteristics like ”Periodical tasks do not generate flow disruption”, “Only good parts can be passed on to the next step” (one of the reasons why it had to be introduced poka-yokes and other quality controls), “Process is designed for stable conditions to standardized work adherence” and “Process and layout can be easily improved”

Thus, the performance of the line production and the cycle time has to upgrade throughout the project as was already mentioned. The demand of the customer implies significant changes in the final assembly line, expecting 15 operators working at the same time, the desegregation of some operations in the same machine and the layout changing, to be enough to decrease the cycle time by 30sec, from 80sec to 50sec.

The new layout can be seen in the Figure 4.12.

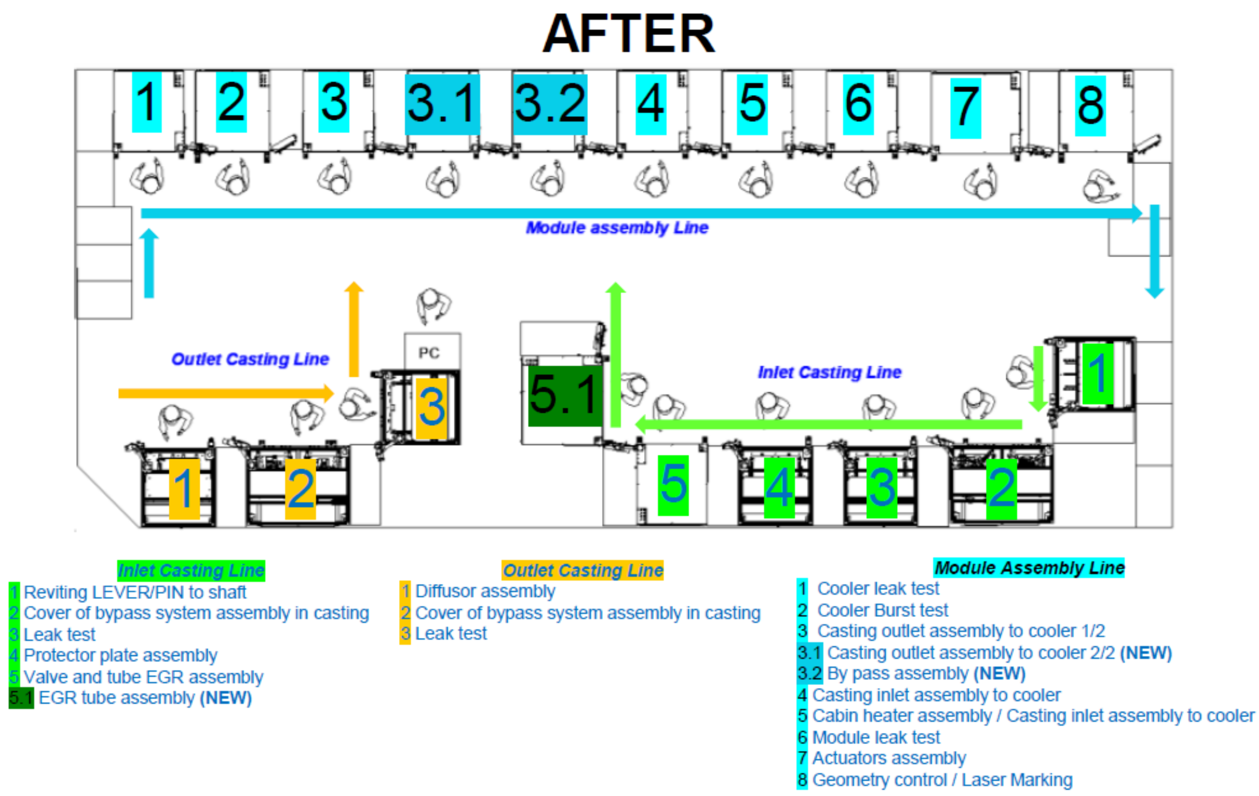


Figure 4.12 - Production Lines Layout After Upgrading

The upgrade had also the objective to increase the Lean Design score, significantly improving the performance of the production line. With these improvements on mind, there were made changes in the layout design and the number of machines/tools was increased. The Lean Design was improved in 4,3%, from 75% to 79,3%, being solved, with this new layout and other methodologies, problems in the Efficiency (78% to 89%), Flexibility(75% to 100%) and Flow (60% to 100%),

In the Efficiency, "Only good parts can be passed on to the next step" was solved, being the only problem encounter currently the periodical tasks that usually affects the flow. This problem has also a plan of resolution for the future, where these periodical tasks will be done during the shifts change and/or days of low product demand. Nevertheless, only good parts will continue in the production line due production line validation after this change and introduction of quality controls, assuring the quality of the final product.

The flexibility factor increased to its maximum due the layout and process improvement and the possibility of building parts after product end of life.

In terms of Flow, it was the factor that increased the most. 40% of improvement are due the separation between processes, introducing 3 more machines/tools and changing the layout, the problem encounter previously ("Process within a production cell is one piece flow") was solved. These new alterations also inducted to a process with more stable conditions to standardized work adherence.

Thus, having some general background in the design and process development, is possible to proceed to a deeper analysis in the subject being study in the project: the automatic validation of technical specifications. An area inside of the process that has its objective knowledge and concepts studied and developed in the product design phase.

5. Automatic Validation of Technical Specifications: Quality Control & Assurance

5.1. Introduction

The automatic validation of technical specifications can be synonymous of quality control and assurance, given the fact that controlling the quality of the final product is validating the customer specifications and it is possible to be done automatically (and it is) in the production line. First of all, was analyzed the developed product (EGR Module), in order to understand "what is", "how it works" and which specifications would be validated and controlled, during its process. In the process phase was seen the operations needed to build a EGR Module, from the raw parts until the final product, comprehending the possibility of introducing mechanisms capable of validating those same specifications.

In this chapter in going to be analyzed the introduction quality control/assurance mechanisms that are responsible for the automatic validations of technical specifications. Will be presented the study necessary for the automation of the production line. The inputs that need to be controlled and validated and the outputs of that same control are the main part of the objective of this academic work. Without the study of which variables are controlled, which mechanisms are going to be used and which outputs will the operator work, the technical part of the production line automation would not be possible. Thus, this chapter will present the preliminary study for the future automation.

5.2. Production Line Quality Assurance

It is necessary to assure the quality of the product during its production. This is one of the main goals of every manufacturer, no matter which field. Like this, the scrap can be reduced, and the reputation of the company/group raises between the possible customers. Thus, there are continuously efforts to optimize the process to a point where the error/failure is reduced to the nullity. One of the techniques to make this possible is introducing Poka-Yokes. They are responsible to reduce non-conformities through potential failure/error elimination, being a method for taking steps to mistake proof a process. It is a foundational tool of both Lean, which targets waste, and Six Sigma, which focuses on defects, with a goal of eliminating every mistake by creating systems that either immediately prevent or detect them. Poke-yoke reduces the waste caused by defects, which can help improve efficiency and save costs in rework or additional processing[44].

Thus, will work as a quality control, given the fact, it ensures the elimination of defects/errors, controlling also technical specifications of the product. In the next part of this chapter, will be presented all the poka-yokes responsible for assuring the quality of the product, fulfilling of all specifications. The production lines analyzed in this subchapter will be the Inlet Casting line, Outlet Casting line and the Module Assembly line. It is specially in these 3 lines that is made the control of specification, therefore quality control.

In the Inlet Casting Line:

- OP500:
    - Mechanical poka-yoke to assure the correct components;
    - Automatic control of pin height after riveting;
- OP560:
    - Mechanical poka-yoke to assure the correct components;
    - Automatic control to assure components presence;
    - Automatic control to assure the correct shaft dimension after riveting;
- OP570:
    - Automatic control to assure only one gasket before assembly;
    - Automatic control to assure the gasket presence;
    - Automatic torque and angle control for each screw;
- OP580:
    - Master parts to assure the correct functionality of leak equipment. The machine automatically forces to pass the master parts each shift, after a maintenance intervention and in each reference change;

- Automatic system to move the flaps simulating the same torque of e actuators for make the leak test between flaps and casting correctly (Figure 5.1);
- Automatic system to move the flaps simulating a lower torque of e-actuators to assure that the by-pass shafts have free movement;

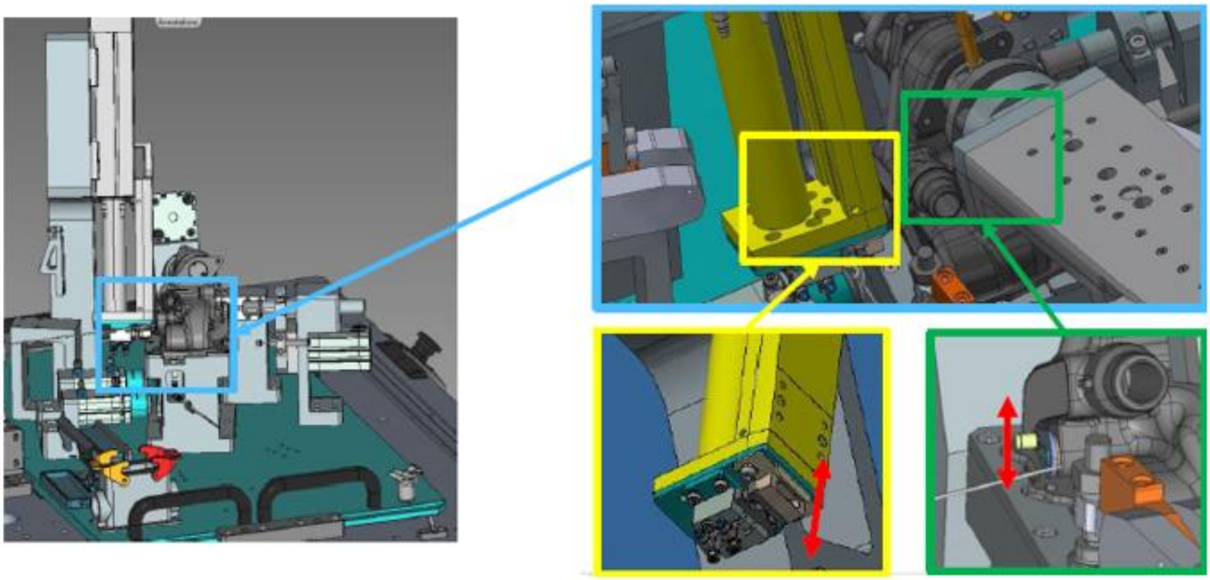


Figure 5.1 - System responsible for moving the flaps and simulate the operation modes

- OP590 & OP600 (Figure 5.2):
  - Automatic poka-yoke to assure the correct position off the poppet before and during assembly (energizing electrically the EGR valve) with this sequence:
    - Check the position of poppet before valve assembly;
    - Check the correct tension value on lock position 4,7 V after valve assembly;
    - Check the valve response time after unlock the valve;
  - Automatic torque and angle control for each screw;
  - Mechanical poka-yoke to assure the EGR tube position;

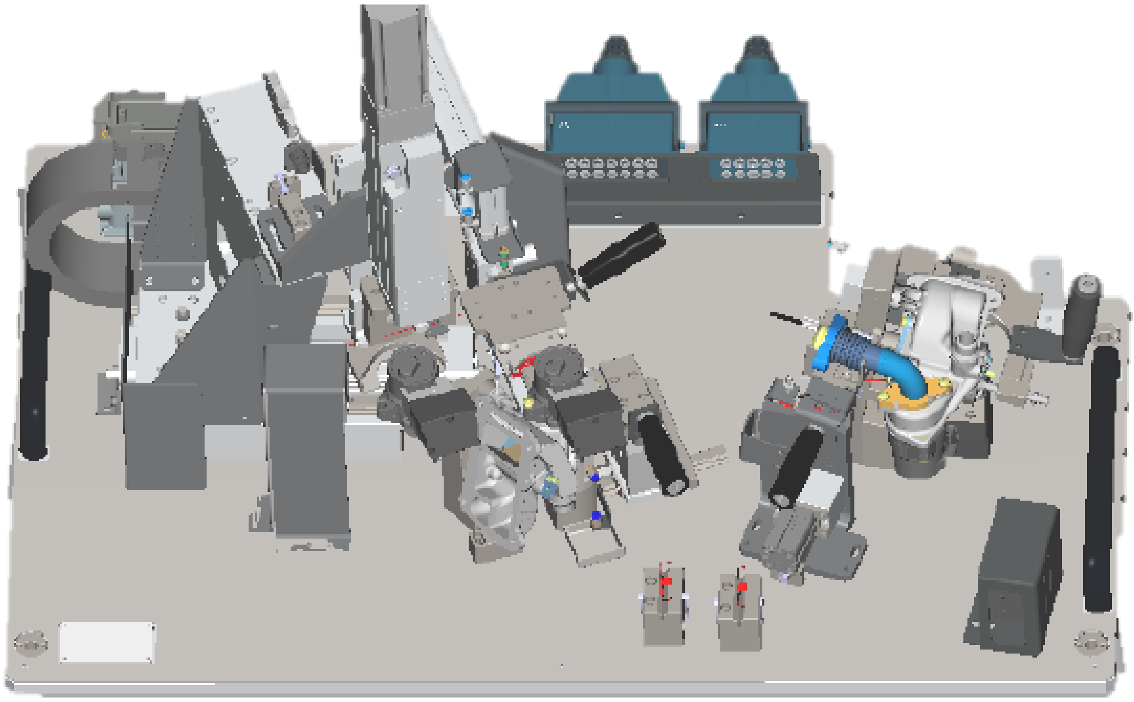


Figure 5.2 - Tooling of the OP590 and OP600

- Automatic control to assure only one gaskets before assembly (Figure 5.3);

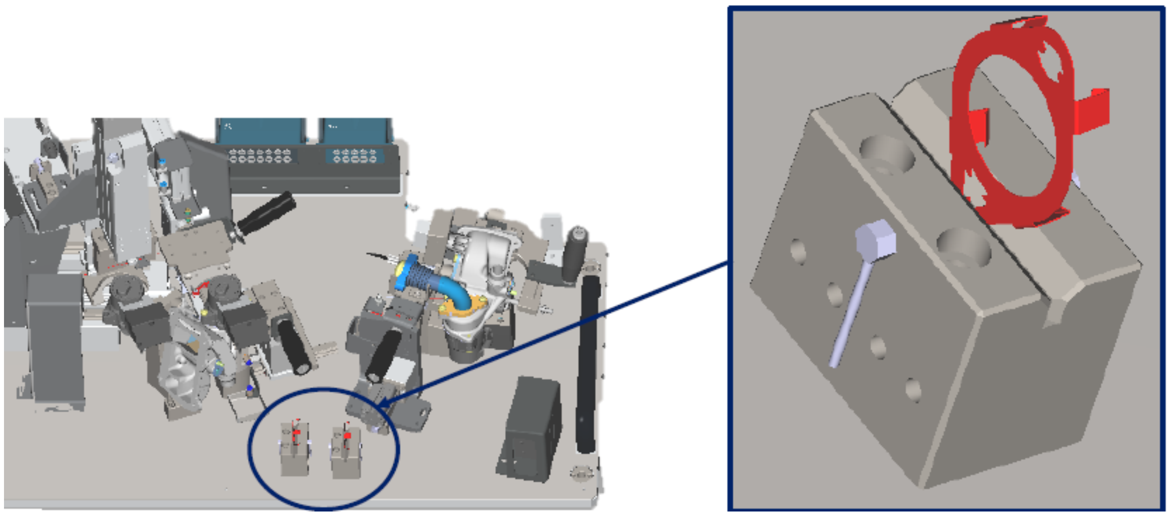


Figure 5.3 - Mechanical Poka-yoke that assure the unity of the gasket

- Mechanical poka-yoke to assure the correct gaskets position (Figure 5.4);
- Automatic controls to assure the gaskets presence and correct position;

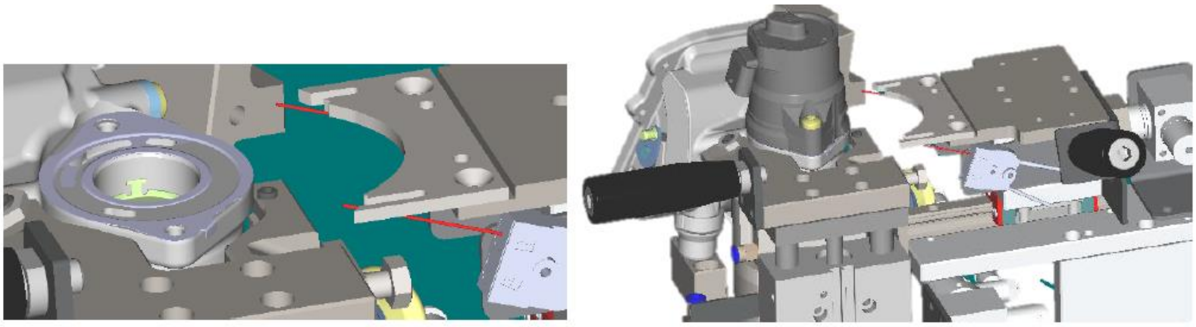


Figure 5.4 - Poka-yokes that assure the correct assemble of parts

Outlet Casting line are present the following poka-yokes:

- OP480 & 510:
  - Mechanical poka-yoke to assure the correct components;
  - Automatic control to assure components presence;
  - Automatic control to assure the correct shaft dimension after riveting;
- OP530:
  - Mechanical poka-yoke to assure the correct components;
  - Automatic control to assure components presence;
- OP550:
  - Automatic control to assure the correct shaft dimension after assembling;
- OP610:
  - Automatic control to assure only one gasket before assembly;
  - Automatic control to assure the gasket presence;
  - Automatic torque and angle control for each screw;
- OP620:
  - Master parts to assure the correct functionality of leak equipment The machine automatically forces to pass the master parts each shift, after a maintenance intervention and in each reference change (Figure 5.5);

  - Automatic system to move the flaps simulating the same torque of e-actuators for make the leak test between flaps casting correctly;
  - Automatic system to move the flaps simulating a lower torque of e-actuators to assure that the by-pass shafts have free movement;

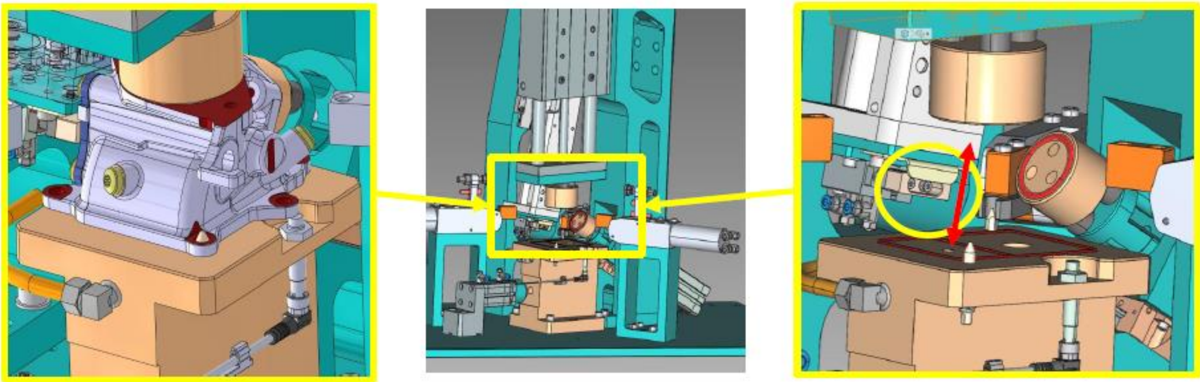


Figure 5.5 - Poka-yoke that assure the correct measure of leak

In the case of the Module Assembly line:

- OP630&640:
  - Automatic control to assure the cooler presence in correct position;
  - Master parts to assure the correct functionality of leak equipment:
    - The machine automatically forces to pass the master parts each shift, after a maintenance intervention and in each reference change;
- OP650:
  - Automatic control to assure the cooler presence in correct position;
  - Mechanical poka-yoke to assure the correct cap to closed the cooler;
  - Master parts to assure the correct functionality of leak equipment. The machine automatically forces to pass the master parts each shift, after a maintenance intervention and in each reference change;
- OP660, OP670 & OP680:
  - Automatic control to assure only one gasket before assembly;

  - Mechanical poka-yoke to assure the correct gaskets position;
  - Automatic control to assure the gaskets and bracket presence;
  - Automatic torque and angle control for each screw;
  - Mechanical poka-yoke to assure the geometry;
- OP690 & OP700:
  - Automatic control to assure only one gasket before assembly;
  - Mechanical poka-yoke to assure the correct gasket position;
  - Automatic control to assure the gasket presence;
  - Automatic torque and angle control for each screw;
  - Mechanical poka-yoke to assure the geometry;
- OP720(in the layout changing, this operation was put before the OP710):
  - Automatic control of laser markings (angle of flaps) to assure the correct;
  - functionality of both e actuators to assure the leak level of flaps;
  - Automatic poka-yoke to assure that the by-pass shafts have free movement (energizing electrically the e actuators applying a lower current);
  - Automatic torque and angle control for each screw;
  - Mechanical poka-yoke to assure the geometry;
- OP710 & OP730:
  - Master parts to assure the correct functionality of leak equipment:
    - The machine automatically forces to pass the master parts each shift, after a maintenance intervention and in each reference change;

The detection and elimination of errors and failures can be made using multiples strategies. There are 5 main types of poka-yokes: position, contact, comparation, counting and checklist.

In these production lines, most of the machines are equipped with cameras responsible for detecting the presence of the correct parts to assemble. There is another mechanism to detect the presence of components using laser sensors that are capable to reach zones that these cameras cannot (most of the times is used to confirm the presence of internal components). There are mechanical poka-yokes present in the components that precludes the assemble of parts wrongly. Also, the specific tooling for each part, creates conditions to assemble the only the correct parts perfectly. Finally, when the process includes screwing there are control of torque, angle and tightening sequence, this advanced poka-yoke is, normally, an ensemble of mechanisms (cameras, force sensors, angles sensors, etc).

5.3. AUTOMATIC PRODUCT VALIDATION: QUALITY CONTROL

In this subchapter, the work is going to reach its climax, given the subject to be presented: Automatic Validation. After comprehending how the production line assure the quality in general (through poka-yokes), it is time to analyze more deeply the quality control of specifications. For understand this matter, was necessary firstly know the product and what technical specifications are going to be validated and controlled. In the first chapter (Product Design and Development: EGR Module) was analyzed the EGR Module and its characteristics, how it was developed, and which parameters have to be controlled. In the second chapter (Product Process and Development: EGR Module) was carried out a study about the process of building this product, being possible to see how many operations are needed and which stations will have the task of validating, being strategically chosen to keep the production flow without breakage without compromising a good control of quality.

Thus, it is going to be analyzed the machines that control automatically technical specifications in the final production line (includes Inlet, Outlet and Module Assembly line). It is going to be presented the machine itself, what it is role and how it does it.

Firstly, following the process flow, the first operation of automatic validation is the OP580 where is tested the leak rate of the inlet sub-assembly and its geometry fulfilment, being after laser marked with a DMC (Datamatrix). The specification analyzed is the leak rate in this component, and it have to be less than 200 ccm (1500L/h) at 600mbar in gas side and 1 ccm at 2,5bar in the coolant side. The tool is presented in Figure 5.6.

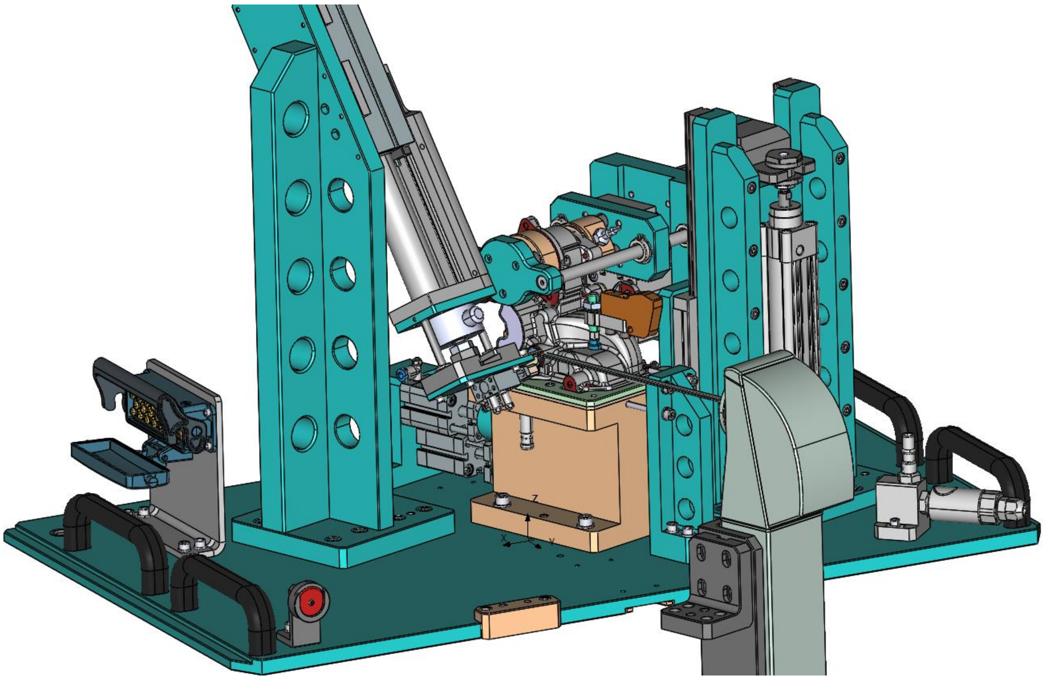


Figure 5.6 - Tooling that measure the Leak of the Inlet Casting

In the Figure 5.7, it is seen how the control of components, in this case, the inlet sub-assembly is made, by the camera.

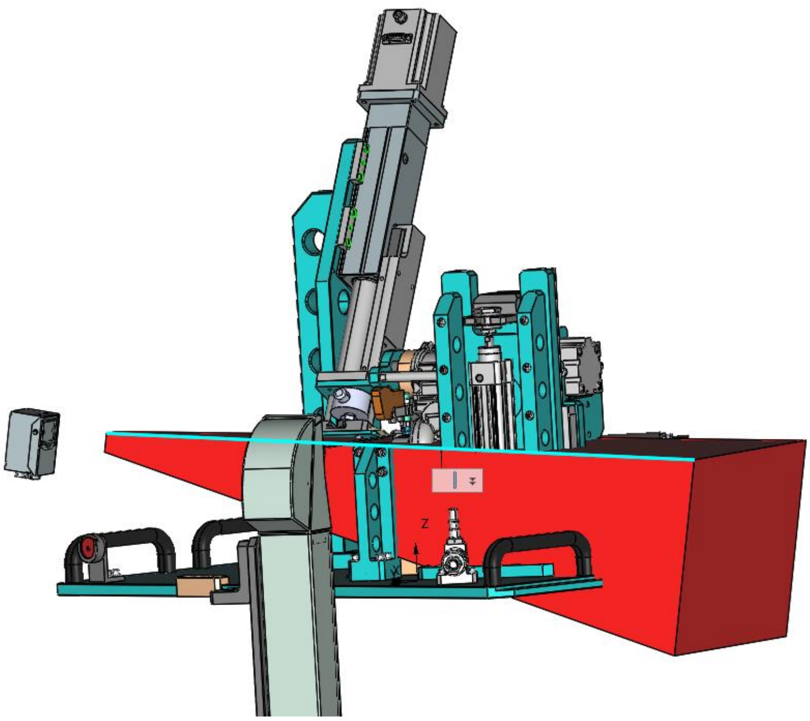


Figure 5.7 – Camera (left) and vision scope (red) that controls the presence and position

The other operation to validate a parameter is the OP620, responsible for the *leak rate test* and *geometry control* in the outlet sub-assembly and posterior laser marking. The specification demanded by the customer is a leak rate less than 200 ccm at 600mbar in gas side and 1 ccm at 2,5bar in the coolant side, basically the same as the inlet sub-assembly. The machine that does the validation is presented in the Figure 5.8.

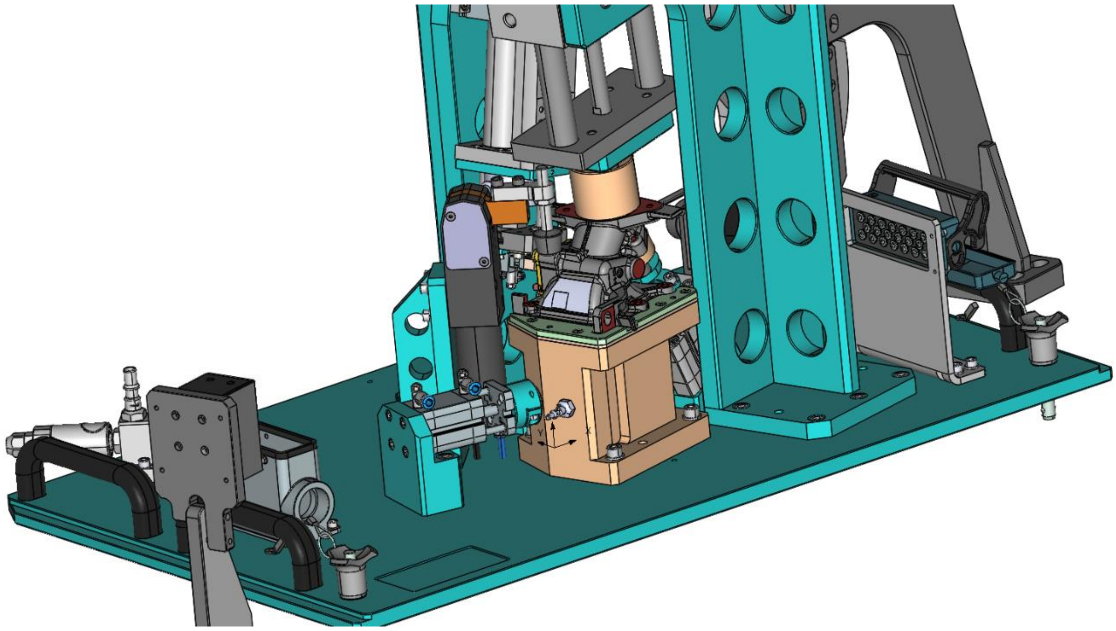


Figure 5.8 - Tooling that measures the leak rate of the Outlet Casting

There is a poka-yoke (camera) to detect the presence of the correct part (Figure 5.9).

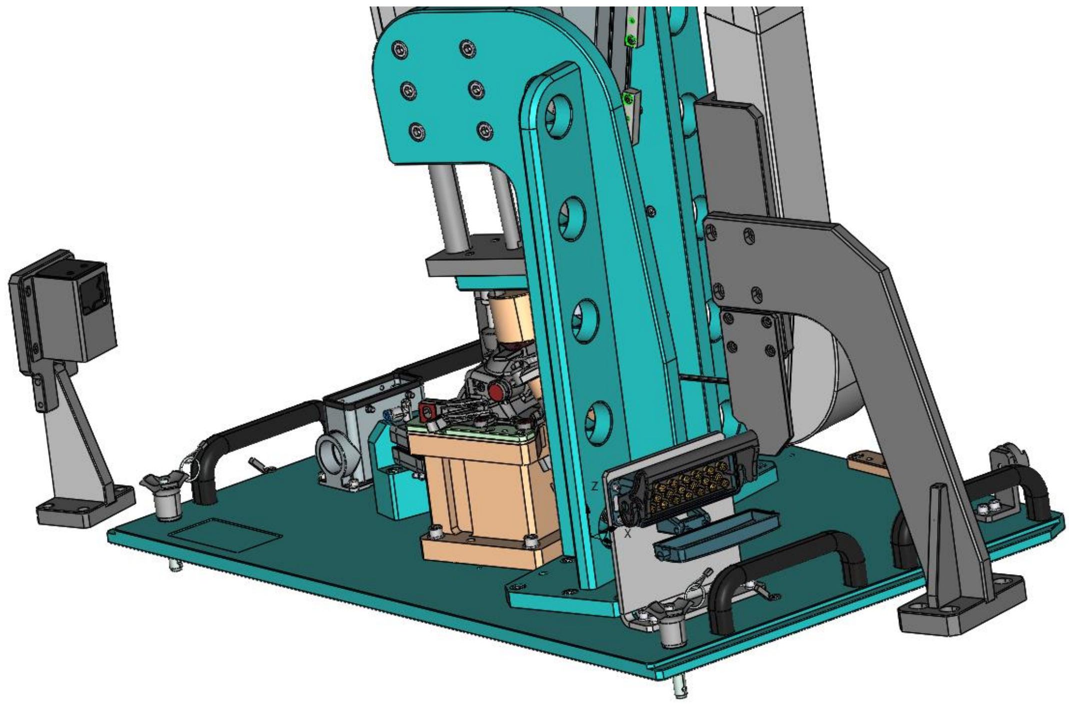


Figure 5.9 - Camera that controls the presence and position

The next operation responsible for validating a technical specification is the OP640, that test the leak rate of the EGR cooler and its geometry. The specification is a leak rate less than 4 ccm at 2,5bar in both gas and coolant side. The machine that does this validation can be seen in the Figure 5.10.

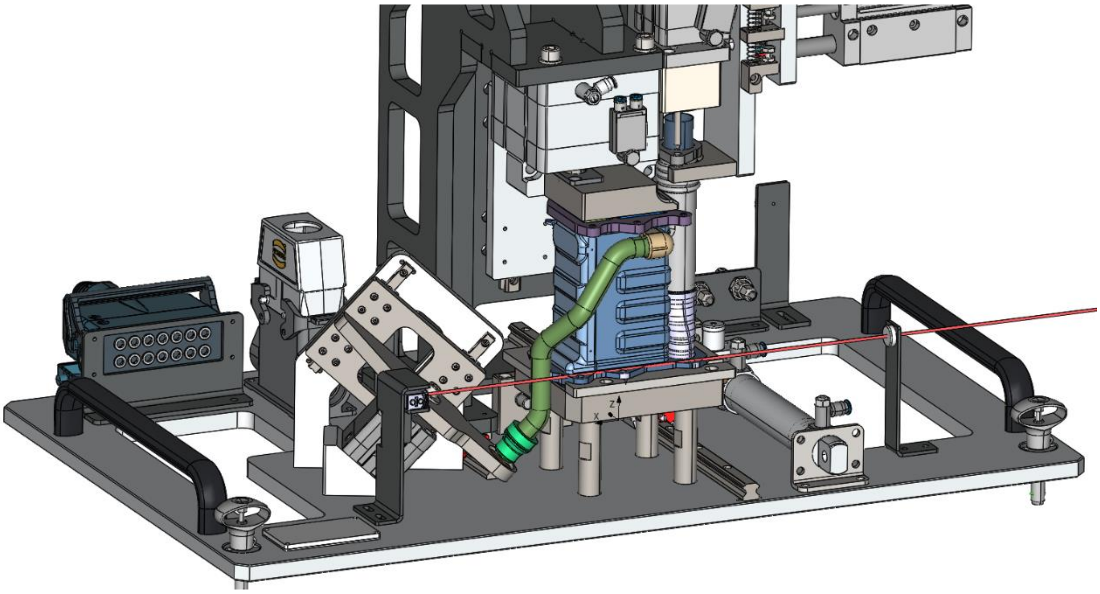


Figure 5.10 - Tooling that measures the leak rate of the Cooler

Different from the other tools, the poka-yoke that detects the presence of the correct cooler and a perfect position for the leak test is not a camera but a laser sensor Figure 5.11.

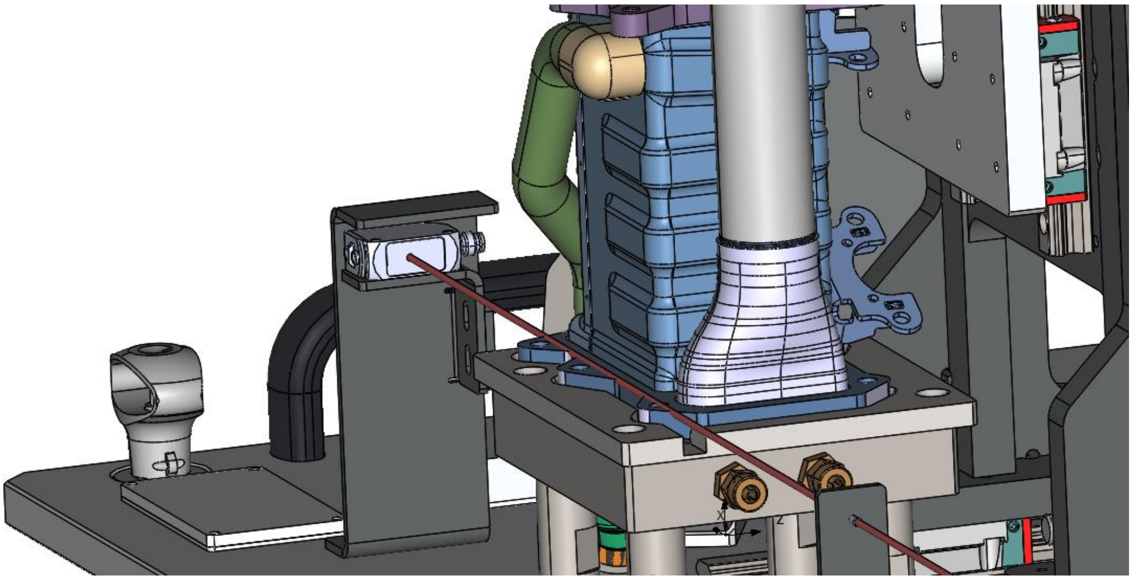


Figure 5.11 - Sensor that controls the presence of the part

Finally, the last operation (OP710) with role of controlling the product quality is one of the process final, and it is made after the assemble of the whole module. It is the EGR Module leak rate test (Figure 5.12). The specification for the module is 600 ccm at 600mbar in the gas side and 4 ccm at 2,5bar in the coolant side.

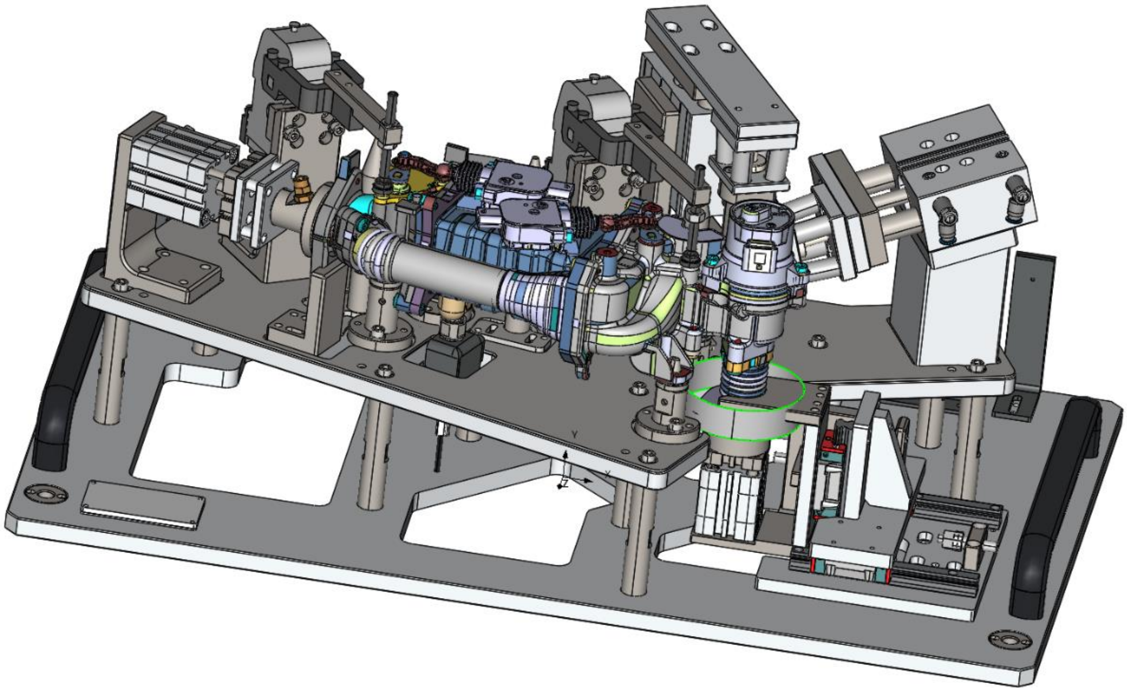


Figure 5.12 - Tooling that measures the leak rat of the whole EGR Module

5.4. Production Line Validation

It was possible to analyze, in the past sub-chapter, which machines/tools are essential for the quality control (fulfillment of specifications). Nevertheless, these machines need to be tested and validated to understand the truthfulness in the given measures. These procedures are imperative to the validation of the production line, therefore to the start of the production. As it was mentioned in the Bibliographic review, the validation of the process may take time, due to several compulsory tests.

Measurement System Analysis (MSAs), Capability and Reproducibility tests, Run@Rate, Final Dimensional Test and Cleanliness Test are the main testing done to validate the product studied in this project (EGR Module). These validation tests are common in the automotive industry, and therefore, some more can be added, depending on the product manufactured.

An MSAs and Capability and Reproducibility tests are done to every tool responsible for a measurement. In this case, the machines presented in the past subchapter will have a MSA each one, due their nature (leak rate test).

In the case of the R@R, is done to the production line itself, measuring the production capacity.

The final Dimensional test and Cleanliness test are done to the parts produced, measuring if the final product is dimensionally “OK”, fulfilling every specification in terms of the interface with the packaging (in this case, the whole engine block) and if the process does not create filings (bigger than a certain specification) in the parts produced, respectively.

A MSA was done to each mode/circuit in the 4 machines previously spoken. It is important to refer that a MSA is done only to tools that measure something (leak rate, length, torque, angle, etc), due to its nature of understand the capacity of the machine to measure correctly and consistently the evaluated feature. The MSA done to these operations had the follow inputs:

- Operators: 3;
- Number of parts measured: 10;
- Measure of each part: 3 times;
- Done to each mode (in case of having it) and/or circuit;
- A certain specification for measure;

For a MSA be successful, there are different parameters that it has to comply with. Firstly, every measure of the inspectors had to be inside of the specification, therefore the measuring system has to be the correct one (in terms of sensibility, capacity, etc). There is an indicator called GRR (Gauge Repeatability & Reproducibility study) that it had an acceptance criteria: If the % Gage R&R is under 10%, the measurement system is generally considered to be an adequate measurement system, between 10 % to 30%, the measurement system may be acceptable for some applications and over 30%, the measurement system is considered to be unacceptable. This indicator is calculated through two other factors obtained by the measuring done. This indicator is the EV (Standard deviation of the measurement system (repeatability)) and the AV (Standard deviation between the operators (reproducibility)). The last indicator that corroborates a MSA study is the NDC (Number of Distinct Categories) and determine the sensitivity of the measuring equipment. The NDC has to be ≥5 to be accepted.

In the Annex A, there will depicted the complete MSAs, in this chapter, only the main results are going to be presented, in the Table 5.1.

Table 5.1 - MSA Results

Operation	Spec	Measures	Correct System	GRR(%)	NDC
OP580 (HP)	1500 L/h	OK	Ok	3,51	40
OP580(LP)	1500 L/h	OK	Ok	2,84	50
OP580(Bypass)	1500 L/h	OK	Ok	3,61	39
OP620(HP)	1500 L/h	OK	Ok	3,01	47
OP620(LP)	1500 L/h	OK	Ok	3,33	42
OP640(Gas)	4 ccm	OK	Ok	9,99	14
OP640(Coolant)	4 ccm	OK	Ok	9,55	15
OP710(Gas)	600 ccm	OK	Ok	0,63	225
OP710(coolant)	4 ccm	OK	Ok	9,81	14

Like this, every MSA was successful, being the process OP640 in both gas and coolant side the most critical ones with values almost outside of the acceptance criteria. This closeness to the edge is due to the nature of the test (high variability of results because of its sensibility).

In terms of the Capability test (Table 5.2), every machine in the production line is submitted to this test. Nevertheless, in this part only is going be considered the tooling analyzed in the last chapter, given the fact that are the ones with interest for this report.

Table 5.2 - Capability Test Results

Operation	Process	Spec/Tolerance	Measurement	Avg	Min	Max	Cpk
580	Leak Inlet (HP)	1500	L/h	894,33	511,78	1478,64	1,18
580	Leak Inlet (Bypass)	1500	L/h	26,25	3,075	1034,25	22,27
580	Leak Inlet (LP)	1500	L/h	973,84	588,79	1463,11	1,19
580	Leak Inlet (Coolant)	1	ccm	0,267	0,036	0,498	1,34

620	Leak Outlet (LP)	1500	L/h	726,23	310,32	1485,73	1,21
620	Leak Outlet (HP)	1500	L/h	541,58	266,70	1534,73	1,28
620	Leak Outlet (Coolant)	1	ccm	0,369	0,015	0,723	1,34
640	Leak Cooler (Gas)	4	ccm	0,47	-0,52	1,94	1,53
640	Leak Cooler (Coolant)	4	ccm	1,05	0,02	3,61	1,88
710	Module Leak (Gas)	600	ccm	33,26	0,01	160,24	1,63
710	Module Leak (Coolant)	4	ccm	-0,79	-1,49	1,34	2,22

This test is important to obtain a Cpk, being this an indicator of how close a process is to perform according to the specification limits and accounting for the natural variability of the process. Bigger the Cpk, less likely is to any part be outside of the tolerances.

Mostly, a good Cpk is over 1,33, nevertheless, this value can be smaller, through customer acceptance. There were some results a little bit unsatisfactory (OP580, both Low-Pressure and High-Pressure modes), but were consider OK by the costumer. In general terms, the results were good, with a lot of tools obtaining a Cpk higher than 1,33.

There is an important note about this test, in the OP580, the mechanisms that measures the Leakage in the Bypass of the Inlet Housing has a Cpk of 22,27, a high value compared with the rest. The reason behind it is the fact of the geometry of this part and its finishing contributes for a good and consistent measurement (in the same OP, but other modes (High Pressure and Low Pressure), the Cpk is lower due to their complexity, the Bypass mode is more simple (flow is more simple, does not have to pass by the hybrid tubes).

A R@R (Run at Rate) was taken in the production line, evaluating its performance, when it comes to fully functional parts produced. The results were satisfactory (Table 5.3, Table 5.4 and Table 5.5), and it can be seen in the table below.

In the Inlet Casting Line:

Table 5.3 - Inlet Casting Line R@R Result

Total Produced	OK Parts	Rework	Scrap
206	196	10	0

From the reworked parts, 9 were due Outside Leak and 1 because of DMC (DataMatrix) reading NOK.

The Outlet Casting Line:

Table 5.4 - Outlet Casting Line R@R Result

Total Produced	OK Parts	Rework	Scrap
213	210	3	0

The 3 parts that needed rework, had the leak issues, 2 in the Low-pressure side and 1 in the High pressure.

In the final assembly line (module):

Table 5.5 - Final Assembly Line R@R Result

Total Produced	OK Parts	Rework	Scrap
195	193	2	0

The 2 parts reworked are due water leakage and poppet seat leakage.

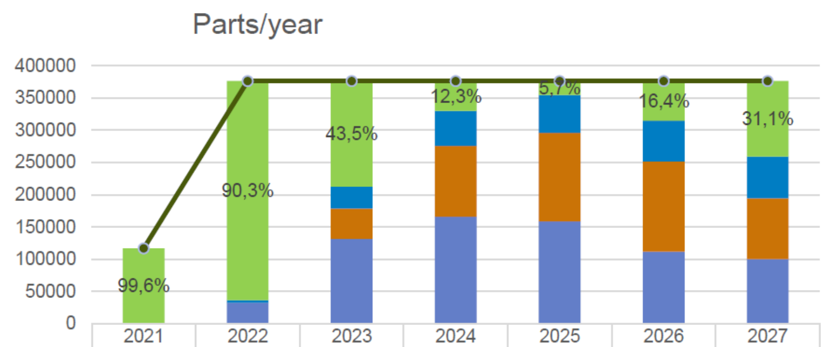
Thus, due this it was possible to understand if the production line, as it was designed, idealized and build, was capable or not to produce parts as requested by the customer. In the data below (Table 5.6) it is possible to see what is expected for the production line, both castings (Figure 5.13) and final assembly lines (Figure 5.14).

Table 5.6 - Conditions of work

Days per Year of Work	~229
Shifts Per Day	3.0
Net Hours per Shift	6.1

Lines	1

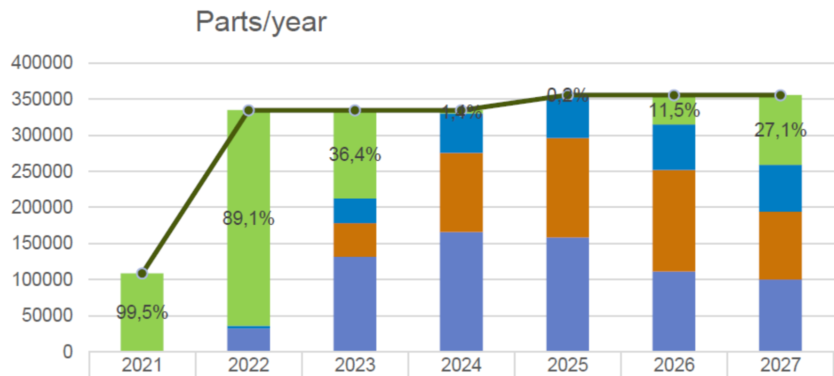
Having these conditions, the performance of the castings in the next years is expected to be:



	2021	2022	2023	2024	2025	2026	2027
Free capacity (%)	116.654	340.109	163.769	46.398	21.632	61.819	117.240
10847		4078	34344	54591	58703	62856	65000
10231			46546	109797	137390	140395	94002
10013	525	32461	131989	165862	158923	111578	100406
Capacity line	117179	376648	376648	376648	376648	376648	376648

Figure 5.13 - Performance of the Casting Production Line

In the case of the final assembly line, with the same conditions:



	2021	2022	2023	2024	2025	2026	2027
Free capacity (%)	108.284	298.259	121.919	4.548	707	40.894	96.315
10847		4078	34344	54591	58703	62856	65000
10231			46546	109797	137390	140395	94002
10013	525	32461	131989	165862	158923	111578	100406
Capacity line	108809	334798	334798	334798	355723	355723	355723

Figure 5.14 - Performance of the Final Assembly Line

The Dimensional test is done firstly to 3 parts produced. All the measures have to be inside of the tolerance (apart from the rest functional characteristics). The dimensions measure and respective results are presented in the Figure 5.15, Figure 5.16, Figure 5.17 and Table 5.7.

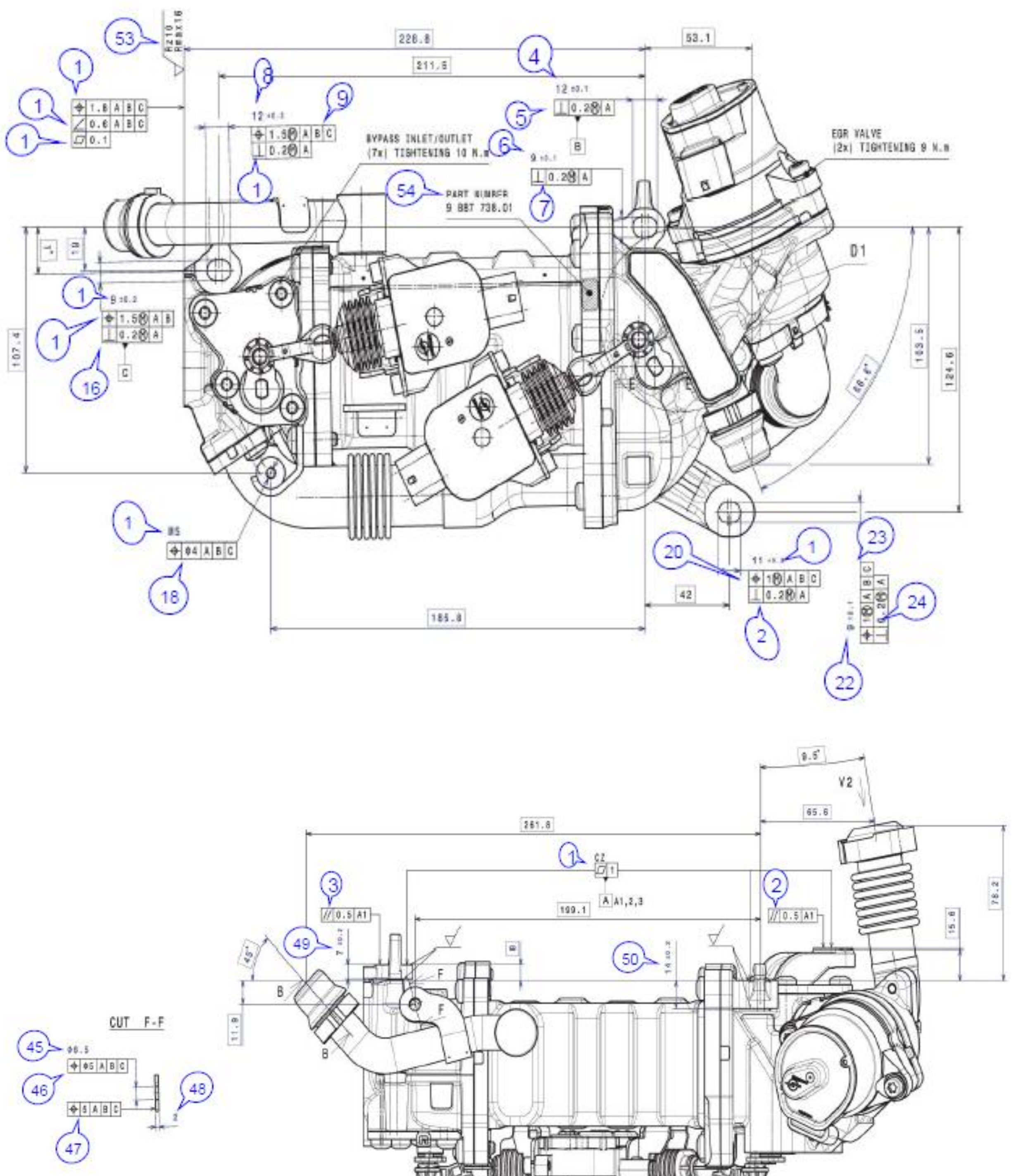


Figure 5.15 - Dimensions Measured (1st part)

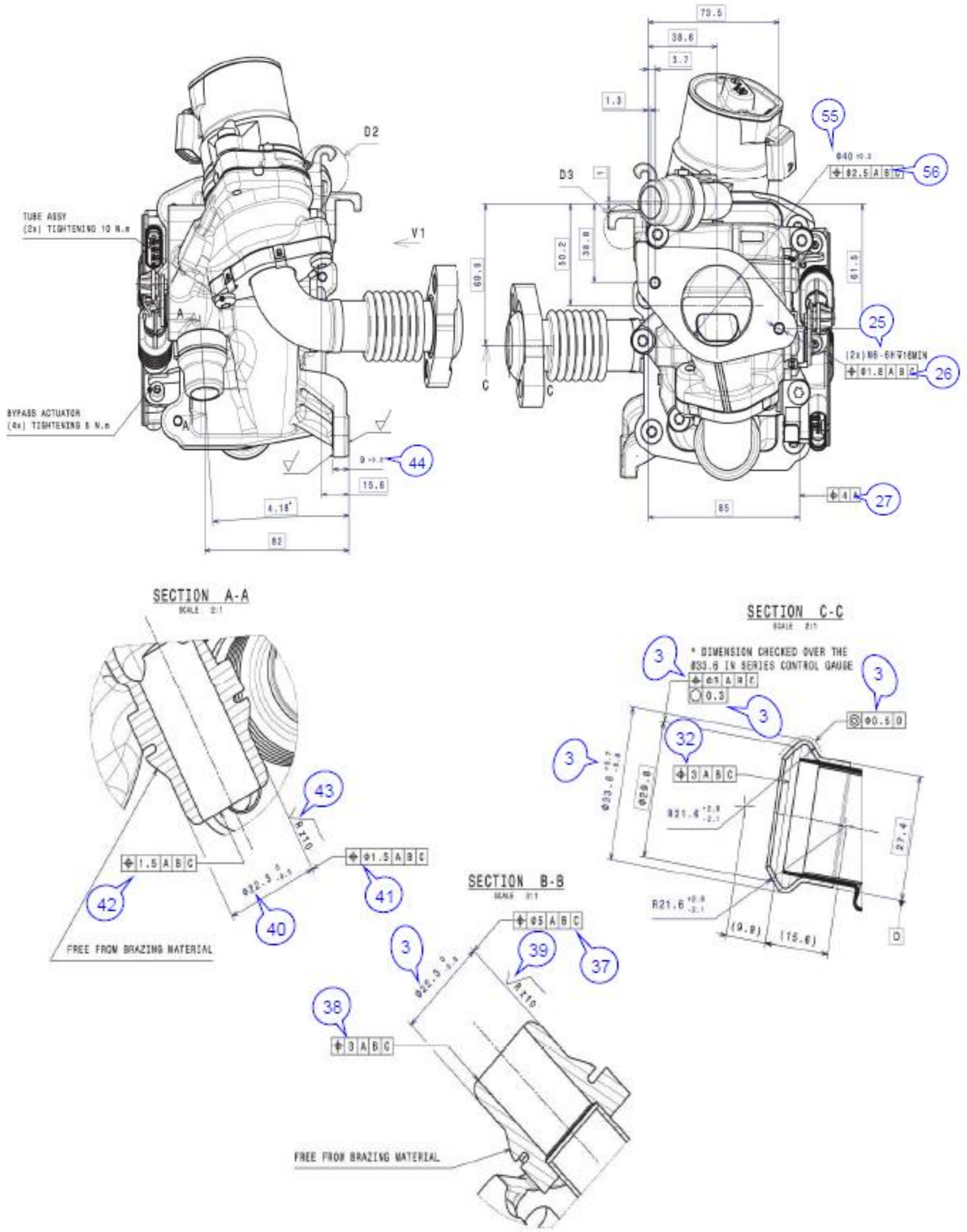


Figure 5.16 - Dimensions Measured (2nd part)

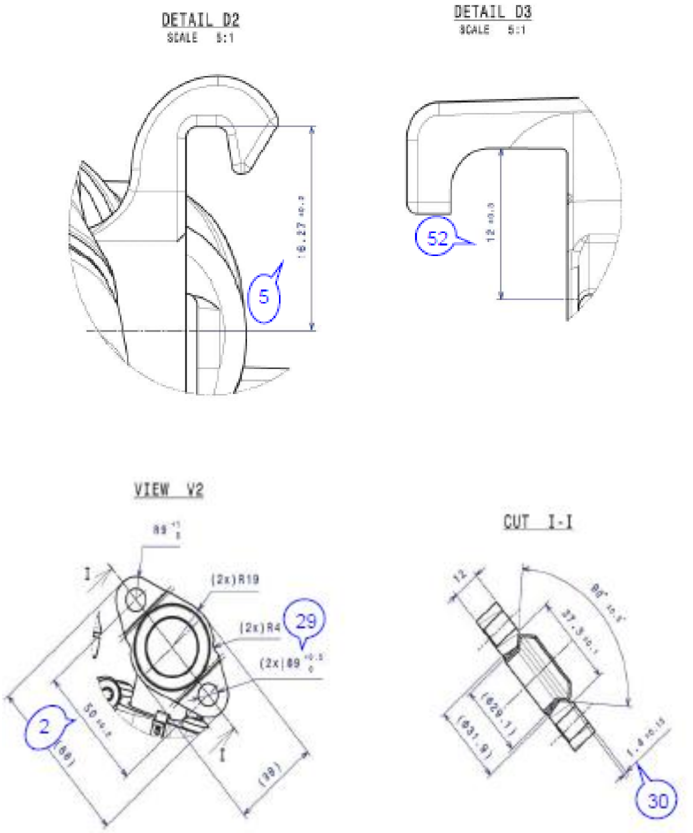


Figure 5.17 - Dimensions Measured (3rd part)

Table 5.7 - Dimensional Report

Ref. No.	Requirements Specifications	Measured data (supplier)			Specifications met	
		PART 01	PART 02	PART 03	Yes	No
1	▱ 1	0.044	0.041	0.048	☒	☐
2	// 0.5 A1	0.045	0.052	0.039	☒	☐
3	// 0.5 A1	0.090	0.077	0.069	☒	☐
4	12 ±0.1	12.049	12.039	12.045	☒	☐
5	⊥ 0.2Ⓜ A	0.007	0.005	0.008	☒	☐
6	9 ±0.1	9.056	9.049	9.051	☒	☐
7	⊥ 0.2Ⓜ A	0.014	0.012	0.017	☒	☐
8	12 ±0.2	12.028	12.031	12.028	☒	☐
9	⌖ 1.5Ⓜ A B C	0.112	0.154	0.136	☒	☐
10	⊥ 0.2Ⓜ A	0.023	0.025	0.021	☒	☐
11	▱ 0.1	0.03	0.05	0.03	☒	☐

12	⌖ 1.8 A B C	0.387	0.411	0.388	☒	☐
13	∠ 0.6 A B C	0.023	0.024	0.027	☒	☐
14	9 ±0.2	9.034	9.031	9.028	☒	☐
15	⌖ 1.5Ⓜ A B C	0.268	0.311	0.289	☒	☐
16	⊥ 0.2Ⓜ A	0.024	0.026	0.022	☒	☐
17	M5	OK	OK	OK	☒	☐
18	⌖ Ø4 A B C	1.131	1.259	1.118	☒	☐
19	11 ±0.2	11.008	11.005	11.003	☒	☐
20	⌖ 1Ⓜ A B C	0.058	0.066	0.063	☒	☐
21	⊥ 0.2Ⓜ A	0.027	0.032	0.029	☒	☐
22	9 ±0.1	9.029	9.017	9.025	☒	☐
23	⌖ 1Ⓜ A B C	0.448	0.523	0.399	☒	☐
24	⊥ 0.2Ⓜ A	0.031	0.041	0.036	☒	☐
25.1	M6-6H ↧16MIN	18.21	18.12	18.26	☒	☐
25.2	M6-6H ↧16MIN	18.52	18.44	18.33	☒	☐
26.1	⌖ Ø1.8 A B C	0.236	0.233	0.254	☒	☐
26.2	⌖ Ø1.8 A B C	0.307	0.283	0.357	☒	☐
27	⌖ 4 A	0.192	0.222	0.158	☒	☐
28	50 ±0.2	50.021	50.018	50.023	☒	☐
29.1	Ø9 +0.5	9.041	9.033	9.037	☒	☐
29.2	Ø9 +0.5	9.033	9.031	9.027	☒	☐
30	1.4 ±0.15	1.378	1.389	1.382	☒	☐
31	◎ Ø0.5 D	0.112	0.106	0.096	☒	☐
32	⌖ 3 A B C	1.683	1.555	1.436	☒	☐
33	⌖ Ø3 A B C	0.739	0.766	0.639	☒	☐
34	○ 0.3	0.048	0.044	0.036	☒	☐
35	Ø33.6 -0.8 / +0.7	33.832	33.861	33.882	☒	☐
36	Ø22.3 -0.3	22.179	22.153	22.173	☒	☐
37	⌖ Ø5 A B C	3.214	3.369	3.247	☒	☐
38	⌖ 3 A B C	1.444	1.285	1.159	☒	☐

39	√Rz10	4.521	3.886	4.113	☒	☐
40	Ø22.3 -0.3	22.124	22.089	22.108	☒	☐
41	⌖ Φ1.5 A B	0.223	0.236	0.254	☒	☐
42	⌖ 1.5 A B C	0.089	0.093	0.101	☒	☐
43	√Rz10	5.412	5.631	5.142	☒	☐
44	9 ±0.2	9.034	9.026	9.039	☒	☐
45	Ø6.5±0.2	6.554	6.541	6.553	☒	☐
46	⌖ Φ5 A B C	2.547	2.369	2.418	☒	☐
47	⌖ 5 A B C	2.698	2.793	2.803	☒	☐
48	2	2.036	2.019	2.023	☒	☐
49	7 ±0.2	7.051	7.044	7.052	☒	☐
50	14 ±0.2	14.049	14.039	14.041	☒	☐
51	16.27 ±0.2	16.311	16.299	16.308	☒	☐
52	12 ±0.3	12.113	12.136	12.154	☒	☐
53	√Rz10 Rmax16	4.23/5.25	4.09/4.83	3.89/4.55	☒	☐
54	PART NUMBE 9 887 738.	9887738.01	9887738.01	9887738.01	☒	☐
55	Ø40 ±0.2	39.902	39.924	39.914	☒	☐
56	⌖ Φ2.5 A B C	0.796	0.808	0.799	☒	☐
57	Initial unit parts group (U.P.G. No.) / Erstverwendungs-Konstruktionsgruppen-Nr	1171	1171	1171	☒	☐
57.1	Trade mark GS91002-A Markenzeichen GS910	BMW	BMW	BMW	☒	☐
57.2	Manufacturing da Herstelldatum	21-07-15	21-07-08	21-07-14	☒	☐
57.3	Supplier name / Lieferantenname	BorgWarner	BorgWarner	BorgWarner	☒	☐
57.4	Part number Sachnummer	8590000	8590000	8590000	☒	☐
57.5	Drawing index Zeichnungsind	08	08	08	☒	☐
57.6	GS91010-2-DM	OK	OK	OK	☒	☐
57.7	Sequencial production number of Produktionszähler des Tages	0001	0001	0003	☒	☐
57.8	Manufacturing coun Herstelland	Portugal	Portugal	Portugal	☒	☐

Obtaining satisfactory results in this report, the dimensional control started to be done at the end of production line, being only measure the dimensions in terms of packaging (engine block). These dimensions can be seen in the Figure 5.18.

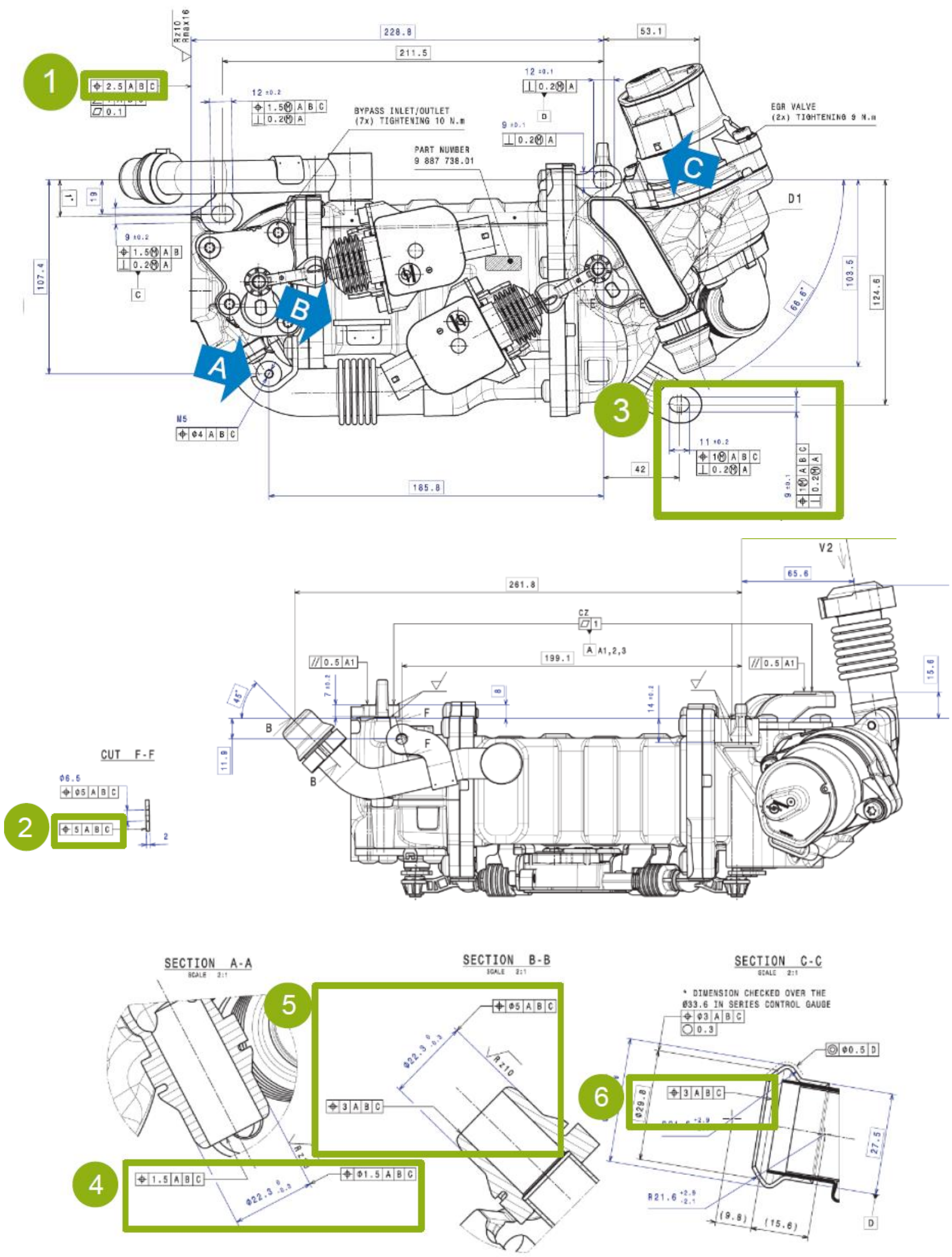


Figure 5.18 - Controlled Dimensions in the Production Line

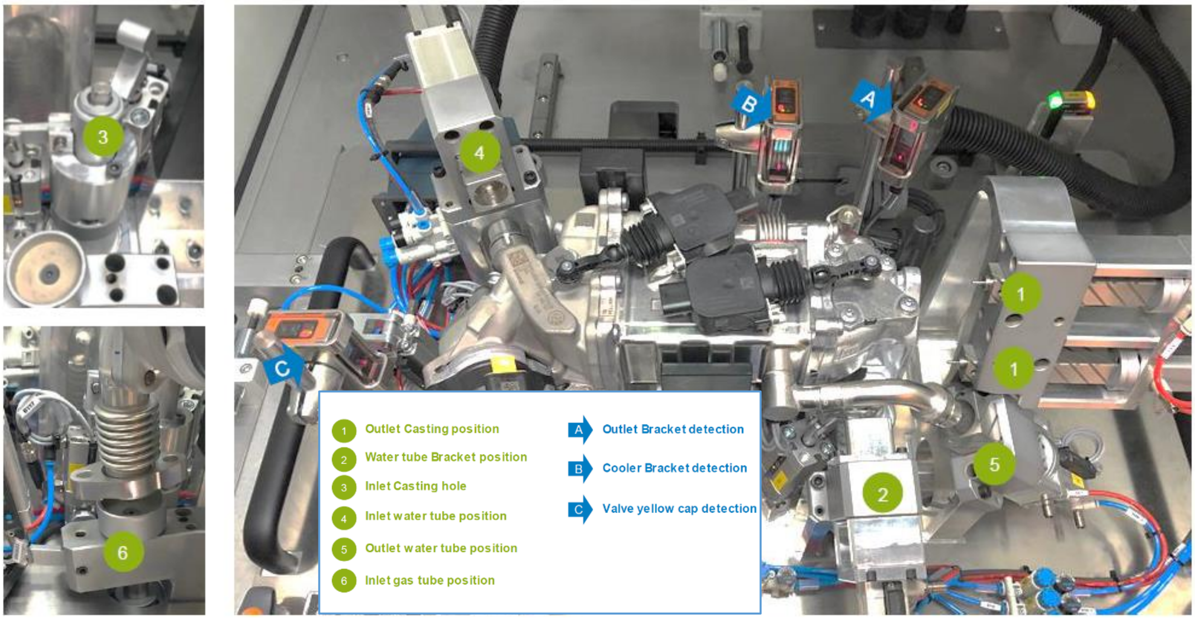


Figure 5.19 - Tooling that does the control

The machine responsible for this geometrical control is presented above (Figure 5.19), and its output below. The control is made automatically (Figure 5.20), and the part validated if every dimension is inside of the inputs (tolerances).

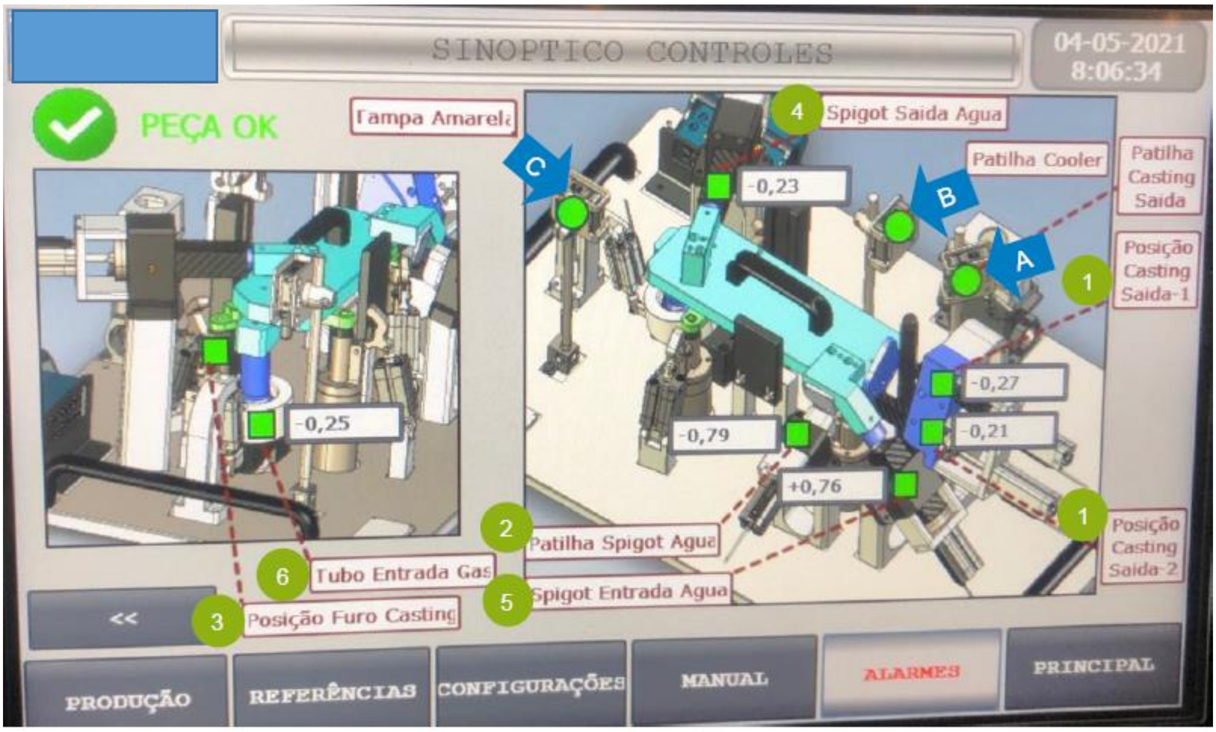


Figure 5.20 - How the results are presented, and the part is validated

The Cleanliness Test was successful. There were tested five complete parts, and they had a specification that permits 45 fillings from 400 μm to 600 μm and if they cannot be bigger than that. The results are in the Table 5.8:

Table 5.8 - Cleanliness Results

Classification By Length	(Particle)			OK	
Weight	Size Limits (μm)	Number	100%	Max Limit	Result
1	100 - 400	2677			OK
1	400 - 600	12		45	OK
1	600 - 1000	0		0	OK
1	> 1000	0		0	OK

Classification By Length	(Reflective, Particle)			OK	
Weight	Size Limits (μm)	Number	100%	Max Limit	Result
1	100 - 400	78			OK
1	400 - 600	5		45	OK
1	600 - 1000	0		0	OK
1	> 1000	0		0	OK

The report given by the laboratory said:

- Maximum particle size found: 596 μm (max. permitted 600 μm)
- Maximum weight of particles permitted is 8mg, being found 2,1mg in 5 parts, being a total of 0,4mg per part;
- Thus, both size and weight are inside of the specification, being this test passed successfully;

Below it is possible to see the two biggest particles found. Both were reflective (metallic) and above 500 of length. First one (Figure 5.21) had a length of 595,56 μm. The second (Figure 5.22) had a length of 509,55 μm.

Figure 5.21 - Biggest Filling found

Figure 5.22 - The second biggest filling

If every test is passed with any kind of problem, being every indicator according to the acceptance criteria, is possible to affirm that these machines are validated, and therefore, be able to start the production in series. There is important thing to keep on mind. In this chapter only were validated the machines that control the quality of the product. To validate the whole production line, every operation from the flow chart has to be submitted to the majority of these tests. The dimensional and cleanliness are the only ones that are made on the final, due to the objective to evaluate the process capacity of produce fully functional parts.

5.5. Future Automation

The 5th chapter analyzes the outputs of the automatic validation of technical specifications, given the fact that are shown how the quality is assured (avoiding the unfulfillment the specifications), controlled (using specific machines that measures the variables previously considered) and finally how the process of build the product and control those same specifications is viable (validating how good it measures and builds). The academic work starts with the design development of the EGR Module where the specifications (inputs) that are going to be analyzed are presented and studied. Then, is shown how the process development, being analyzed how the process of build the product was developed and the fundamentals behind it. With these two firsts parts, was possible to study the automatic validation of technical specifications, namely mechanisms that control the fulfilment of those specifications and classifies the part built (outputs).

Thus, this study was fundamental to understand the process of automate a production line in order to control variables. The implementation of automatisms is a long and complex study to be done was not carried out in this academic work, but all the preparation for it was done during this work. The system is idealized, having the inputs to control, the wanted outputs well defined, how the control will be made, and which mechanisms are going to be used. The next step is to implement sensors, concept and idealize the machines/tools, program the PLCs that controls the machines, etc. To be more understandable, there is a scheme below in the Figure 5.23, that explains the steps of the production line automation and how the study of the automatic validation of technical specification contributes and is indispensable for the future automation.

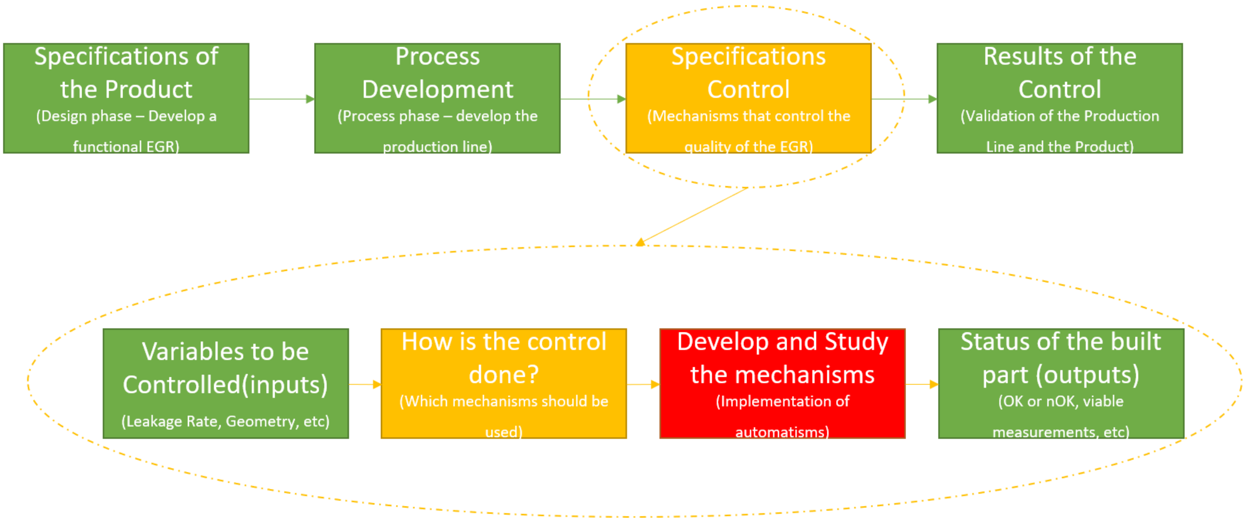


Figure 5.23 - Status of the academic work (green - done; red - not done; yellow - ongoing)

6. Final Considerations

6.1. Conclusion

The study of automatic validation of technical specifications is an area in constant development due the variability of factors that are introduced in every project. Despite the specificity of the studied product, most of these mechanisms are transversal to the automotive industry, and therefore, a lot of strategies are common and can be used in a vast range of products.

Understanding the EGR system and how it is produced lead to a correct development of both design and process. The guideline for the process development is the conception of the product, given the specifications of the product, is idealized a methodology of control, ideally, in an automatic way.

The European Standards for emissions and the awareness for the passenger safety required an important assurance and control of quality, thanks to pursue of improve in those two areas, the first one due to the obligation of the new EURO rules and the second because of the brand desire of have the best quality and security, to be more appealing to the clients.

The solution for the quality assurance of the product was using mechanisms that contributes for the nullity of the error, therefore for the quality of the product. Poka-yokes are the most common ones due to its simplicity and effectiveness. Ideally, if in every operation there were a poka-yoke and no-human interference, that quality of the product would be almost 100% assured. This utopia is not possible (yet), nevertheless it is important to assure and control the quality the best way possible, resorting to machines that validate the final product automatically and to tests that validate the measures and performance of these machines.

The machines responsible for the automatic validation of technical specifications are validated with multiple tests. These tests are the guarantee that the product have a minimum of quality. Logically, if the process that assemble the product is capable and reject every NOK part, the only thing left will be a product with quality, fulfilling every specification given by the client.

In terms of automatic validation process, there is still a long way, this academic work studied and prepared the automation of the production line, analyzing the inputs, possible automatisms to be introduced and in what way this implementation contributes to the product quality. In the process was developed machines directly responsible for validating the specifications being those machines also validated. The theoretical part behind the automation was not studied and could be a future work. The programming of PLCs, introduction of sensors and how the automation works was not possible to be study due to the timeline and the extension of the academic work.

Thus, this project contributed to BorgWarner in the study of the necessary conditions for the implementation of automatisms, and therefore to the automation of the production line. Identifying which variables should be controlled, how the control can be done, which outputs are wanted and how the machines responsible for this control were validated.

6.2. FUTURE DEVELOPMENTS

As mentioned before, this field are in continuously development and because of this, a lot of improvements can be done and should be done. These improvements may be done in the product and process level.

In terms of product, would be ideal if there is created parts with only one way of assembling, like this part of the flexibility of the product will be lost, which does not mean that is something bad or undesirable. This loss of flexibility would also mean loss of variability, and like that more control of the quality of the final product.

In terms of process, there is currently Engineers working only in the increase of the production lines performance. More poka-yokes could be introduced, decreasing exponentially the possibility of an error. These mechanisms would be mostly where there the most occurrence of failures previewed in the FMEA (design and process). Usually, in the automotive area, the production lines work 24h/7days, being the machines/tools submitted an enormous fatigue, thus, a production line validation more often will be an asset, because testing the machines again will provide information about the status of them. Acting consonant the results of the validations (maintenance, substitution, changes for increase the performance, etc).

The main goal and principal future work proposed is the implementation of the automatisms studied in this academic work. The current status is: the process is validated but there is no information about how the automatisms are implemented, given the fact that is a subcontracted company that does this implementation. Thus, in the future should be studied how to implement the mechanisms that validate the specifications, given that in this work was only analyzed how to validate the machines which automatically validates the specifications (process validation).

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ANNEXS

ANNEX A: COMPLETE MSAs

ANNEX A.1: MSA COOLER LEAK TEST (GAS SIDE)

INSPECTOR/		MUESTRA											MEDIA
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	1,30	1,07	0,96	0,74	0,90	0,88	0,94	0,89	0,83	0,94		0,945
2,	2	1,08	1,19	0,90	0,82	0,81	0,92	1,13	0,79	0,78	0,87		0,929
3,	3	1,25	1,07	0,89	0,85	0,89	0,82	1,12	0,79	0,74	0,93		0,935
4,	AVE	1,2	1,1	0,9	0,8	0,9	0,9	1,1	0,8	0,8	0,9	$\bar{X}_a$=	0,9363
5,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_a$=	0,116
6. B	1	1,17	1,06	0,92	0,78	0,85	0,81	1,03	0,85	0,78	0,84		0,909
7,	2	1,29	1,21	0,96	0,81	0,82	0,89	0,98	0,81	0,76	0,88		0,941
8,	3	1,11	1,13	0,90	0,84	0,89	0,78	1,10	0,79	0,79	0,91		0,924
9,	AVE	1,2	1,1	0,9	0,8	0,9	0,8	1,0	0,8	0,8	0,9	$\bar{X}_b$=	0,9247
10,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_b$=	0,091
11. C	1	1,09	1,17	0,98	0,77	0,86	0,86	0,99	0,80	0,79	0,85		0,916
12,	2	1,16	1,09	1,00	0,84	0,90	0,91	1,11	0,85	0,81	0,91		0,958
13,	3	1,25	1,20	0,99	0,79	0,80	0,78	0,97	0,78	0,82	0,88		0,926
14,	AVE	1,2	1,2	1,0	0,8	0,9	0,9	1,0	0,8	0,8	0,9	$\bar{X}_c$=	0,9333
15,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_c$=	0,089
16. PART												$\bar{\bar{X}}$=	0,9314
AVE ($\bar{X}p$)		1,189	1,132	0,944	0,804	0,858	0,850	1,041	0,817	0,789	0,890	R_p=	0,400
17,	($\bar{R}_a + \bar{R}_b + \bar{R}_c$) / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	0,0987
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	0,012
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	0,255
20,	% de medidas fuera de limites de Medias							Tiene que ser >50%					55,56%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}} \times K_1$		Trials	K1	% EV	=	100 (EV/TV)
	=	0.0000 x 0,5908		2	0,8862		=	100(0.0000/0.0001)
	=	0,05829		3	0,5908		=	9,99 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% AV	=	100 (AV/TV)
	=	{(0.000 x 0,5231)^2 - (0.000 ^2/(10 x 3))}^1/2					=	100(0.0000/0.0001)
	=	0,00000	Appraisers	2	3		=	0,00 %
n=piezas		r=repeticiones	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% GRR	=	100 (GRR/TV)
	=	{(0.0000^2 + 0,0000^2)}^1/2					=	100(0.0000/0.0001)
	=	0,05829		Parts	K_3		=	9,99 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0001^2 - 0.0000^2)}^1/2		4	0,4467	% PV	=	100 (PV/TV)
	=	0,58041		5	0,4030		=	100(0.0001/0.0001)
Varición Total (TV)				6	0,3742		=	99,50 %
TV	=	{(LST - LIT)/6}		7	0,3534			
	=	{(0.0003 - -0.0001) /6}		8	0,3375	ndc	=	1.41*(PV/GRR)
	=	0,58333		9	0,3249		≈	14
				10	0,3146	ndc = number of distinct categories		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.2: MSA COOLER LEAK TEST (COOLANT SIDE)

INSPECTOR/		MUESTRA										MEDIA		Análisis de las medidas						% Total Variation (TV)		
REPETICION #		1	2	3	4	5	6	7	8	9	10			Repetibilidad - Variación del Equipo (EV)								
1. A	1	1,20	1,22	1,20	1,10	1,14	1,09	1,06	1,07	0,95	0,99		1,102	EV	=	$\bar{\bar{R}} \times K_1$		Trials	K1	% EV	=	100 (EV/TV)
2,	2	1,27	1,30	1,18	1,09	1,12	1,07	1,07	1,03	0,95	0,93		1,101		=	0.0000 x 0,5908		2	0,8862		=	100(0.0000/0.0000)
3,	3	1,28	1,13	1,07	1,07	1,08	0,99	1,01	0,99	0,91	0,99		1,052		=	0,03978		3	0,5908		=	9,55 %
4,	AVE	1	1	1	1	1	1	1	1	1	1	$\bar{X}_a$=	1,0850	Reproducibilidad - Variación de los Inspectores (AV)								
5,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_a$=	0,081	AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% AV	=	100 (AV/TV)
6. B	1	1,22	1,28	1,21	1,05	1,16	1,01	1,07	1,01	0,98	0,91		1,090		=	{(0.000 x 0,5231)^2 - (0.000 ^2/(10 x 3))}^1/2					=	100(0.0000/0.0000)
7,	2	1,21	1,17	1,15	1,11	1,09	1,00	1,03	1,06	0,96	0,95		1,073		=	0,00000	Appraisers	2	3		=	0,00 %
8,	3	1,19	1,19	1,20	1,09	1,17	1,06	1,07	1,03	0,96	0,96		1,092	n=piezas		r=repeticiones	K_2	0,7071	0,5231			
9,	AVE	1	1	1	1	1	1	1	1	1	1	$\bar{X}_b$=	1,0850	Repetibilidad & Reproducibilidad (R & R)								
10,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_b$=	0,056	GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% GRR	=	100 (GRR/TV)
11. C	1	1,29	1,15	1,17	1,10	1,11	1,10	1,08	1,02	0,93	0,97		1,092		=	{(0.0000^2 + 0.0000^2)}^1/2					=	100(0.0000/0.0000)
12,	2	1,27	1,19	1,10	1,07	1,15	1,09	1,01	1,07	0,91	0,94		1,080		=	0,03978		Parts	K_3		=	9,55 %
13,	3	1,21	1,21	1,13	1,12	1,10	1,00	1,07	0,98	0,96	0,97		1,075	Variación de la Pieza (PV)				2	0,7071			
14,	AVE	1	1	1	1	1	1	1	1	1	1	$\bar{X}_c$=	1,0823	PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
15,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_c$=	0,065		=	{(0.0000^2 - 0.0000^2)}^1/2		4	0,4467	% PV	=	100 (PV/TV)
16. PART												$\bar{\bar{X}}$=	1,0841		=	0,41476		5	0,4030		=	100(0.0000/0.0000)
AVE ($\bar{X}_p$)		1,238	1,204	1,157	1,089	1,124	1,046	1,052	1,029	0,946	0,957	R_p=	0,292	Varición Total (TV)				6	0,3742		=	99,54 %
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	0,0673	TV	=	{(LST - LIT)/6}		7	0,3534			
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	0,003		=	{(0.0002 - -0.0001) /6}		8	0,3375	ndc	=	1.41*(PV/GRR)
19,	$\bar{\bar{R}} \times D_4{}^* = UCL_R$											UCL_R	0,174		=	0,41667		9	0,3249		≈≈	15
20,	% de medidas fuera de limites de Medias							Tiene que ser >50%					55,56%					10	0,3146	ndc = number of distinct categories		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.3: MSA INLET LEAK TEST (HIGH-PRESSURE)

INSPECTOR/		MUESTRA										MEDIA	
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	870	1195	829	1070	997	651	1134	1384	851	1284		1026,500
2,	2	863	1192	822	1063	990	668	1131	1381	868	1281		1025,900
3,	3	862	1194	821	1062	989	660	1133	1383	860	1283		1024,700
4,	AVE	865	1194	824	1065	992	660	1133	1383	860	1283	$\bar{X}_a$=	1025,7000
5,	R	8	3	8	8	8	17	3	3	17	3	$\bar{R}_a$=	7,800
6. B	1	875	1201	835	1076	996	656	1140	1383	856	1283		1030,100
7,	2	871	1191	821	1062	998	676	1130	1389	876	1289		1030,300
8,	3	858	1185	812	1053	997	656	1124	1391	856	1291		1022,300
9,	AVE	868	1192	823	1064	997	663	1131	1388	863	1288	$\bar{X}_b$=	1027,5667
10,	R	17	16	23	23	2	20	16	8	20	8	$\bar{R}_b$=	15,300
11. C	1	882	1208	842	1083	1003	663	1147	1390	863	1290		1037,100
12,	2	853	1180	807	1048	992	651	1119	1386	851	1286		1017,300
13,	3	867	1192	826	1067	994	648	1131	1381	848	1281		1023,500
14,	AVE	867	1193	825	1066	996	654	1132	1386	854	1286	$\bar{X}_c$=	1025,9667
15,	R	29	28	35	35	11	15	28	9	15	9	$\bar{R}_c$=	21,400
16. PART												$\bar{\bar{X}}$=	1026,4111
AVE ($\bar{X}_p$)		866,778	1193,111	823,889	1064,889	995,111	658,778	1132,111	1385,333	858,778	1285,333	R_p=	726,556
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	14,8333
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	1,867
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	38,270
20,	% de medidas fuera de limites de Medias							Tiene que ser >50%					100,00%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}} \times K_1$		Trials	K1	% EV	=	100 (EV/TV)
	=	0.0015 x 0,5908		2	0,8862		=	100(0.0009/0.0250)
	=	8,76353		3	0,5908		=	3,51 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% AV	=	100 (AV/TV)
	=	{(0.002 x 0,5231)^2 - (0.009 ^2/(10 x 3))}^1/2					=	100(0.0000/0.0250)
	=	0,00000	Appraisers	2	3		=	0,00 %
n=piezas		r=repeticiones	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% GRR	=	100 (GRR/TV)
	=	{(0.0009^2 + 0,0000^2)}^1/2					=	100(0.0009/0.0250)
	=	8,76353		Parts	K_3		=	3,51 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0250^2 - 0.0009^2)}^1/2		4	0,4467	% PV	=	100 (PV/TV)
	=	249,84635		5	0,4030		=	100(0.0250/0.0250)
Varición Total (TV)				6	0,3742		=	99,94 %
TV	=	{(LST - LIT)/6}		7	0,3534			
	=	{(0.1500 - 0.0000) /6}		8	0,3375	ndc	=	1.41*(PV/GRR)
	=	250,00000		9	0,3249		≈≈	40
				10	0,3146	ndc = number of distinct categories		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.4: MSA INLET LEAK TEST (LOW-PRESSURE)

INSPECTOR/		MUESTRA											MEDIA
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	4,2	4,5	5,3	5,5	5,1	3,7	4,4	4,5	5,7	4,2		4,710
2,	2	4,1	4,3	5,3	5,7	5,3	3,6	4,1	4,7	6,0	4,0		4,710
3,	3	4,4	4,6	5,7	6,0	5,7	3,9	4,3	5,0	6,2	4,1		4,990
4,	AVE	4	4	5	6	5	4	4	5	6	4	$\bar{X}_a$=	4,8033
5,	R	0	0	0	1	1	0	0	0	1	0	$\bar{R}_a$=	0,390
6. B	1	4,3	4,2	5,6	5,9	5,8	3,5	4,3	4,3	6,1	4,4		4,840
7,	2	4,1	4,4	5,1	5,6	5,4	3,9	4,5	4,6	5,9	4,2		4,770
8,	3	4,2	4,5	5,4	5,1	5,6	3,8	4,5	4,4	6,3	4,5		4,830
9,	AVE	4	4	5	6	6	4	4	4	6	4	$\bar{X}_b$=	4,8133
10,	R	0	0	1	1	0	0	0	0	0	0	$\bar{R}_b$=	0,380
11. C	1	4,2	4,4	5,2	5,3	6,3	3,7	4,6	5,0	6,0	4,0		4,870
12,	2	4,4	4,6	5,5	4,8	5,7	3,5	4,1	4,8	5,8	4,3		4,750
13,	3	4,3	4,3	5,1	5,1	6,4	3,8	4,3	4,4	6,3	4,1		4,810
14,	AVE	4	4	5	5	6	4	4	5	6	4	$\bar{X}_c$=	4,8100
15,	R	0	0	0	1	1	0	1	1	1	0	$\bar{R}_c$=	0,430
16. PART												$\bar{\bar{X}}$=	4,8089
AVE ($\bar{X}p$)		4,244	4,422	5,356	5,444	5,700	3,711	4,344	4,633	6,033	4,200	R_p=	2,322
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	0,4000
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	0,010
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	1,032
20,	% de medidas fuera de limites de Medias								Tiene que ser >50%				67,78%

Análisis de las medidas							% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)									
EV	=	$\bar{\bar{R}} \times K_1$			Trials	K1	% EV	=	100 (*EV*/*TV*)
	=	0.0000 x 0,5908			2	0,8862		=	100(0.0000/0.0008)
	=	0,23632			3	0,5908		=	2,84 %
Reproducibilidad - Variación de los Inspectores (AV)									
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$					% AV	=	100 (*AV*/*TV*)
	=	{(0.000 x 0,5231)^2 - (0.000 ^2/(10 x 3))}^1/2						=	100(0.0000/0.0008)
	=	0,00000		Appraisers	2	3		=	0,00 %
n=piezas		*r=repeticiones*		K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)									
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$					% GRR	=	100 (*GRR*/*TV*)
	=	{(0.0000^2 + 0,0000^2)}^1/2						=	100(0.0000/0.0008)
	=	0,23632			Parts	K_3		=	2,84 %
Variación de la Pieza (PV)					2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$			3	0,5231			
	=	{(0.0008^2 - 0.0000^2)}^1/2			4	0,4467	% PV	=	100 (*PV*/*TV*)
	=	8,32998			5	0,4030		=	100(0.0008/0.0008)
Varición Total (TV)					6	0,3742		=	99,96 %
TV	=	{(*LST* - LIT)/6}			7	0,3534			
	=	{(0.0050 - 0.0000) /6}			8	0,3375	ndc	=	1.41*(*PV*/*GRR*)
	=	8,33333			9	0,3249		≈≈	50
					10	0,3146	*ndc = number of distinct categories*		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.5: MSA INLET LEAK TEST (BYPASS)

INSPECTOR/		MUESTRA											MEDIA
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	923	1196	882	1123	1050	1257	1135	1385	1457	1285		1169,300
2,	2	917	1195	876	1117	1044	1261	1134	1384	1461	1284		1167,300
3,	3	911	1197	870	1111	1038	1267	1136	1386	1467	1286		1166,900
4,	AVE	917	1196	876	1117	1044	1262	1135	1385	1462	1285	$\bar{X}_a$=	1167,8333
5,	R	12	2	12	12	12	10	2	2	10	2	$\bar{R}_a$=	7,600
6. B	1	929	1202	888	1129	1056	1263	1141	1391	1463	1291		1175,300
7,	2	914	1192	873	1114	1041	1258	1131	1381	1458	1281		1164,300
8,	3	920	1206	879	1120	1047	1276	1145	1395	1476	1295		1175,900
9,	AVE	921	1200	880	1121	1048	1266	1139	1389	1466	1289	$\bar{X}_b$=	1171,8333
10,	R	15	14	15	15	15	18	14	14	18	14	$\bar{R}_b$=	15,200
11. C	1	914	1187	873	1114	1041	1248	1126	1376	1448	1276		1160,300
12,	2	921	1199	880	1121	1048	1265	1138	1388	1465	1288		1171,300
13,	3	927	1213	886	1127	1054	1283	1152	1402	1483	1302		1182,900
14,	AVE	921	1200	880	1121	1048	1265	1139	1389	1465	1289	$\bar{X}_c$=	1171,5000
15,	R	13	26	13	13	13	35	26	26	35	26	$\bar{R}_c$=	22,600
16. PART												$\bar{\bar{X}}$=	1170,3889
AVE ($\bar{X}p$)		919,556	1198,556	878,556	1119,556	1046,556	1264,222	1137,556	1387,556	1464,222	1287,556	R_p=	585,667
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	15,1333
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	4,000
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	39,044
20,	% de medidas fuera de limites de Medias								Tiene que ser >50%				100,00%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}} \times K_1$		Trials	K1	% EV	=	100 (EV/TV)
	=	0.0015 x 0,5908		2	0,8862		=	100(0.0009/0.0250)
	=	8,94077		3	0,5908		=	3,58 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% AV	=	100 (AV/TV)
	=	{(0.004 x 0,5231)^2 - (0.009 ^2/(10 x 3))}^1/2					=	100(0.0001/0.0250)
	=	1,30903	Appraisers	2	3		=	0,52 %
n=piezas		r=repeticiones	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% GRR	=	100 (GRR/TV)
	=	{(0.0009^2 + 0,0001^2)}^1/2					=	100(0.0009/0.0250)
	=	9,03609		Parts	K_3		=	3,61 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0250^2 - 0.0009^2)}^1/2		4	0,4467	% PV	=	100 (PV/TV)
	=	249,83664		5	0,4030		=	100(0.0250/0.0250)
Varición Total (TV)				6	0,3742		=	99,93 %
TV	=	{(LST - LIT)/6}		7	0,3534			
	=	{(0.1500 - 0.0000) /6}		8	0,3375	ndc	=	1.41*(PV/GRR)
	=	250,00000		9	0,3249		≈≈	39
				10	0,3146	ndc = number of distinct categories		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.6: MSA OUTLET LEAK TEST (HIGH-PRESSURE)

INSPECTOR/		MUESTRA										MEDIA	
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	1556	1375	1272	974	1250	1457	1244	995	960	952		1203,500
2,	2	1564	1382	1264	979	1278	1449	1250	991	971	961		1208,900
3,	3	1553	1379	1249	980	1265	1447	1250	992	974	966		1205,500
4,	AVE	1558	1379	1262	978	1264	1451	1248	993	968	960	$\bar{X}_a$=	1205,9667
5,	R	11	7	23	6	28	10	6	4	14	14	$\bar{R}_a$=	12,300
6. B	1	1559	1383	1252	982	1160	1452	1255	1011	966	954		1197,400
7,	2	1557	1378	1259	978	1183	1445	1248	1004	970	960		1198,200
8,	3	1560	1374	1263	973	1179	1458	1253	999	975	957		1199,100
9,	AVE	1559	1378	1258	978	1174	1452	1252	1005	970	957	$\bar{X}_b$=	1198,2333
10,	R	3	9	11	9	23	13	7	12	9	6	$\bar{R}_b$=	10,200
11. C	1	1562	1380	1260	976	1204	1450	1247	995	961	965		1200,000
12,	2	1555	1378	1268	979	1195	1448	1252	1006	969	960		1201,000
13,	3	1560	1381	1271	982	1220	1451	1252	1020	973	963		1207,300
14,	AVE	1559	1380	1266	979	1206	1450	1250	1007	968	963	$\bar{X}_c$=	1202,7667
15,	R	7	3	11	6	25	3	5	25	12	5	$\bar{R}_c$=	10,200
16. PART												$\bar{\bar{X}}$=	1202,3222
AVE ($\bar{X}_p$)		1558,444	1378,889	1262,000	978,111	1214,889	1450,778	1250,111	1001,444	968,778	959,778	R_p=	598,667
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	10,9000
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	7,733
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	28,122
20,	% de medidas fuera de limites de Medias							Tiene que ser >50%					97,78%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}} \times K_1$		Trials	K1	% *EV*	=	100 (*EV*/*TV*)
	=	0.0011 x 0,5908		2	0,8862		=	100(0.0006/0.0250)
	=	6,43972		3	0,5908		=	2,58 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% *AV*	=	100 (*AV*/*TV*)
	=	{(0.008 x 0,5231)^2 - (0.006 ^2/(10 x 3))}^1/2					=	100(0.0004/0.0250)
	=	3,87068	Appraisers	2	3		=	1,55 %
n=piezas		*r=repeticiones*	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% *GRR*	=	100 (*GRR*/*TV*)
	=	{(0.0006^2 + 0.0004^2)}^1/2					=	100(0.0008/0.0250)
	=	7,51347		Parts	K_3		=	3,01 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0250^2 - 0.0008^2)}^1/2		4	0,4467	% *PV*	=	100 (*PV*/*TV*)
	=	249,88707		5	0,4030		=	100(0.0250/0.0250)
Varición Total (TV)				6	0,3742		=	99,95 %
TV	=	{(*LST* - LIT)/6}		7	0,3534			
	=	{(0.1500 - 0.0000) /6}		8	0,3375	ndc	=	1.41*(*PV*/*GRR*)
	=	250,00000		9	0,3249		≈≈	47
				10	0,3146	*ndc = number of distinct categories*		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.7: MSA OUTLET LEAK TEST (LOW-PRESSURE)

INSPECTOR/		MUESTRA											MEDIA
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	536	1312	433	1493	1043	539	498	349	588	347		713,800
2,	2	543	1294	434	1488	1034	557	502	354	590	346		714,200
3,	3	531	1290	437	1499	1023	558	500	353	595	342		712,800
4,	AVE	537	1299	435	1493	1033	551	500	352	591	345	$\bar{X}_a$=	713,6000
5,	R	12	22	4	11	20	19	4	5	7	5	$\bar{R}_a$=	10,900
6. B	1	535	1293	435	1490	1030	547	509	355	593	343		713,000
7,	2	541	1300	440	1494	1026	541	501	350	589	340		712,200
8,	3	539	1302	439	1499	1038	550	504	352	590	348		716,100
9,	AVE	538	1298	438	1494	1031	546	505	352	591	344	$\bar{X}_b$=	713,7667
10,	R	6	9	5	9	12	9	8	5	4	8	$\bar{R}_b$=	7,500
11. C	1	440	1298	439	1488	1020	559	499	351	598	346		703,800
12,	2	433	1295	442	1491	999	542	506	353	592	341		699,400
13,	3	437	1310	435	1497	1005	550	508	355	589	340		702,600
14,	AVE	437	1301	439	1492	1008	550	504	353	593	342	$\bar{X}_c$=	701,9333
15,	R	7	15	7	9	21	17	9	4	9	6	$\bar{R}_c$=	10,400
16. PART												$\bar{\bar{X}}$=	709,7667
AVE ($\bar{X}p$)		503,889	1299,333	437,111	1493,222	1024,222	549,222	503,000	352,444	591,556	343,667	R_p=	1149,556
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	9,6000
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	11,833
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	24,768
20,	% de medidas fuera de limites de Medias							Tiene que ser >50%					100,00%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}}$ x K_1		Trials	K1	% EV	=	100 (EV/TV)
	=	0.0010 x 0,5908		2	0,8862		=	100(0.0006/0.0250)
	=	5,67168		3	0,5908		=	2,27 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% AV	=	100 (AV/TV)
	=	{(0.012 x 0,5231)^2 - (0.006 ^2/(10 x 3))}^1/2					=	100(0.0006/0.0250)
	=	6,10279	Appraisers	2	3		=	2,44 %
n=piezas		r=repeticiones	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% GRR	=	100 (GRR/TV)
	=	{(0.0006^2 + 0,0006^2)}^1/2					=	100(0.0008/0.0250)
	=	8,33139		Parts	K_3		=	3,33 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0250^2 - 0.0008^2)}^1/2		4	0,4467	% PV	=	100 (PV/TV)
	=	249,86114		5	0,4030		=	100(0.0250/0.0250)
Varición Total (TV)				6	0,3742		=	99,94 %
TV	=	{(LST - LIT)/6}		7	0,3534			
	=	{(0.1500 - 0.0000) /6}		8	0,3375	ndc	=	1.41*(PV/GRR)
	=	250,00000		9	0,3249		≈	42
				10	0,3146	ndc = number of distinct categories		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.8: MSA MODULE LEAK TEST (GAS SIDE)

INSPECTOR/		MUESTRA										MEDIA	
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	1,00	3,00	31,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,700
2,	2	1,00	3,00	31,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,700
3,	3	1,00	3,00	31,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,700
4,	AVE	1	3	31	0	8	2	7	15	0	0	$\bar{X}_a$=	6,7000
5,	R	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	$\bar{R}_a$=	0,000
6. B	1	1,00	3,00	32,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,800
7,	2	1,00	3,00	32,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,800
8,	3	1,00	3,00	32,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,800
9,	AVE	1	3	32	0	8	2	7	15	0	0	$\bar{X}_b$=	6,8000
10,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_b$=	0,000
11. C	1	1,00	3,00	31,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,700
12,	2	1,00	3,00	31,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,700
13,	3	1,00	3,00	31,00	0,00	8,00	2,00	7,00	15,00	0,00	0,00		6,700
14,	AVE	1	3	31	0	8	2	7	15	0	0	$\bar{X}_c$=	6,7000
15,	R	0	0	0	0	0	0	0	0	0	0	$\bar{R}_c$=	0,000
16. PART												$\bar{\bar{X}}$=	6,7333
AVE ($\bar{X}p$)		1,000	3,000	31,333	0,000	8,000	2,000	7,000	15,000	0,000	0,000	R_p=	31,333
17,	($\bar{R}_a + \bar{R}_b + \bar{R}_c$) / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	0,0000
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	0,100
19,	$\bar{\bar{R}}$ x D_4* = UCL_R											UCL_R	0,000
20,	% de medidas fuera de limites de Medias								Tiene que ser >50%				100,00%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}}$ x K_1		Trials	K1	% *EV*	=	100 (*EV*/*TV*)
	=	0.0000 x 0,5908		2	0,8862		=	100(0.0000/0.0008)
	=	0,00000		3	0,5908		=	0,00 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% *AV*	=	100 (*AV*/*TV*)
	=	{(0.000 x 0,5231)^2 - (0.000 ^2/(10 x 3))}^1/2					=	100(0.0000/0.0008)
	=	0,05231	Appraisers	2	3		=	0,63 %
n=piezas		*r=repeticiones*	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% *GRR*	=	100 (*GRR*/*TV*)
	=	{(0.0000^2 + 0,0000^2)}^1/2					=	100(0.0000/0.0008)
	=	0,05231		Parts	K_3		=	0,63 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0008^2 - 0.0000^2)}^1/2		4	0,4467	% *PV*	=	100 (*PV*/*TV*)
	=	8,33317		5	0,4030		=	100(0.0008/0.0008)
Varición Total (TV)				6	0,3742		=	100,00 %
TV	=	{(*LST* - LIT)/6}		7	0,3534			
	=	{(0.0045 - -0.0005) /6}		8	0,3375	ndc	=	1.41*(*PV*/*GRR*)
	=	8,33333		9	0,3249		≈≈	225
				10	0,3146	*ndc = number of distinct categories*		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

ANNEX A.9: MSA MODULE LEAK TEST (COOLANT SIDE)

INSPECTOR/		MUESTRA										MEDIA	
REPETICION #		1	2	3	4	5	6	7	8	9	10		
1. A	1	-0,07	0,06	2,78	0,12	-0,02	-0,45	-0,11	-0,10	-0,18	-0,23		0,180
2,	2	-0,05	-0,15	2,96	0,18	-0,08	-0,40	-0,12	-0,03	-0,24	-0,12		0,195
3,	3	0,10	-0,08	2,78	0,27	-0,03	-0,38	-0,09	-0,14	-0,11	-0,15		0,217
4,	AVE	-0,01	-0,06	2,84	0,19	-0,04	-0,[illegible]	-0,11	-0,09	-0,18	-0,17	$\bar{X}_a$=	0,1973
5,	R	0,17	0,21	0,18	0,15	0,06	0,07	0,03	0,11	0,13	0,11	$\bar{R}_a$=	0,122
6. B	1	-0,05	0,02	2,84	0,14	-0,16	-0,43	-0,09	-0,04	-0,16	-0,27		0,180
7,	2	-0,06	-0,08	2,87	0,19	-0,01	-0,41	-0,13	-0,06	-0,25	-0,15		0,191
8,	3	0,03	-0,06	2,73	0,20	-0,01	-0,35	-0,12	-0,19	-0,18	-0,13		0,192
9,	AVE	-0,03	-0,04	2,81	0,18	-0,06	-0,40	-0,11	-0,10	-0,20	-0,18	$\bar{X}_b$=	0,1877
10,	R	0,09	0,10	0,14	0,06	0,15	0,08	0,04	0,15	0,09	0,14	$\bar{R}_b$=	0,104
11. C	1	-0,06	-0,06	2,76	0,14	-0,15	-0,44	-0,10	-0,12	-0,24	-0,28		0,145
12,	2	-0,07	-0,13	2,78	0,16	-0,10	-0,42	-0,14	-0,15	-0,22	-0,14		0,157
13,	3	0,07	-0,15	2,74	0,21	-0,07	-0,31	0,06	-0,18	-0,17	-0,19		0,201
14,	AVE	-0,02	-0,11	2,76	0,17	-0,11	-0,39	-0,06	-0,15	-0,21	-0,20	$\bar{X}_c$=	0,1677
15,	R	0,14	0,09	0,04	0,07	0,08	0,13	0,20	0,06	0,07	0,14	$\bar{R}_c$=	0,102
16. PART												$\bar{\bar{X}}$=	0,1842
AVE ($\bar{X}p$)		-0,018	-0,070	2,804	0,179	-0,070	-0,399	-0,093	-0,112	-0,194	-0,184	R_p=	3,203
17,	$(\bar{R}_a + \bar{R}_b + \bar{R}_c)$ / (# OF APPRAISERS) =											$\bar{\bar{R}}$=	0,1093
18,	(Max $\bar{X}$ - Min $\bar{X}$) =											$\bar{X}_{DIFF}$=	0,030
19,	$\bar{\bar{R}} \times D_4{}^* = UCL_R$											UCL_R	0,282
20,	% de medidas fuera de limites de Medias								Tiene que ser >50%				88,89%

Análisis de las medidas						% Total Variation (TV)		
Repetibilidad - Variación del Equipo (EV)								
EV	=	$\bar{\bar{R}} \times K_1$		Trials	K1	% EV	=	100 (EV/TV)
	=	0.0000 x 0,5908		2	0,8862		=	100(0.0000/0.0001)
	=	0,06459		3	0,5908		=	9,69 %
Reproducibilidad - Variación de los Inspectores (AV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% AV	=	100 (AV/TV)
	=	{(0.000 x 0,5231)^2 - (0.000 ^2/(10 x 3))}^1/2					=	100(0.0000/0.0001)
	=	0,01009	Appraisers	2	3		=	1,51 %
n=piezas		r=repeticiones	K_2	0,7071	0,5231			
Repetibilidad & Reproducibilidad (R & R)								
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$				% GRR	=	100 (GRR/TV)
	=	{(0.0000^2 + 0,0000^2)}^1/2					=	100(0.0000/0.0001)
	=	0,06538		Parts	K_3		=	9,81 %
Variación de la Pieza (PV)				2	0,7071			
PV	=	$\{(TV^2 - GRR^2)\}^{1/2}$		3	0,5231			
	=	{(0.0001^2 - 0.0000^2)}^1/2		4	0,4467	% PV	=	100 (PV/TV)
	=	0,66345		5	0,4030		=	100(0.0001/0.0001)
Varición Total (TV)				6	0,3742		=	99,52 %
TV	=	{(LST - LIT)/6}		7	0,3534			
	=	{(0.0003 - -0.0001) /6}		8	0,3375	ndc	=	1.41*(PV/GRR)
	=	0,66667		9	0,3249		≈	14
				10	0,3146	*ndc = number of distinct categories*		

For information on the theory and constants used in the form see *MSA Reference Manual, Fourth Edition*

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