UNIVERSITÀ DI PARMA

DIPARTIMENTO DI INGEGNERIA ED ARCHITETTURA

DOTTORATO DI RICERCA INDUSTRIALE IN INGEGNERIA INDUSTRIALE
CICLO XXXVI

RACK & PINION ACTUATOR DESIGN ENHANCEMENT USING A MULTIDISCIPLINARY METHODOLOGY BASED ON DESIGN-TO-VALUE INTEGRATED WITH FEA AND PRIORITIZATION OF TEAMWORK: CRITICAL ANALYSIS OF OBTAINED ADVANTAGES AND BENEFITS OF FACED SETBACKS

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ANNI ACCADEMICI 2020/2021 – 2022/2023

Abstract

The work presented in this thesis investigates the benefits of introducing a new original multidisciplinary methodology that integrates in a global homogeneous process the benefits of the state of the art of product development techniques, mechanical finite element analysis and collaborative teamwork strategies [*1*]. For exposing this interdisciplinary and Holistic [*2*] new Product Development approach, a case study is presented, focusing on a re-design project of a pneumatic rack and pinion actuator for valve actuation, first time designed in 1984, investigating the potential of joint application of the Design to Value (DtoV) process, coupled with design techniques utilizing FEA simulations, and giving high priority to teamwork during the execution of the project.

The rack & pinion actuator is a mature product, having nevertheless a constant demand from the valve automation market. The final objective of this study is to show how it is possible to optimize its design, obtaining compliance with the requirements of the last versions of main international product standards, increasing weight efficiency and performances, while maintaining high safety and reliability, and at the same time to also simplify the design, with a reduction of components construction complexity and a simplification of assembling procedures, according to the growing demand for a lean production.

The methodology applied for the actuator design improvement is based on the instruments and procedures foreseen by the DtV process, coupled with design techniques based on FEA, called “Design by Analysis”, that are going to re-place, or integrate, the verifications of “Design by Formulas”, used in the occasion of the first design. Focusing on this new design strategy, originally not available, and orienting the design choices for maximizing the product value according to the findings of DtV process, it is possible to obtain important benefits and introduce a totally renewed and more efficient actuator.

The high importance of the “secret ingredient” represented by giving high priority to teamwork during all the activities will be also presented. In fact, the principle that guided all the activities during the execution of the studied Design Enhancement Project was valorizing the power of teamwork, focusing the team on Safety and Reliability.

In a First step of the application of the methodology, the procedures and tools foreseen by the “Design-to-Value” process for fostering improvement ideas generation are applied. Investigations were carried out involving all the company functions interacting with the product, and every single part and feature of the actuator was the subject of in-depth study, by means of techniques developed in the context of the theory of “Product Design and Development” [3], like “teardown analysis” and “function analysis”. After completing the classification of the contents constituting its most important sources of value, by integrating the investigations by means of other useful techniques like “House of Quality”, the subsequent step has been to outline the input for detailed design phase, by choosing the best value increase proposals and officializing them in “Design Change Proposals”, elaborated for the purpose of obtaining efficient construction solutions.

The design change proposals have been the driver of the second phase of the project, dedicated to the detailed design activities aimed to the re-design of the actuator. The peculiarity of this project has been to combine the “classical” approach for structural verifications based on formulas, and then called "Design by Formulas", with advanced FEA simulations, called "Design by Analysis", aiming to stress, deformation, and topology optimization, obtaining a much higher level of accuracy confirmed by experimental validation phase. Furthermore, the conformity of the actuator parts finalized to containing pressure has been verified with respect to an international standard for pressure vessels (EN13445-3), as required by the main actuator product standards (EN15714, ISO12490, API 6DX).

Finally, a two-step experimental validation is foreseen, for confirming the results of the calculations and simulations, based on a preliminary test plan to be performed on a "mockup" prototype, followed by a series of in-depth tests to be performed on a complete detailed prototype, only after the main positive confirmations have been achieved thanks to “mockup”. Experimental tests have the purpose to validate the safety of the parts under pressure as well as confirming the good reliability and fatigue life of the parts subjected to mechanical loads, as required for the obtainment of certification for use up to SIL 3 Safety Instrumented Systems (SIS), in accordance with EN61508 (SIL = Safety Integrity Level) [*5*].

This new value-oriented design strategy, implemented with a sort of “secret ingredient” [*6*] given by collaborative teamwork, allowed to obtain tangible benefits and introduce a totally renewed more efficient actuator. Preliminary results obtained thanks to the project show that the approach based on the described multimethodology, makes it possible to optimize the design of the actuator, maintaining safety, reliability, and increasing performances. In particular, for the studied prototype, the achieved weight reduction is -8% and economic efficiency increase, expressed in $/Nm, is expected to be +22%.

Keywords: Design-to-Value, Finite Element Analysis, Pneumatic Rack&Pinion Valve Actuator, Teamwork

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1 Introduction and objectives of the activity

This thesis brings to fulfillment the research activities that I developed during my PhD path.

In fact, this thesis touches all the themes and the activities that I had the opportunity and fortune to carry out during the 3 years of my industrial doctorate in industrial engineering (XXXVI Cycle). Thanks to PhD path, I had the opportunity to lay a solid foundation of knowledge, in the field of advanced mechanical design, useful for my activity as R&D engineer at Flowserve s.r.l. company, for which I currently work, and to make original contributions in the field of the activities where I work.

First, I could greatly increase my knowledge in subjects in which I needed to have detailed skills, such as in the field of machine design by using Finite Element simulations. Furthermore, thanks to the research projects carried out and summarized in this thesis, I was able to touch on innovative themes, tackling in a new and original way some activities related to the development of industrial products, with particular attention to fluid actuators, present on the market for some time. I tried to make my contribution by seeking new solutions for the execution of design enhancement and value increase projects. Finally, over the three years I was able to greatly improve my mindset, for facing machine design problems with scientific rigor and an orientation towards innovation, thanks also to the advanced seminars and sector conferences that I was able to attend.

During the first year of PhD, thanks to the training plan proposed by my tutor, I laid the theoretical foundations on which to build the research projects developed in the following years and resumed by the work presented in this thesis. I learned the theoretical basis necessary to use Finite Element simulations correctly and wisely, as a fundamental tool for carrying out structural and topology optimization analyses, as well as for integrating existing structural design checks based on calculations. In particular, I focused my attention on comparisons between theoretical results (based on literature formulas, such as Roark's Formulas) and results obtained with FEA, regarding verifications of pressure vessels made up of circular plates and cylindrical tubes connected via bolted unions. During the first year I was also able to attend interdisciplinary courses ("Introduction to scientific research methods", "Study skills: English for Academic Purposes") which allowed me to have the methodological tools to start developing the research project reported in the thesis.

During the second year of the PhD course, I began to develop the research topic here reported, focused on the identification of new approaches and techniques for the execution of industrial product design improvement projects, with a special focus on pneumatic actuators for the automation of valves. For the purpose of performing in an efficient way the detailed structural design activities required by the project, I carried out analyzes about component design techniques "by formulas", for component sizing in normal and special working conditions (for example, in presence of a blast load), particularly delving into the analysis of formulas in accordance with international standards for pressure vessels, such as EN13445-3 and ASME BPVC Sec VIII Div.1.

Furthermore, I began to undertake studies about the topic of "Value engineering", and in particular of "Design to Value" (DtV) as a useful tool to guide choices during a product renewal. I explored these topics in depth by starting a collaboration with a unit of the company where I work that supports all the business units in "product development" activities, contributing to a preliminary study for a possible meliorative re-design of a heavy duty yoke pneumatic actuator.

Furthermore, during the second year I continued my training path, which has been very important to me thanks to the direct positive impacts on the detailed design activities described in a chapter of this text, by following, according to the suggestion of my tutor, all the lessons of the courses "Machine Construction" and "Introduction to non-linear Problems in Mechanics".

At the same time, I continued the study of the use of FEA (Finite Element Analyses), thus learning new additional tools to integrate static simulations, such as the introduction of non-linearities, and also learning how to perform new types of simulation, such as linear and non-linear dynamics, explicit dynamics. In this way I could develop one of the two main themes of my research project, concerning the intensive use of FEA in all phases of detailed design, using simulations to verify the behavior of entire actuator functions, through models of the entire assembly, as shown in Figure 1.

The third year of PhD completed the preliminary activities carried out in the previous two years with the development of the themes that are treated in the following chapters of this thesis, and which also constituted the subject of contributions, prepared to present the results of the analyzes on the occasion of two seminars and for a mechanical design magazine.

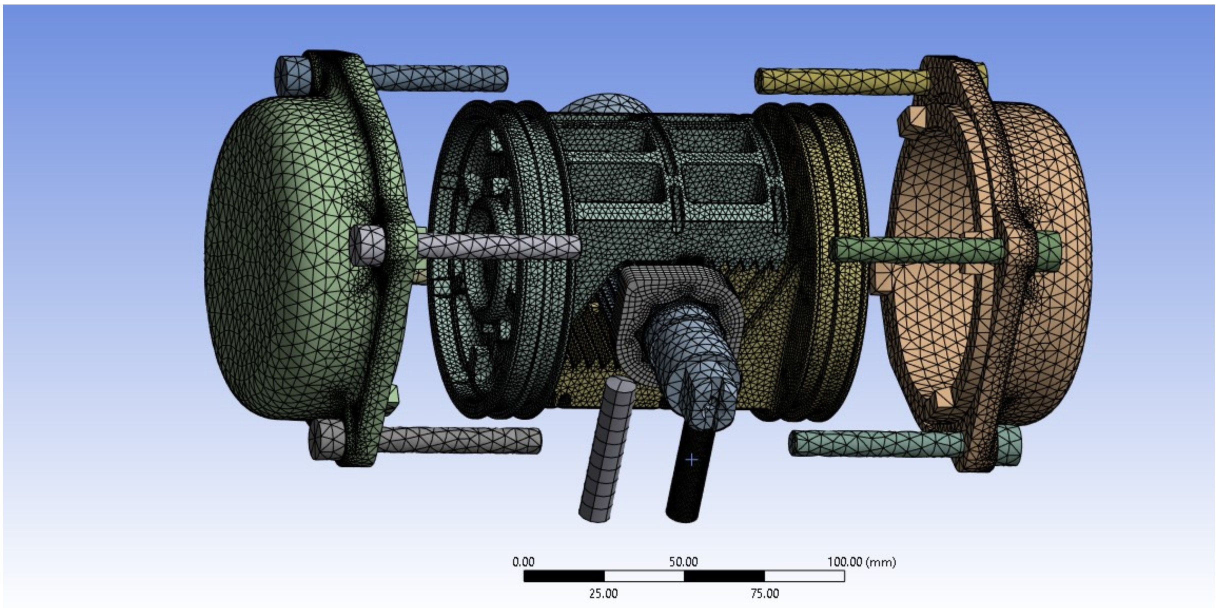


Figure 1. mesh of one of the models created to study the new proposed version of angular stroke regulation system.

In particular, I focused on a project to optimize the design of a series of valve actuators, of "Rack and Pinion" type, which have been on the market for 4 decades. As already shortly mentioned in the Abstract, the novelty of the approach consists in the concomitant application to the project of "design to value" techniques and of detailed design techniques based on finite element simulations, as a useful tool to try to implement as much as possible the proposals of design improvement. The project in fact involved the creation of an inter-functional company team (Design, Production, Quality, Purchasing, Product Management) that according to DtV procedures has been aimed at identifying "Design Change Proposals" which maximize the value of the product for customers.

The detailed design of the modifications, based on virtual prototyping and advanced simulation techniques, was aimed to a meliorative re-design of the components, understood as improving their reliability and weight characteristics, thanks to the optimization of their

topology. Furthermore, the growing demand for easy-to-maintain products has led to the execution of studies to maximize the simplicity of construction solutions and assembly procedures, values that are also useful for lean manufacturing purposes.
Experimental tests carried out on a "mockup" prototype made it possible to obtain an initial confirmation of the validity of the design choices and of the introduced design enhancements, in terms of safety and performances. Finally, analyzes were conducted of the positive impact of the applied approach (safety, reliability, efficiency, sustainability, economic efficiency and therefore profitability), and considerations on the introduction and diffusion of the combined "DtV" and "Design Enhancement" activities, applied to mature products still having a constant demand from companies operating in the manufacturing sector.
Finally, during the third year of PhD I continued to deepen my training path in the field of product development, from a methodological point of view and of advanced design techniques, by following the lessons of the courses "Principles and methods of industrial design" and "Mechanics of materials and structural integrity”.

Publications

As part of the research activities carried out, it was possible to present the following three contributions:

1 – “Multimethodology based on Design-to-Value (DtV), integrated with simulation techniques and prioritization of teamwork for the optimization of a pneumatic rack & pinion actuator”, 52nd AIAS Conference, under publication in “IOP Conference Series: Material Science and Engineering”;

2 – “Design-to-Value (DtV) e Gioco di Squadra”, published in the magazine “Il Progettista Industriale”, n° 1, January, 2024.

3 – “Optimization of a Rack & Pinion pneumatic actuator by applying the Design-to-Value approach”, 12th KOD Conference, under evaluation for publication in “Machine and Industrial Design in Mechanical Engineering – Proceedings of KOD 2024” Springer Series Mechanisms and Machine Science.

2 The need for high value Products – case study of the actuator

Enhancing a product competitiveness is a challenge that can be effectively ad-dressed by integrating Value Engineering tools, simulation-focused design techniques and a "secret ingredient" given by the application of recent teamwork theories to support product ideation by Design Teams [*1*], as shown by the story of the actuator report-ed in this thesis.

A common goal that industries aspire to is to place on the market products that are on one side very economically efficient, and on the other one also able offering customers the greatest possible value, ensuring thanks to these two fundamental aspects their survival in highly competitive sectors. To respond to these needs, in some cases it is also possible that a company decide to renew a consolidated product in its portfolio.

To tackle innovation in development or re-design projects, a useful approach can be based on the simultaneous application of the Design to Value (DtV)cross-functional process, increasing its effectiveness thanks to the combination with design techniques exploiting simulations and with a working method valorizing teamwork and exchange of mutual know-how [*4*], as illustrated in Figure 2.

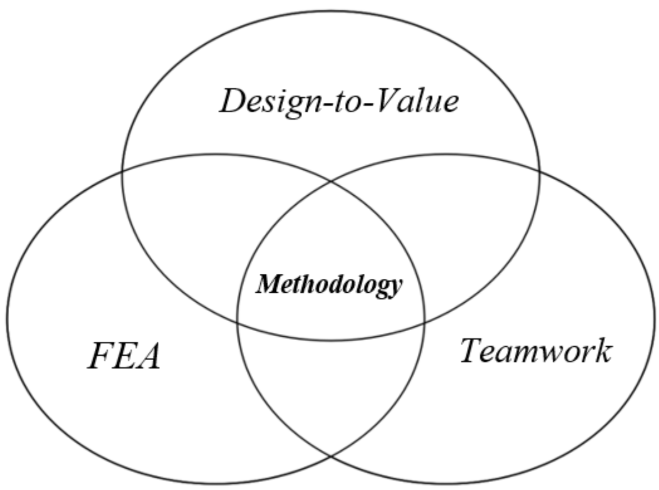


Figure 2. Fundamental components of the integrated re-design methodology.

To describe the potential of the proposed multi-methodology, its application to a design improvement project, concerning a pneumatic actuator, used for automation of quarter-turn valves, and present on the market for four decades is here exposed. During the activities, for simplicity, the methodology at the basis of the project plan has been informally called "VAL-TEAM-FEA".

The objective of the project is to optimize its design, orienting its features according to the most important sources of value perceived by customers and operators of the sector.

DESIGN ENHANCEMENT TARGETS
1 - Efficiency Increases
- Increase of weight efficiency by reducing the weight of casted and machined components
- Increase of performances in term of delivered torque at parity of diameter, with related increase of energy efficiency
2 – Reduction of construction complexity
- Reduction of the number of construction drawing codes
- Reduction of the total number of components
- Increase of use of standard commercial components
- Adoption of design solutions oriented to easy assembling- disassembling procedure, with benefits both during production and maintenance activities
- Where possible, modularity achievement, with re-use of parts in more than one actuator size
3 – Product Compliance
- Compliance with last version of actuator main international standards (EN15714, ISO12490, API6DX)
- Compliance with last version of a reference pressure vessels design standard EN13445-3

Table 1. Resume List of main improvements to be achieved as targets of Actuator re-design project.

The upgrade interventions have been chosen in accordance with the results of the DtV investigations, and are aimed, on the one hand, at increasing efficiency in terms of weight and performances, and on the other to reduce its construction complexity, in accordance with a growing demand for a lean manufacturing. Constraint and concomitant source of value is to guarantee compliance with the requirements of latest versions of international reference standards for actuators and pressure vessels.

As it will be described in any of the chapters of the thesis about specific details, the Design-to-Value process is in fact a very power tool for defining ways to maximize the value of the product, by resorting to a series of targeted actions, allowing to improve crucial aspects of the product contributing to its sources of value. The first look to the target of the value increase project is reported in Table 1. Furthermore, a picture resuming how Design-to-Value helped in defining these goals is reported in Figure 3.

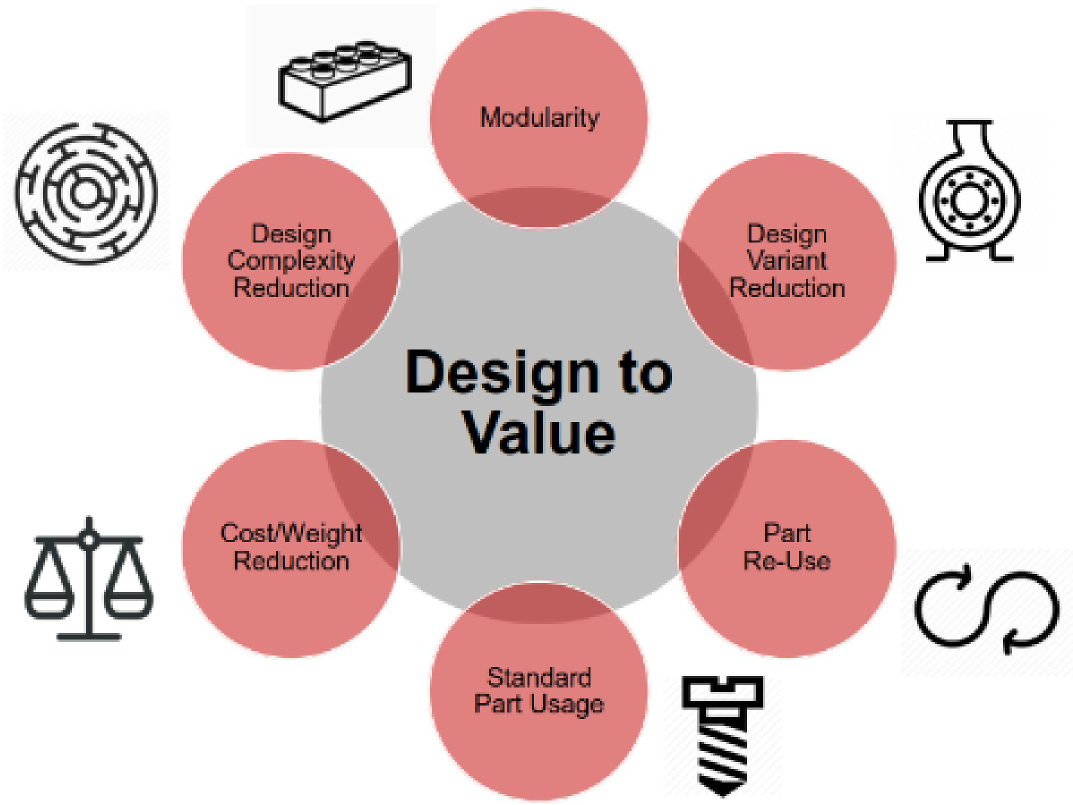


Figure 3. Design Enhancement Goals for the actuator defined thanks to the application of DtV process.

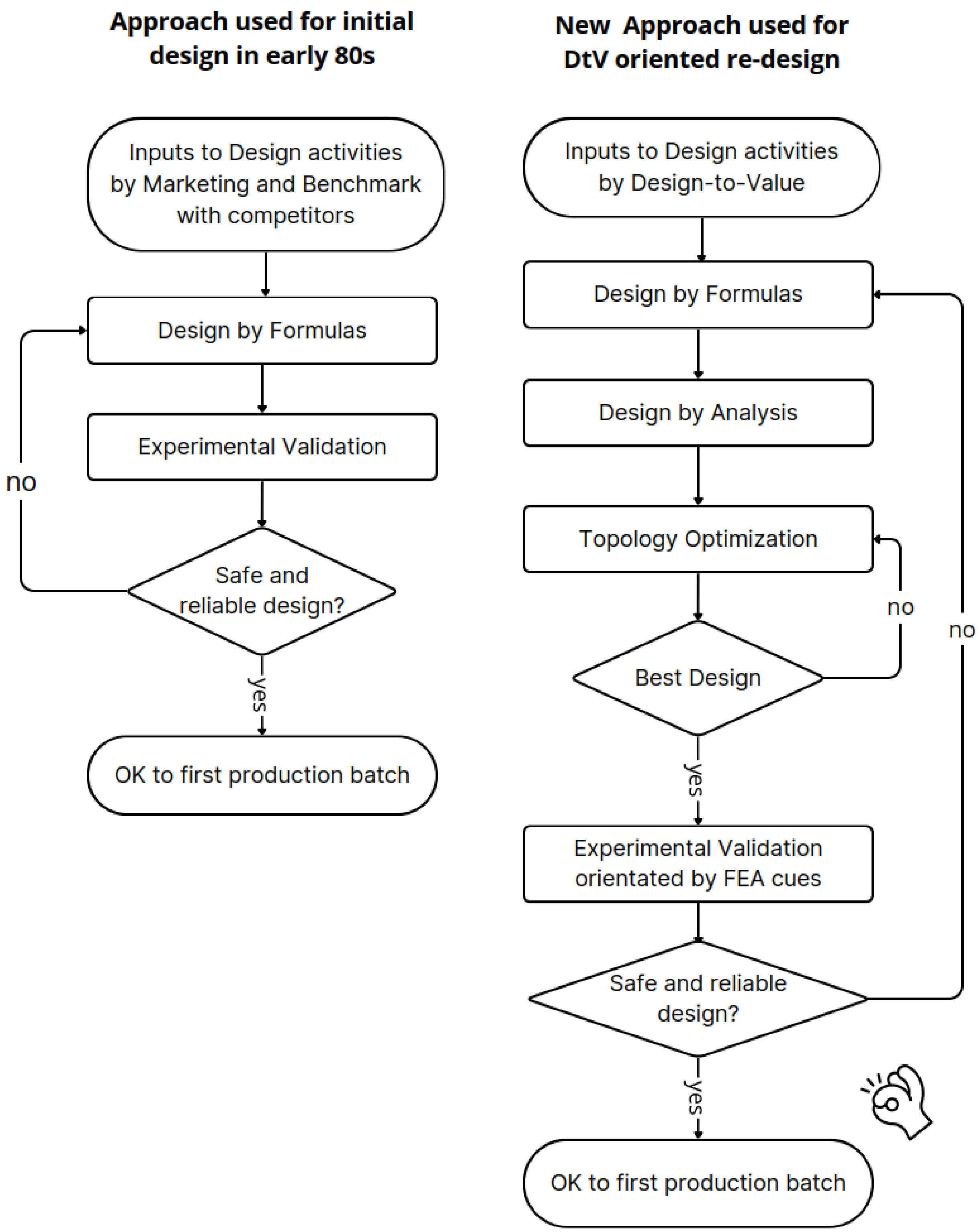


Figure 4. "Traditional" design process and new studied process applied to actuator project.

The team's guiding principle during the project execution has been to prioritize teamwork as much as possible, and to contribute with a team play to the common goal of designing a cutting-edge product in terms of safety and reliability.

For detailed design activities, the approach used on the occasion of initial design, exclusively based on traditional "Design by Formulas" techniques, has been radically modified, by integrating it with an extensive use of FEA simulation techniques, aimed at topology optimization of the components [7]. The flow chart of the detailed design phase is summarized in the block diagram of Figure 4. The project results highlight that the investigated methodology can be a useful tool in achieving a concrete meliorative update of the product.

For better quantifying the achievement of the design improvement objectives, during the project objectives definition phase a series of Performance Indices have been identified and defined. These Performance indices are related to the main sources of values of the product. In this way the degree of satisfaction of the performance requirements that have been set for the new design can be better clarified.

In particular, the following Performance Indices have been taken into consideration. The formulas for the definition of each index and the numerical results are presented in paragraph 12.2 “Actuator components and functions improvement”.

- ***Ip*** : complexity reduction index *Ip*, monitoring the simplification of the design, expressed as the percentage reduction in the number of part codes necessary for assembling the actuator;

- ***It***: in the context of design simplification, also an index of reduction in the total assembly time *It* has been introduced, expressed as percentage reduction with respect to original assembly time;

- ***Iw***: weight improvement index *Iw*, expressed as percentage reduction of the new proposed version of the actuator with respect to the old design one;

- ***Ic***: the improvements described by the previous indices, and in particular, reduction of codes, weight reduction (thanks to several actions, among which the simplification of components, with relative reduction in machining time), simplification of assembly activities with reduction of assembly time, lead to an indirect economic benefit. For this reason, the cost performance index *Ic* has been also introduced, expressed by the percentage reduction of the production cost of the new design with respect to the old one;

- ***Im***: one of the identified most important sources of value of the actuator is represented by the ability to deliver high torque values, and for this reason a torque efficiency index *Im* has been introduced, expressed as the percentage improvement between the MOT (Max Operating Torque, in Nm) of the new model compared to the old one.

- ***Ik***: Finally, a KPI (key performance indicator) has been introduced for better representing the combined improvement in cost and torque, expressed by the percentage reduction between the new and old design about the cost in dollars expended for each Nm of delivered torque ($/Nm).

In the following chapters the fundamental steps of the project will be described, and the benefits obtained will be analyzed in detail. The necessary resources and main difficulties that could be encountered will be also described.

In the first part of the thesis a description of the studied product subjected to design enhancement is provided. The key features will be presented, in particular, the ones guaranteeing its performances in terms of safety (pressure containing parts), reliability (bushings and plain pads) and efficiency (dependency of delivered torque on rack-pinion connection features). In the second part of the thesis also a general introduction of Design to Value process in the context of Value Engineering will be provided. In the next chapters we will go into detail about the studied project and all its executive phases.

3 Product description

The pneumatic rack & pinion actuator is a mature product, receiving nevertheless a constant demand from the valve automation industry. The studied model was firstly designed in 1984 and is shown in Figure 5.

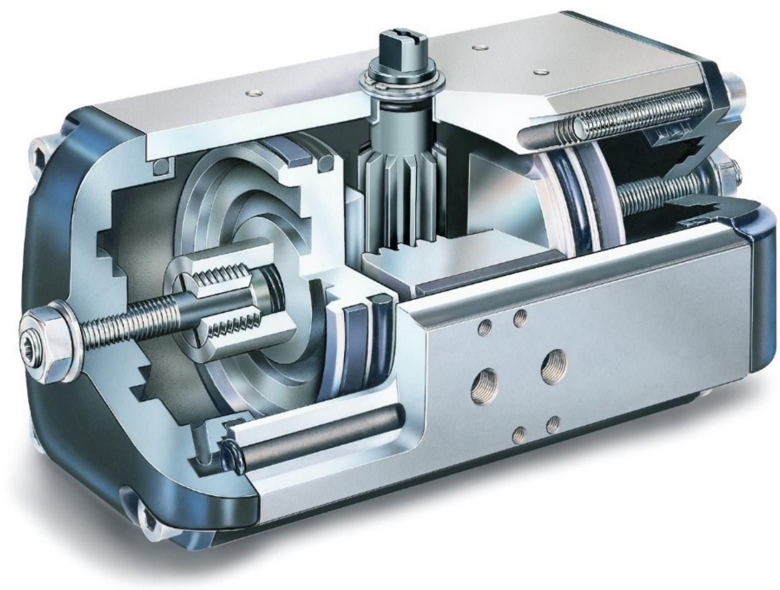
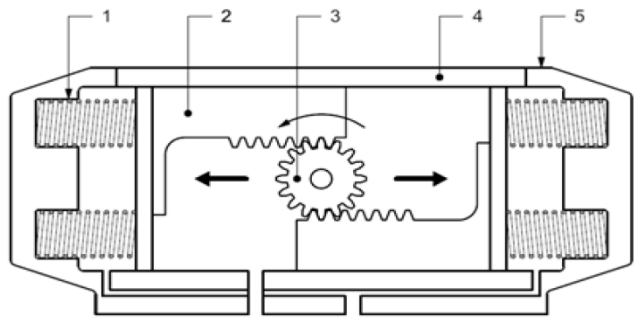


Figure 5. Section of the version of the rack and pinion actuator designed in 1984.

An aluminum alloy hollow center body contains two pneumatic pistons, shaped so as to lodge to linear gears (the racks), engaging a circular gear located on a vertical shaft (the pinion), as schematized in Figure 6.



1	Springs
2	Piston provided with Rack
3	Pinion
4	Extruded Body
5	End Cap

Figure 6. Schematization of a "rack & pinion" mechanism used in a "spring-return" pneumatic actuator and main nomenclature of the components.

This mechanism allows in this way to convert the linear motion of the pistons, moved by the pressure, into the rotary motion of the pinion. The shaft contains a machining in the lower end allowing the direct connection to valve stem or the coupling to adapter joints.

The actuator is suitably powered by a pneumatic control system in the central chamber between the two pistons or in the chambers external to the pistons, so that to obtain clockwise and anti-clockwise rotations, and operate in this way valves with 90° stroke, such as ball or butterfly valves. In the external chambers between pistons and lateral closing flanges, compression springs can be located, as represented in Figure 6 , making a "spring return" function available. In this configuration the force for performing one of the two strokes is generated by the potential energy accumulated by compressing the springs under pressure action during the previous stroke. In "double acting" function both strokes are operated by pressure.

Springs return configurations are suitable to be used in "fail-safe" applications ("Fail- Close" or "Fail-Open"), as they guarantee to perform the emergency function also when the pneumatic supply fails, or the electrical signals of the control system fail.

Figure 7. Full range of the sizes composing the series the studied actuator belongs to.

The actuator studied belongs to a series composed by 11 different sizes. The range of delivered torques varies from 10 Nm of MOT (Maximum Operating Torque) for the smallest model, up to a MOT of 5000 Nm for the bigger one. The model chosen for the analyses of the project is among the smaller models of the series, having an MOT of 180 Nm. Nevertheless, as it is possible to notice from Figure 7, the different sizes have a scalar design, so the aim of the project is to find and test good solutions that could be then applied to all other models of the series.

3.1 Description of torque generation mechanism

In a "double acting" actuator the torque delivered is perfectly constant during all the stroke and equal for both strokes, while in a "spring return" actuator the delivered torque curves are different for the two strokes, and present characteristic decreasing/increasing trends, caused by the linear reaction of the springs.

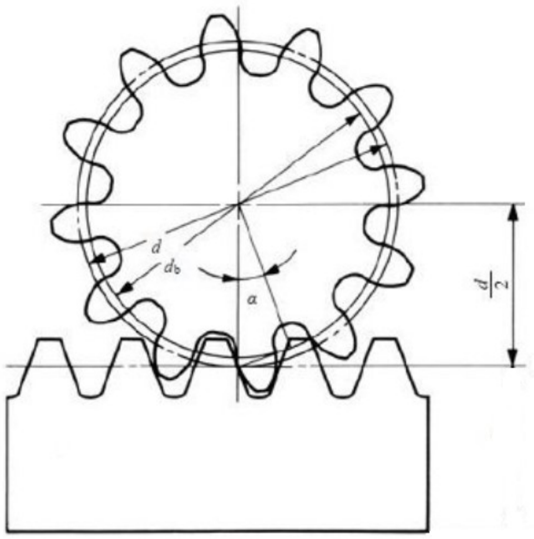


Figure 8. pinion pitch circle diameter. Its radius coincides with the "moment arm" of the torque produced by the movement of the piston rack.

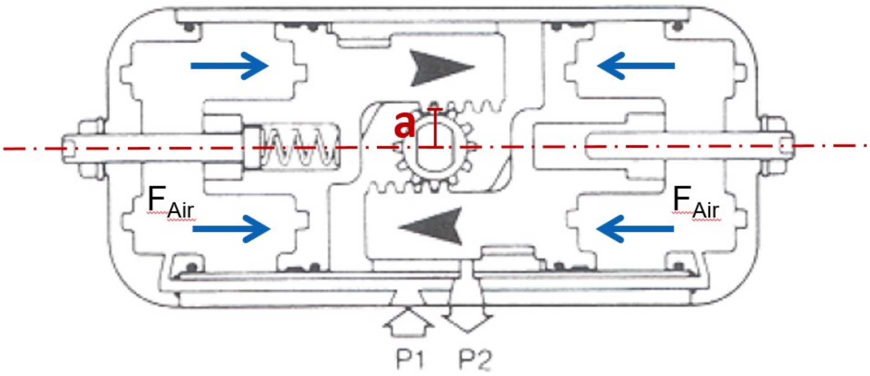
These trends of the delivered torques are linked to the characteristics of the mechanism producing them. In particular, in this type of actuators the torque is generated by the force that the piston transfers to the output shaft, through a "moment arm" equal to the radius of the pitch diameter of the pinion (*d/2*), as shown in Figure 8.

The transmitted torque (*T*) can therefore be written in a canonical form "*force multiplied by moment arm*". For a double acting actuator, where the force acting on the piston is produced by the pressure (F_{air}) only, considering the transmission efficiency (η) and the fact that the pistons producing the torque are two, the delivered torque is expressed by formula (1).

$$T = F_{air} \frac{d}{2} \eta$$

(1)

Figure 9 shows a schematization of the torque transmission mechanism in the case of a double-acting actuator, and the resulting torque curve, showing a constant value.



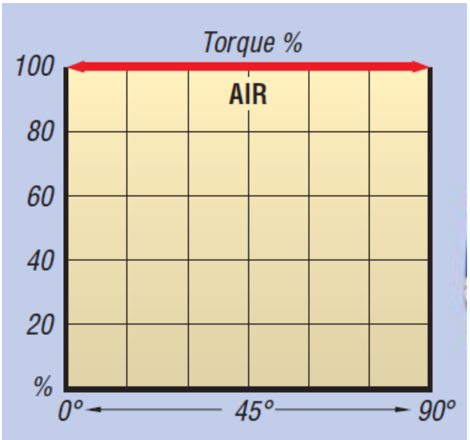


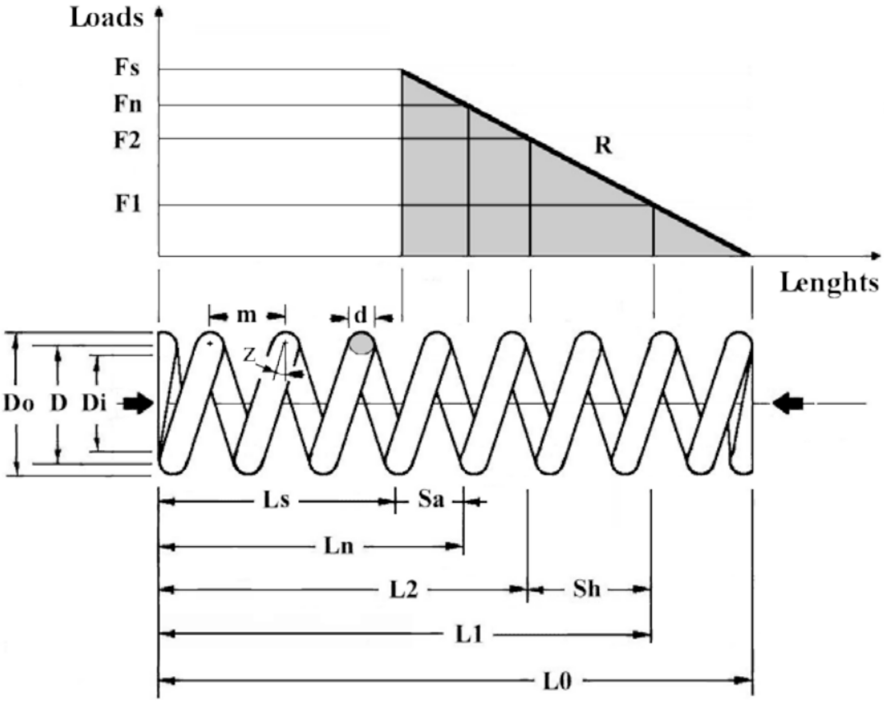
Figure 9. Scheme of the forces producing the torque in a double acting actuator and corresponding torque graph.

In case of a "spring return" actuator, in one of the two strokes the force generating the torque is exerted by springs. The force has therefore a linearly decreasing trend, varying from a maximum to a minimum, following the change in the deflection of the springs between two pre-compressed working positions, at 0° and 90°, the values of which are decided during design for obtaining the desired forces. During this stroke the torque formula is always of the type of (1), by replacing (F_{air}) with (F_{spring}). *Fspring* in its turn is expressed by equation (2), where L_2 and L_1 are the design “working lengths” of the spring, as represented in Figure 10 [8].

$$F_{spring} = k \, \Delta L = k \, (L_2 - L_2) \qquad (2)$$

$$T = (F_{air} - F_{spring}) \, \frac{d}{2} \, \eta$$

(3)



L1, L2 = working lengths
L0 = free length
Lc = length at solid
Ln = minimal operating length

Figure 10. Parameters for the definition of the geometry of a compression spring. (photo courtesy [8])

The presence of the springs also affects the stroke generated by pressure, causing a slight reduction in the delivered torque, since as the stroke proceeds, the springs are gradually compressed. The applicable formula is thus slightly modified and assumes the form of equation (3).

Figure 11 show a schematization of the torque transmission mechanism in the case of a single-acting actuator, and the resulting torque chart, showing linear decreasing values, for both the strokes. It is important to notice that the "end" of the stroke powered by pressure coincides with the "start" of the stroke powered by springs.

This behavior must be taken into consideration during the choice of the right actuator model to be coupled to each valve., so as to guarantee to have a certain safety factor, expressed as ratio between actuator torque and valve torque, above a certain value typically 1.3, for all the points of their torque charts.

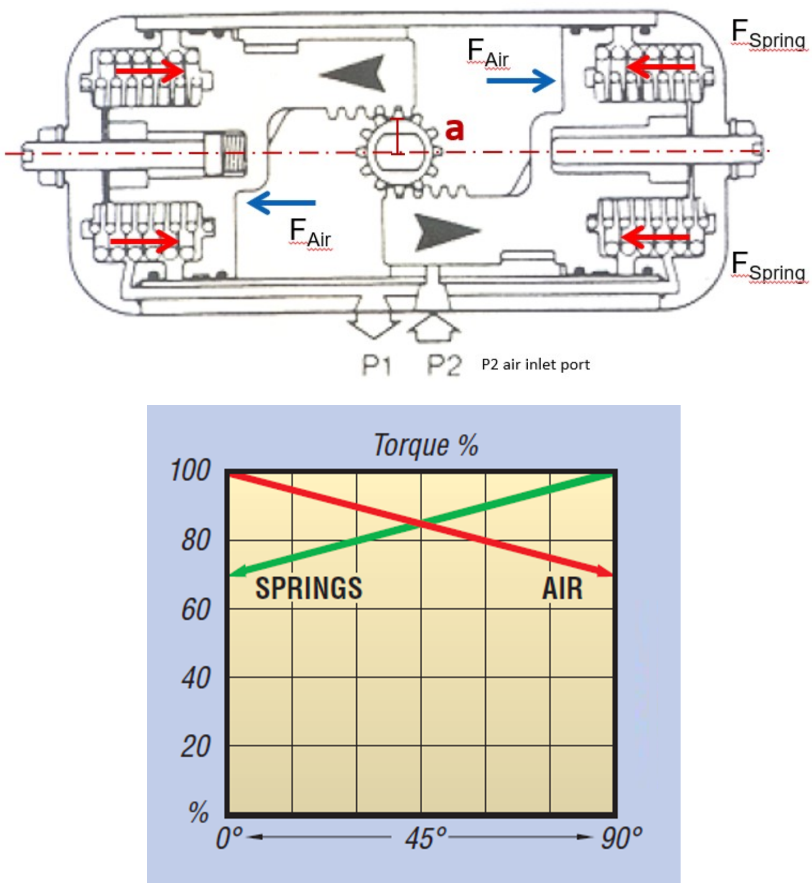


Figure 11. Scheme of the forces producing the torque in a single acting actuator and corresponding torque graph.

Rack & Pinion actuators are built to cover a torque range that can reach approximately a limit of 5000 Nm. For higher torques this type of actuator is no longer advantageous and it is preferred to switch to scotch-yoke actuators. In fact, scotch-yoke mechanism benefits of a geometric gain, allowing to achieve, greater torques delivered at the extremes of the strokes. In addition, scotch-yoke actuators feature a modular design having less construction limitations than a Rack & pinion actuator, where all the components are housed inside a single center body.

The considerations reported in this paragraph regarding the mechanism used by the actuator to generate torque are important because, as it will be explained in next paragraphs, one of the main proposals to increase the value of the actuator that emerged from DtV investigations concerns the increase of its efficiency expressed in terms of produced torque at parity of diameter. In particular, the main factors contributing to the generation of the torque, such as the "moment arm", given by the pitch radius of the pinion, the working lengths of the springs, and the transmission efficiency (η) will be studied, to try to find effective improving solutions, allowing to increase the delivered torque, whilst maintaining the safety and reliability of the actuator.

4 Design-to-Value (DtV): introduction to the process

This cross-functional process is one of the last and most advanced value-oriented design approaches. It is an evolution of processes like "Value Analysis / Value Engineering" (VA/VE) and is aimed to maximizing the total value of a product [3] [9] [10]. The DtV technique focuses on the value attributed by customers and industry experts on the product available features and functions. DtV is also related to the consolidated method of the “Quality Function Deployment”, that can be seen as its predecessor or “mother” [42]. DtV target is to understand what the most interesting requirements are, and translate them into design choices, "shaping" the product based on what is awarded by customers as it satisfies real needs, and makes the product perceived as having a high value [11] [13].

4.1 Brief Resume of the five main phases composing the process

During the process implementation, five fundamental steps can be identified, based on cooperation and information exchange, as described in the following bullet points.

1 – ***Creation of a cross-functional Team*** – at the beginning of the activities, a working group responsible for implementing the DtV process is set up. This team is composed of representatives from all the company functions that interact with the product: Design, Production, Assembling, Quality Assurance, Sales, Marketing, After Market and Customer Care. The team often comprehends the sub-team that will work on the implementation of the new product development of the existing product renewal. Team members work together since the beginning of the project to achieve the improvement goals. Within the team, a manager of the DtV process, a manager of the whole Product development/renewal project, and an Engineering or R&D manager responsible of design and standard/certification compliance are usually identified. The wheel reported in Figure 12 lists the representatives of all the functions asked to participate to DtV process, the relations with their managers, and with the relations with the project manager of the whole design enhancement project.

Figure 12. Scheme resuming all the representative of the company functions contributing to DtV process as well as actuator re-design project.

2 – *Understanding the value for the customer* - it is essential during this step to acquire and analyze information about expectations, needs, suggestions, and problems related to the product, expressed by customers and industry experts. During this phase, quantitative and qualitative surveys are organized in this regard. These activities can be carried out by the members of the DtV team belonging to Marketing and After sales departments, having direct contact with customers and listening to their opinions.

3 – *Generation of improvement ideas* – During periodic workshops, the team performs brainstorming activities aimed to the generation of ideas on component optimizations, innovative construction solutions or possible new features contributing to the "guiding" sources of value defined by the DtV during previous steps. The proposals are in fact oriented to improve the functions of the product identified as main contributors to increase its value and are focused on attributes and details that emerged as most precious from the "Voice of the customers and experts" surveys. The emerged ideas are collected and catalogued, so that they could be evaluated and ordered by priority using tools of value engineering, as shown for the case of the actuator in Table 6. . This phase of the DtV process will be explored in more detail in Chapter **Error! Reference source not found.**, dedicated to a more detailed description o f the activities organized by the team and of the tools used to booster group work.

4 – *“Teardown Analysis”* - An effective technique for helping the generation of improvement ideas consists in examining a sample of the product, by completely disassembling it in the presence of the team and analyzing on a bench each individual part in front of its drawing. The direct contact with the components helps to understand details and to facilitate group discussion on new improvement ideas. Furthermore, the functions of the components are studied through tools of “function analysis”, according to the principles of Value Analysis/Value Engineering. Finally, during the teardown, all the actions required for assembly/disassembly procedures are also studied, to identify the most difficult steps, in search of simpler and faster alternative solutions. The process followed for performing the Teardown will be explored in more detail in Chapter 6, where a discussion of main aspects that could be improved will be also presented.

5 - *“Design Change Proposals” (DCP)* – The proposals emerged from all the previous steps constitute a large pool, from which, thanks to the classification methods, the team draws the best ones to be included in the final design plan. For the actuator project, during review meetings the ideas were analyzed with group discussion, using as a support some tools belonging to methodologies from “function analysis” and “quality function deployment”. A tool for the choice of the final proposed design changes for the actuator is shown in Table 6, where proposals are reviewed using a “House of Quality” table. These topics will be presented in detail in Chapter 7 together with a detailed description of each proposal for improvement.

Figure 13 graphically summarizes [3] the way in which the steps just described are linked to form a uniform and continuous process that allows the development of new competitive products or the re-design of existing products to maximize their potential value.

As it is possible to notice from Table 6, among main elements of value, DtV takes into consideration safety, reliability, ease of use and maintenance, weight optimization and economic efficiency. Through DtV an attempt is made to understand which characteristics of the product are the most interesting for customers and industry experts, and to translate them into design choices, ensuring that the product is perceived as having a high value [11].

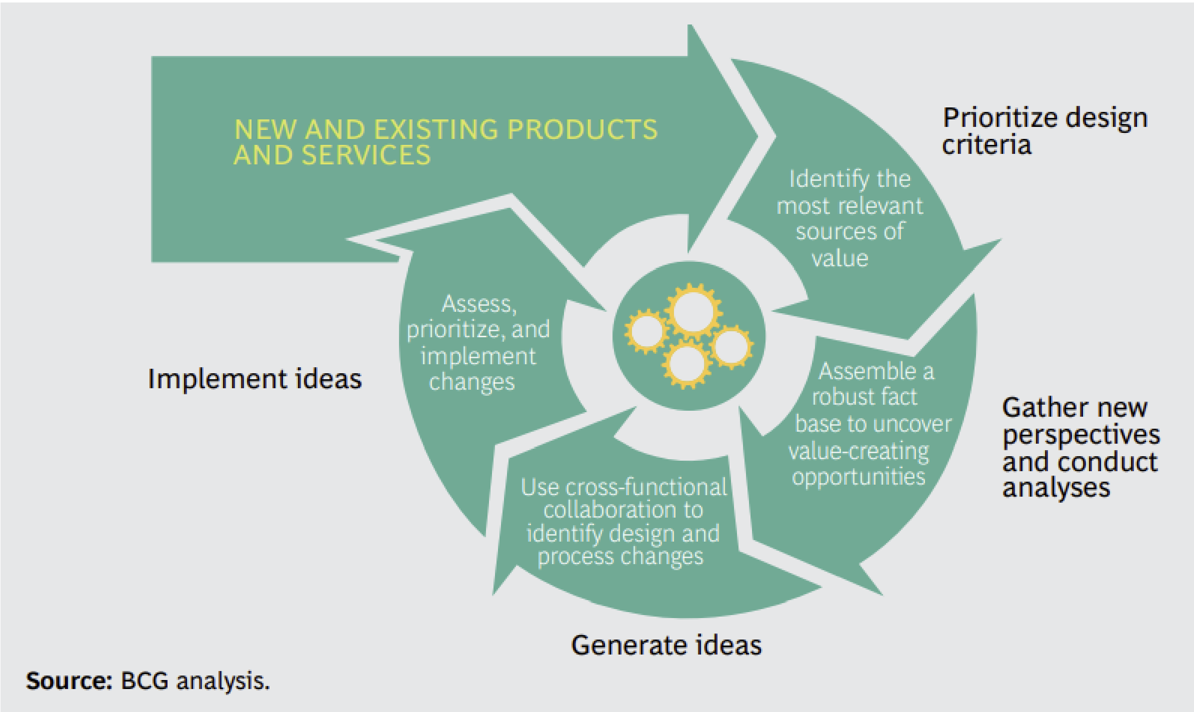


Figure 13. Scheme resuming the steps composing the main phases to be implemented for the application of DtV process (Photo courtesy BGC Analysis).

The "Design to Value" is one of the instruments developed in the field of "value engineering", a discipline aiming to improve the value of a product in every stage of its life cycle. In the context of DtV, improvement indices can be introduced, for monitoring the performances of the new product with respect to a baseline or for monitoring the performance improvements obtained through product re-design. For example, in the case of the studied project, a mass reduction index ***Iw***, a cost efficiency index ***Ic*** and other useful kpi (key performances indicators) have been introduced, showing the percentage improvements, with equal safety and reliability, with respect to the old model, taken as a baseline to evaluate the impact of new design improvements. These indicators are in-depth described in Chapter 12 “Final Considerations”.

4.2 DtV from Project Management Point of View

In the part of the project of product development / product re-design dedicated to the application of the DtV, the project manager could begin to define the timeline for the execution of the whole project, as well as the resources to be dedicated to the subsequent activities [*12*], as for example the resources for the detailed design stage, where the issue of new 3d models, drawings, calculations and FEA analyses must be developed. Furthermore, an initial estimate of the costs necessary for the construction of the prototypes used for validation is performed, as well as a first estimations of the CapEx (“Capital Expenditures”, as for example costs for new cast patterns, tooling, production lines modifications) necessary for the implementation of the project up to the construction of the first production batch.

Project execution times is very important, as the time-to-market required to make available the new updated version of the product - the new enhanced actuator version in the case of the studied project - is one of the main factors the company financing the project can be interested in. Furthermore, it is very important to continuously monitor the total cost of the project. The project in fact usually could include not only the development of the first model or size used as a prototype for verifying the introduced improvements, but also the development of all the remaining sizes if available, for completing the full product series.

It is important to underline that also after DtV process has been completed, there may be further opportunities throughout the product lifecycle for improving it. For example, so-called "Design-to-Cost" techniques can be used to exploit the opportunities related to the change of materials or surface treatments of individual components, replacing the old ones with new more advantageous ones. These new opportunities could arise due to availability of new suppliers, new materials, or new production technologies (for example, availability of very fast and competitive addictive manufacturing technologies in future).

4.3 Additional sources of value -environmental and social impact

Improvements of environmental value and subsequently social value can also be accounted among the objectives of the application of DtV. Attention to sustainability and ethics are important factors that luckily are gaining an increasing attention by customers. The re-design is an occasion to move towards solutions having a low environmental footprint. Investigations about the impact in terms of carbon dioxide emissions can be performed with the aim of moving from major to minor energy-intensive production processes. In addition, the simplification of a component by foreseeing a reduction in mass and in the time required for its machining allows for a reduction in the total required energy required for the component production also. For Carrying out environmental impact analysis it is possible to use several softwares dedicated to these evaluations.

Figure 14. Resume of the factors assessed by "Solidworks® Sustainability® Express" for evaluating the environmental impact of a component.

For example, during the actuator re-design project, for complying with ESG (Environmental, Social, and Governance) policies related to the proper execution of R&D projects, it has been possible to start introducing some simple analyses for estimating the total CO_2 reduction linked to actuator manufacturing by means of the Solidworks® tool "Sustainability® Express", a software using Life Cycle assessment for determining the environmental impact of a product, as shown in Figure 14 (image courtesy of Solidworks®).

In fact, Life Cycle assessment consider what happens in the stages of production, use and final disposal of the product. This also includes the impact of the transportation occurring between the stages. The choices on used materials, manufacturing process (milling, casting, …) and other factors can result in very big different effects on environment. Analyzing these impacts is important in order to make correct and conscious choices.

By means of this type of tools if is in fact possible to obtain comparisons of the total impact related to the production of components, in terms of material and energy consumption. The purpose is to find solutions more efficient, then using fewer material and less energy, so as to improve the ecologic performance and obtain as a concomitant positive result an improvement of product cost also.

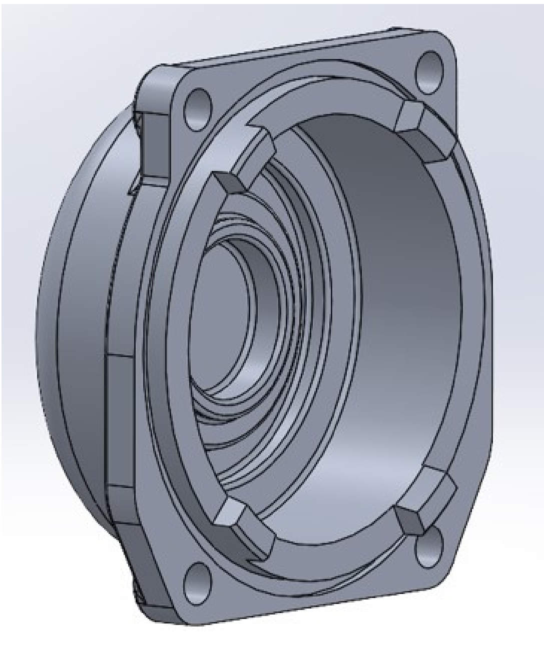


Figure 15. Actuator end cap examined with Environmental Impact Analysis.
Material and energy for production and machining, energy for transportation and end of life use have assessed, for the purpose of understanding and increasing the environmental and social value of the component.

For example, for the studied actuator, the results of the analyses have shown that a part produced on a large scale and obtained by casting of ductile cast iron, such as the closure flat end (“end cap”) shown in Figure 15, has a lower impact than the same component obtained from a machined carbon steel sheet. This result could be evident for small components but for large closure flanges the analysis can be a useful tool to guide toward correct choices.

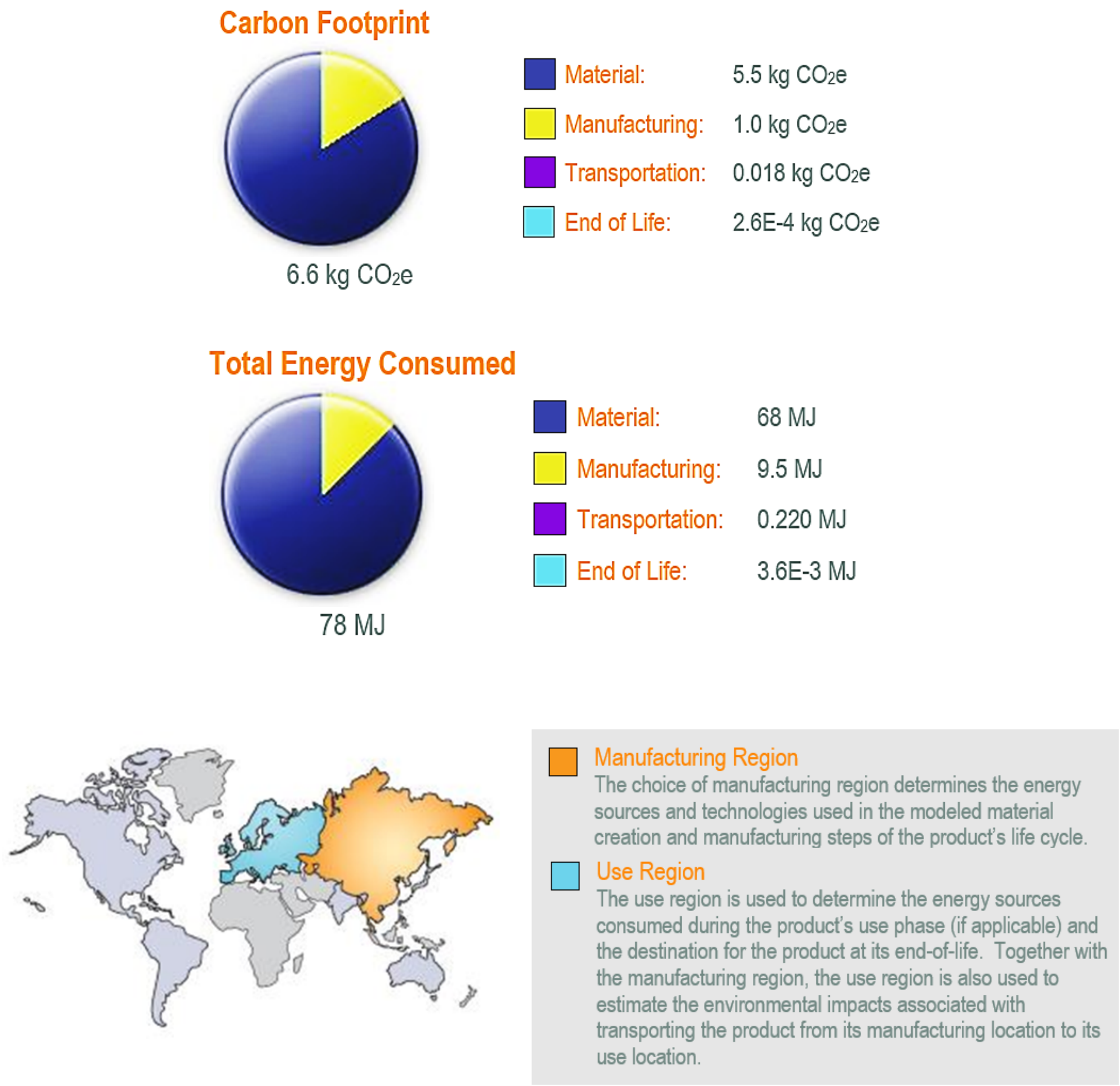


Figure 16. Results of the environmental and energy impact analysis performed on actuator end cap.
Lateral End Caps are produced by die casting of Aluminium alloy. In the studied situation they are produced in Asia and intended to actuators installed in Europe.

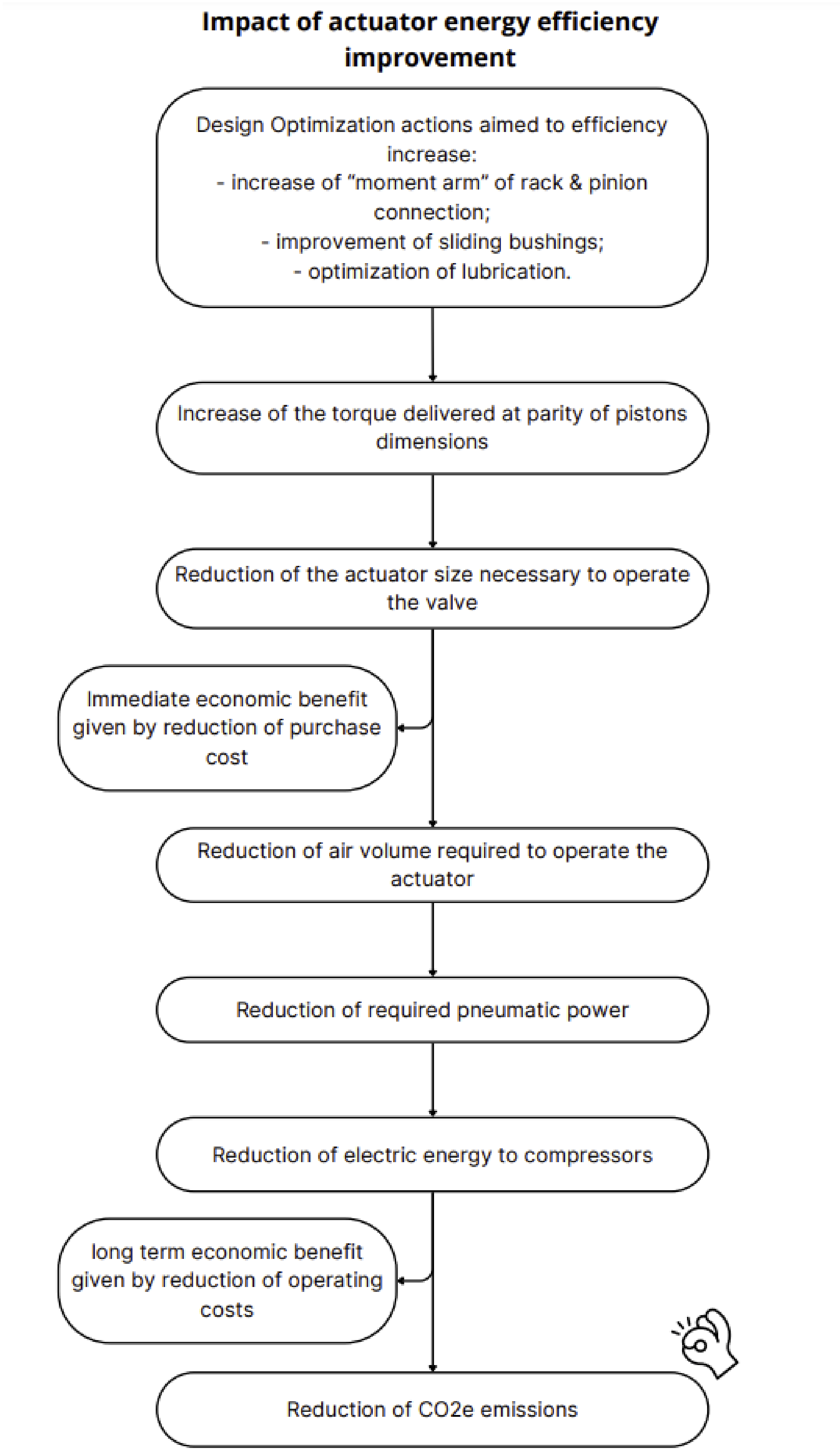


Figure 17. Flow Chart resuming the potential positive impacts of energy efficiency increase in the case of the studied actuator.

Figure 16 shows the results of the analyses of environmental impact (expressed as carbon footprint in tons of equivalent CO_2) and energy impact (expressed as energy consumed in Mega Joules) for the end cap shown in Figure 15, considering a manufacturing by die casting of aluminum alloy in Asia and usage for assembling an actuator installed in Europe.

The analyzes allowed to establish how local production of parts is more ecological than sourcing them from countries in geographically far areas, due to the reduction of energy consumption linked to transport, that, as it is possible to notice from Figure 16, is an important source of emissions and energy usage. It therefore emerged even more clearly that transport is a key element greatly influencing the production of components, and its cost impacts a lot in determining supply chain choices and indirectly ecological impact. There is a certain threshold above which the transport cost is too high, then it is no more economically efficient then no more a benefit for product competitiveness to produce geographically far away, with a concomitant benefit of local production given by best ecological efficiency.

Figure 18. Cartoon courtesy of Leewardists™.

Another source of value, directly related to environmental value, is the maximization of energy efficiency. For example, this improvement has been set as an important goal of the re-design project of the actuator. An increase in the torque delivered at parity of diameter of the pistons leads to a reduction of the actuator size necessary to move the valve, with a consequent reduction in both cost of purchase of the equipment and, from environmental point of view, a minor pneumatic power necessary to operate the actuator in performing the open-close manoeuvres. The importance of energy efficiency is resumed in the flow chart of Figure 17.

A final observation that emerged from the investigations carried out during the analyzed project, is that for an industrial product intended to the installed in the field, like the studied actuator, the search for an increase in value led to a "lean" design, favoring simple and functional solutions, compared to a more complex design provided with "extra" features, like, for example, a more pleasant layout with aesthetics shapes. The achievement of these values would require sacrificing other values considered as more important for the customers using this type of products, such as simplicity of assembly and extreme attention to minimizing weight and cost. This concept can be summed up ironically by the cartoon of Figure 18.

5 Generation of Improvement Ideas

This phase of the activities is based on periodic inter-functional meetings and workshops, actively involving the entire team. Brainstorming activities, based on teamwork, allow the team to generate ideas about component optimizations, innovative construction solutions or new features that contribute to improve the design according to the "guiding" sources of value defined by the DtV.

The proposals are in fact oriented by the attributes that emerged as most valuable from the "Voice of the customers and experts" surveys, and are oriented by functions of the product that contribute to increasing its value, as shown in Table 6 for the case of the actuator.

DtV could also bring out conflicting internal views across functions and different views on what constitutes customer value. These constructive “conflicts” stimulate the discussion and bring decisions commonly agreed. In the studied re-design, concerning a product that has been on the market for many years, opportunities have been investigated also related to possible new materials and new production processes not available at the time of initial design.

Ground rules

- ✓ No rank or position – one person – one vote
- ✓ There are no stupid questions
- ✓ There are no forbidden topics – mention all problems
- ✓ Everyone gets a chance to talk
- ✓ Be open minded – listen to other points of view
- ✓ No blame, only solutions
- ✓ Be positive – have fun!
- ✓ Embrace & trust the process

Figure 19. Ground rules for a good development of brainstorming workshops.

During this phase it is very important to carry out a constant search for the compromise between giving the maximum possible value and choosing solutions entailing a cost that allows the product to be competitive, which is an indispensable constraint for the company, so as it could be able to disseminate the product in the market.

During the meetings held in this phase of the project, the rules of brainstorming are applied. Brainstorming is a creative process, developed in the late 1930s [*14*], that involves generating a large number of ideas or solutions with regards to the proposed challenge. It is then a technique aimed to improve creative thinking, and it represents a valuable tool for generating creative solutions, fostering teamwork, and encouraging innovative thinking. It can be applied to a wide range of contexts, from business strategy to, for example, product development, as in the case of actuator re-design.

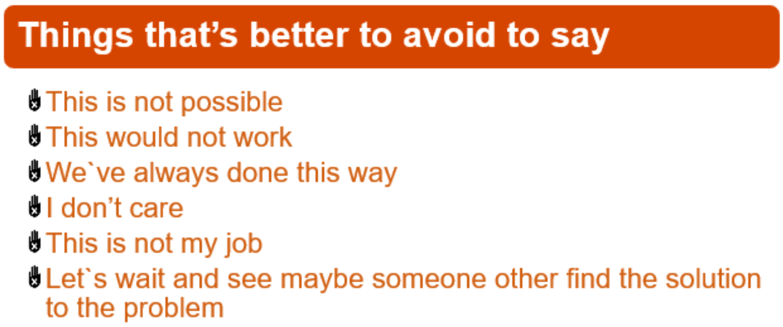


Figure 20. tricks for having the right positive attitude during brainstorming meetings.

The primary goal of brainstorming is to encourage free thinking, and idea generation without immediate criticism or evaluation. For this reason, during the meetings of the actuator project, before starting the activities a moderator shared the team a presentation with slides containing the suggestions resumed in Figure 19 and Figure 20. The aim of these recommendations is to encourage team cohesion, and promoting a positive attitude, so that participants could feel comfortable sharing their thoughts. Reducing the fear of judgement during idea generation is very important, so as to encourage open dialogue. Workshop participants should feel free to be open to explore seemingly wild or unconventional ideas also. Creativity thrives when people are willing to step outside their comfort zones, but for doing that a right environment is necessary.

As mentioned in the title of this thesis, during the actuator re-design project one of the factors that mainly contributed to overcome many difficulties and issues has been the power of teamwork and of an “positive and “optimistic” team [*15*]. The effectiveness of the rules of brainstorming can be in fact easily extended to all the activities [*16*]. One of the aspects noticed during the project is that, when carrying out activities in team, using a positive and constructive language helps create a supportive environment.

For example, an approach for encouraging idea development/problem solving, that luckily team members easily adopted, is the one remined in Figure 20 also: instead of saying “That won’t work,” team members can say, “What if we modify this idea for considering ….”. In fact, instead of dismissing or criticizing ideas, a much more effective and fruitful environment is established when teammates build upon others’ ideas or combine them with their own. This creates a collaborative atmosphere, where ideas can be improved through contributions of multiple team members, and where people actively listen to others.

Another key factor during the project has been that all participants were well disposed to give their contribute. There has been no need to encourage team members to participate to discussions. Accordingly, some of the rules for a good brainstorming consist in making sure that also quieter team members could have an opportunity to share their ideas and preventing any team member from dominating the conversation.

For helping collecting ideas, tools encouraging team collaboration and the birth of new proposals can be used. For the studied project, during the meetings blackboards were used and they have been populated with sketches, post-its and concept maps. Furthermore, to collect and share on PCs all the ideas, a software tool among the many currently available was chosen (MURAL®), encouraging collaboration and visual thinking. Figure 21 shows some “collaboration area” created using MURAL® software, where each team member could propose ideas, or write down his opinions regarding proposals made by others via virtual post-it.

After the brainstorming sessions the participants reflect on presented ideas. This review can lead to further insights and improvements to the ideas, that will be presented to other team members during following workshops. In addition, each member of the project team implements personal investigations for proposing new ideas. During these analyses public documentation, such as technical bulletins of competitors and articles on online magazines of the sector can be analyzed. In this way it is possible to have an immediate comparison with other products dedicated to same applications offered by competitors.

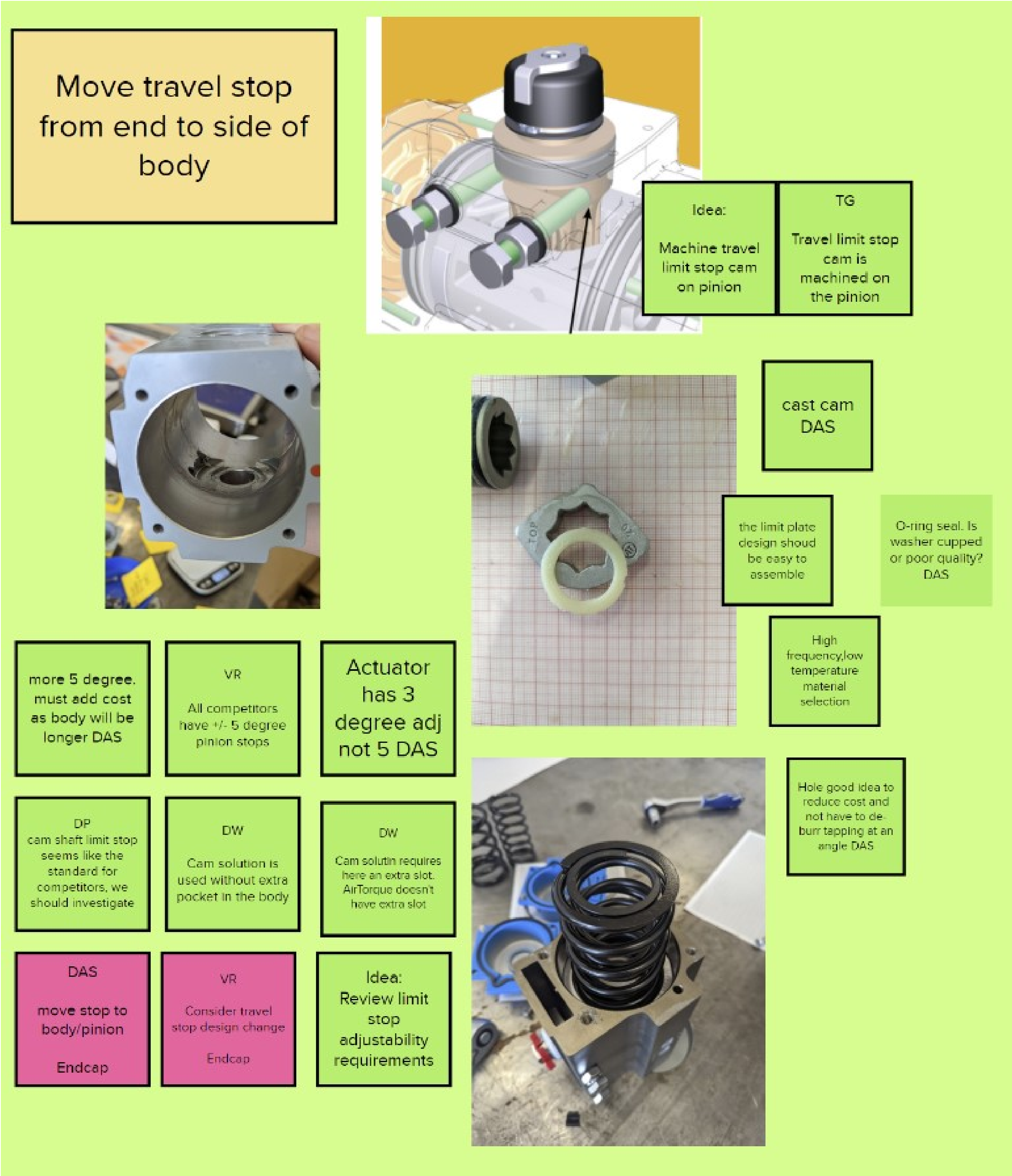


Figure 21. Virtual blackboard created with MURAL® software where team members can leave post-it for facilitating the discussion.

However, comparative analyzes with competitors are limited, as the objective of value increase project must not be to align the product with other manufacturers, but rather to be focused on trying to obtain innovation and original solutions. Furthermore, an approach oriented towards approaching competitors' products could create additional problems, such as the possibility to incur in patented solutions.

On the other hand, a project of re-design for renewing a product is an opportunity to align its features to the ones that became "standard" characteristics present in main competitors, and that, in case of missed re-alignment, could lead with time to a constant decreasing competitiveness of the product. In the case of the actuator, as we will get back with discussions in the next chapters, one of the points that has been identified as "critical" to guarantee its good competitiveness concerns the performance expressed by the torque delivered for at parity of diameter (and supply pressure), which in its turns brings to a better economic efficiency expressed in Nm/$, that is in terms of available torque for every dollar spent on the purchase. Following the investigations carried out during DtV process, the team understood that for having a great source of value it is necessary to try to improve torque efficiency by bringing it to the average level of competitor products, many of which were developed in later years than the studied actuator, placed on the market in 1984. Therefore, within the scope of the re-design project, according to DtV results, one of the main objectives to be achieved to increase the value of the product is set as trying to enter the group of the most torque efficient competitors present on the market.

Thanks to the investigations performed in the context of DtV process by means of teamwork and individual researches by team members, Improvements ideas in the following areas have been identified:

a. improvement of the topology of components,

b. ideas for reducing the number of components,

c. ideas for simplifying the architecture of product mechanisms (for example, the angular strokes adjustment system),

d. ideas for simplifying the assembling activities.

e. Ideas for obtaining a performances improvement, expressed in terms of Nm at parity o diameter, then in terms of Nm/kg or Nm/$.

f. Ideas for clearly defining the mechanical transmission efficiency (η) of the actuator, through a series of careful experimental tests, so as to have precise parameters to be used in the performance calculations.

Descriptions of the technical solutions proposed to implement each one of the different improvement proposals are presented in Chapter 7 “Design Change Proposals”. In the same chapter, the methodology used to classify and prioritize these proposals will be presented, describing how, in the design phase, the changes that have been assessed as the most profitable are carried out.

5.1 Contributions to the discussion focused on specific aspects provided by company departments

During the phase of the DtV project dedicated to brainstorming activities for ideas generation, presentations by the various departments involved were discussed during the workshops. These presentations aim to stimulate discussions and make it easier to identify possible areas where improvements could be achieved. The aim is to optimize all the aspects contributing to increasing what have been identified as the main sources of value of the product, according to Table 6. Main contributions to the investigations presented by the company departments involved of DtV process for the actuator re-design project are briefly set out in following sub-paragraphs.

5.1.1 Supply Chain - Review on main sources of cost

For helping identifying the components affecting most the cost of the actuator, and therefore for evaluating which are the actions to focus on in order to achieve the greatest impact, the team members belonging to Supply Chain department prepared a Pareto analysis, finding the list of the main components constituting by percentage the total cost of the actuator.

From this analysis, reported in Figure 22, it clearly emerged that the components where it is profitable to invest resources in order to obtain tangible optimizations are the following ones:

- Extruded center body
- Casted pistons
- Casted lateral end caps

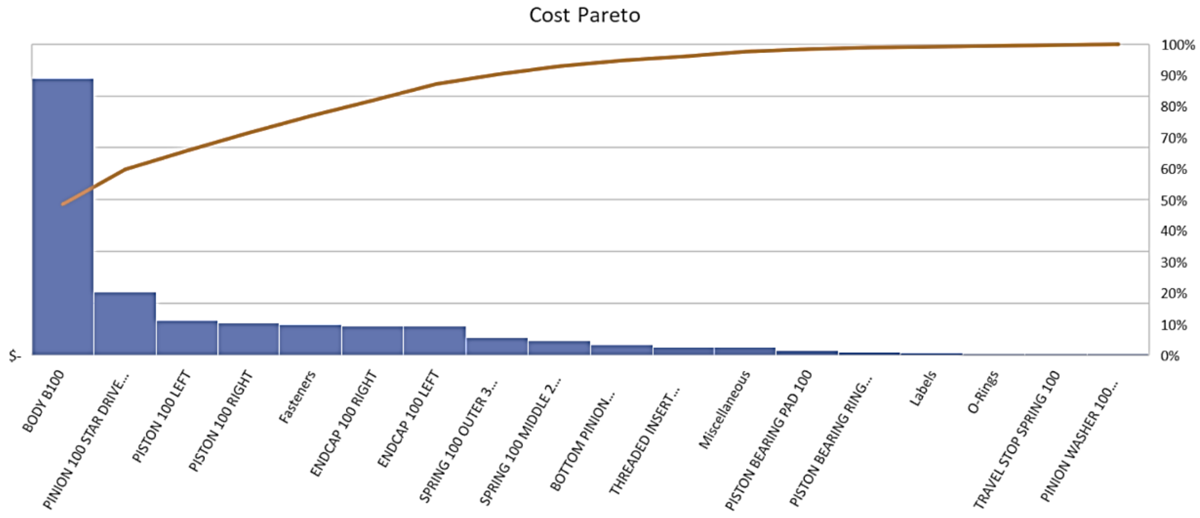


Figure 22. Pareto Analysis of actuator components mainly contributing to the material cost.

Supply chain team members also described to the team how, for the old version of the actuator also, most of the components are already purchased using a globally distributed network of suppliers, as shown in Figure 23, by performing economic analyzes about most advantageous procurement choices. Increasing value through an accurate campaign of suppliers' selection has therefore proven to be a difficult voice to further optimize.

Figure 23. Geographical distribution of the suppliers of actuator components.

5.1.2 Production – Analysis of assembling procedure

The active collaboration of the teammates belonging to production department made it possible to provide the DtV team with important information for preparing important proposals that contribute to increase the value of the product.

Thanks to a joint analysis between the supply chain and production, it was possible to compare by percentage the cost of the assembly activities, restricted to cost of work hours, with respect to the cost of all the components. As it is possible to notice from Figure 24, the labor cost does not largely affect the cost of the product (fixed production costs are not taken into consideration, so as not to overly complicate the analysis). Nevertheless, one of the sources of value identified as most appreciated is the simplification of construction choices, so as to obtain, on one hand, ease of maintenance, and on the other, a possible further reduction in time and equipment needed for assembly, according to lean production principles [*17*].

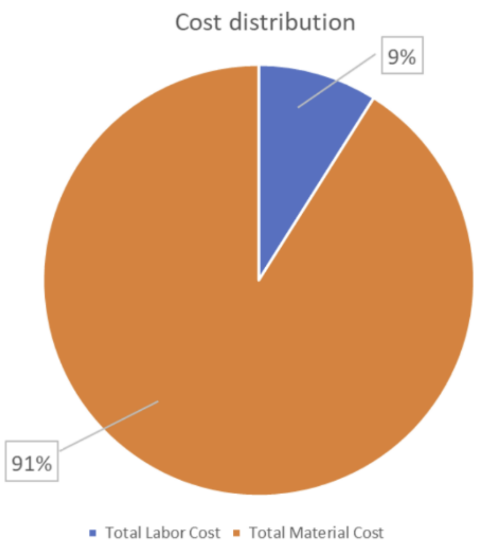


Figure 24. Percentage comparison between actuator labor cost for assembling and components cost.

For better studying possible simplifications of construction solutions, to be implemented during re-design phase, in collaboration with the teammates of production department, an analysis of the procedure for assembling an actuator was carried out, recording and photographing all necessary steps, noting order of execution and required time for each one.

No.	Assembly Steps	Assembly Step description	Start time	[sec]
S00		Visually inspect for damages and overall quality and Fix product label centrally to the “back"of the actuator.	0:00:00	**5**
S01		Visually inspect for damage and overall quality including surface coating,paying particular attention to the finish of the top journal and bottom groove diameters for nicks.	0:00:05	**5**
S02		Fit greaesd "o-ring" to upper groove using appropriate tool.	0:00:11	**6**
S03		Fit greaesd "o-ring" to groove in body top	0:00:15	**4**
S04		Install the pinion into the body	0:00:21	**6**
S05		Put pinion washer and steel pinion washer at the top of pinion, and then use circlip pliers to install pinion circlip to the groove	0:00:39	**18**
S06		Apply some grease to the inside ends of the body	0:00:48	**9**
S07		Visually inspect for damage and overall quality. Install guide band onto the left and right piston seperately	0:00:55	**7**

Figure 25.Extract from the analysis of the actuator assembling procedure, finalized to find possible simplifications.

Figure 25 illustrates some of these steps. This study is important because it allows to identify the most complicated steps, requiring higher time for execution (for example, the insertion of a pinion guide bush possible only by means of a special press, after a precise positioning of the actuator). The design simplification actions will be therefore focused on these difficult steps, as will be described in various sections of next chapters. Furthermore, the assembling and disassembling procedures, comprising the actions of Figure 25, are in deep studied by the DtV team also in the occasion of the "teardown" analysis of a sample, as it will described in Chapter 6 "Teardown Analysis" and "Function Analysis".

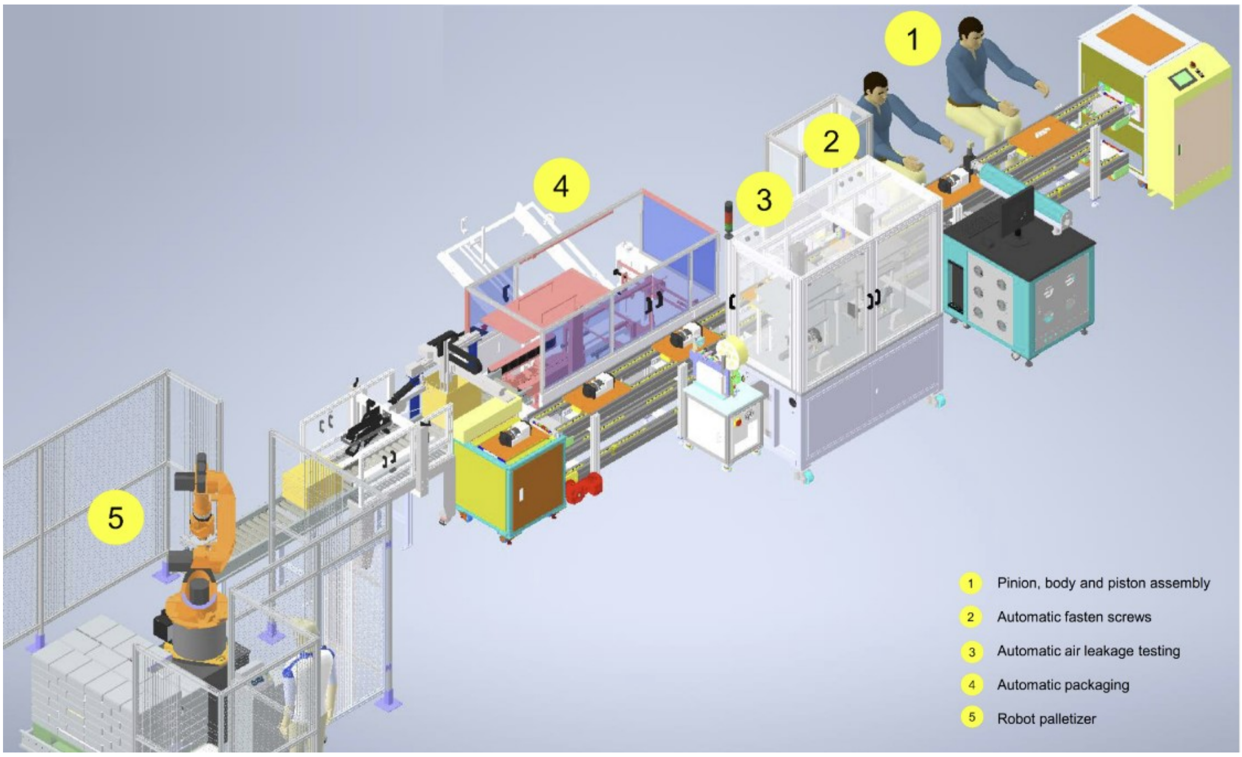


Figure 26. Concept for a possible semi-automation of actuator assembling line.

Finally, among the proposals that were shared during this phase regarding the simplification of assembling activities, one directly arrived from production department, concerning the semi-automation of the assembly line. A preliminary study had already been carried out in past, as shown in Figure 26.

Thanks to automatic machinery that autonomously performs some of the steps required by the assembly procedure, it is possible to greatly reduce the average assembly time of each unit leaving the production line. The increase of value brought by this type of actions concerns a direct reduction in costs, with a consequent:

1) increase of profitability
2) Possible reduction of selling price with gain of competitivity.

As in the case of the research for globally most convenient suppliers by supply chain, production automation also belongs to a category of value improvements due to a direct increase in profitability. Improvement interventions of this type have been taken into consideration during this phase, also if they do not directly concern re-design choices.

Regarding semi-automatic production, the shared proposal did not involve for its implementation the need for modifications of component design for adapting them to the use of automatic assembly machines. If need for component adjustments will arise in the future, it will be possible to carry out a further re-design, always within the scope of a "Design to X" project, but this time related to "Design to Assembly" [*18*].

5.1.3 Quality Assurance - Review on product quality and non conformities

In this phase of the discussions, the teammates from Quality Assurance department presented a series of data regarding the critical aspects that need to be kept under control for guaranteeing a good quality of the product during production, testing and life in the field.

In fact, beyond the quality of the design itself, related to many factors like robustness and performance, the production quality of the actuator also, directly linked to its overall reliability, is identified as one of its main sources of value.

Historical Data were presented regarding the main sources of non-compliance recorded during actuator production, as shown in Figure 27. This discussion allowed the DtV team to orient many of the design improvement proposals. In fact, any proposal of modification must always respect the fundamental condition of guaranteeing a high quality of the product. An example can clarify the importance of this joint analysis with Quality Assurance.

During detailed re-design phase, when it was necessary to decide how to optimize the castings of pressure containing parts such as pistons and lateral end caps, it has been very important to consider that castings are a source of many non-conformities, according to information received from Quality Assurance, and are therefore critical components to be studied accurately. For this reason, the meliorative re-design choices also concerned the choice of casting processes and casting materials with good properties about pressure tightness, eliminating variants that would increase the risk of blowholes, causing possible leakages.

For example, during material grade definition, ADC10Z aluminum alloy has been preferred to the similar and most less costly ADC12, because the latter has lower suitability to pressure tightness, and then a greater risk of porosity causing pressure leakages.

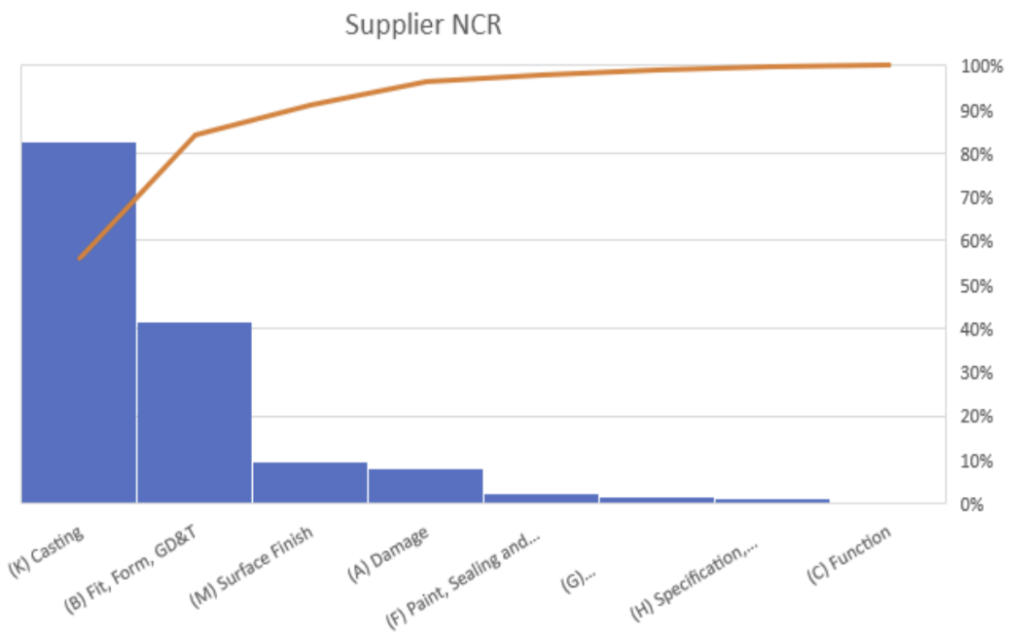


Figure 27. Main causes of Non conformities registered during actuator production

5.1.4 Com Ops and Marketing - Review of "Voice of the customer"

During the brainstorming workshops finalized to ideas generation, the DtV team members belonging to Marketing and After sales departments presented the results of the quantitative and qualitative investigations performed for acquiring information from customers and industry experts.

According to main principles guiding the analyses of "Voice of the customer" (VOC) [*19*], investigations were focused to fully understand which are the real expectations and needs about the product, for analyzing the problems related to the current version of the actuator and for catching suggestions.

VOICE OF THE CUSTOMER INTERVIEW
1 - When considering a rack & pinion actuator, what are the key features you expect?
2 – How many years have you used rack & pinion actuators?
3 – What is key factor impacting your purchasing decision for this type of product? (Price, lead-time, …)
4 – Do you expect the actuator maximum design pressure to be 10 barg (150psig) or 12 barg (174 psig) or other?
5 – What is the key benefit you get from rack & pinion actuators?
6 – What are the key decision-making factors in selection of a rack & pinion actuator supplier?
7 – If you are A distributor, what is the stock level (estimated quantity each year) you maintain? Do you stock parts for conversions or complete units?
8 – What valve brand and valve types do you typically provide with rack & pinion actuators?
9 – Are there applications or problem areas you have experienced using rack & pinion actuators?
10 – What do you believe we need to consider for improving our rack & pinion actuators? If design related, what features are we missing? If price related, what percentage is the price gap?
11 – In addition to our brand, are other rack & pinion actuators provided and why?

Table 2. Questionnaire shared with customers as part of VOC investigations.

Among the actions carried out for the investigations, a list of accurate questions, reported in Table 2, was sent to a series of distributors, representatives, and end-users. The respondents provided very important comments, reviewed on the occasion of the meetings. The provided answers contributed fundamentally to define the primary sources of value towards which design enhancement efforts should be aimed, as shown in Table 5 and Table 6.

By analyzing the answers provided by customers and distributors, some keywords emerged, being recurrent in the answers to all the asked questions. It clearly emerged that customers attribute a great value to the following features:

- ***V*** **Efficiency**: high torques delivered by compact actuators.
- ***V*** **Price**: customers are looking for a competitive product with a price in line, if not better, that competitors;
- ***V*** **Reliability**: the actuator must be able to be used in emergency functions with high reliability and must be SIL certified;
- ***V*** **Durability**: the actuator must be able to perform a high number of cycles and have a very long operating life, if well maintained;
- ***V*** **ISO interface**: the coupling system with the valve must be in compliance with international standards indications;
- ***V*** **Corrosion resistance**: special versions must be available, suitable for applications in extreme environmental conditions, such as offshore plants.

Other important elements of value also emerged, linked not to the product itself, but to the organization of the structure that sells the product, such as:

- ***V*** **Lead-time**: customers desire that their orders are processed in the shortest time possible;
- ***V*** **Technical support**: Customers attribute a high value to a well-organised and reactive service and customer care network, able to satisfy customer requests in a timely manner;

A term that came up many times in customer responses is the concept of "product having a High Quality", on a general level. This term includes all the characteristics contributing to give the product a high value, and is the common element for all the identified keywords reported above.

The keywords have been formalized as official "sources of value", having a high importance in the context of Design to Value process. The Design Change Proposals developed as main output of DtV are intended to maximize these sources of value.

The same keywords are also used as input in the analyzes described in paragraph 7.2 "Classification of the Proposals", aimed to assign priorities to the improvement proposals, depending on the impact they have on the final value of the product in the eyes of the customers.

6 “Teardown Analysis” and “Function Analysis”

In the context of the DtV process, as part of the activities aimed at generating ideas for increasing the value of the product, the use of integrative tools developed in the field of product design can be very useful. Among these tools there is the "teardown analysis" of the product, which in turn can be carried out in conjunction with a "Function analysis". In the following paragraphs their description and their application to actuator re-design project is presented.

6.1 Teardown Analysis

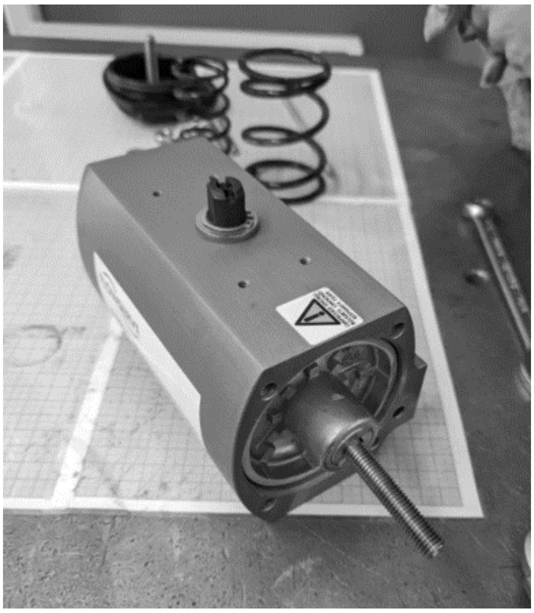
An effective technique for helping the generation of improvement ideas consists in examining a sample of the product, by completely disassembling it in the presence of the team [9], and analyzing on a bench each individual part, as shown in Figure 28. The direct contact with the components helps understand details and facilitate group discussion on new improvement ideas [*20*]. During the teardown, all the actions required for assembly/disassembly procedures are also studied, to identify the most difficult steps, in search of simpler and faster alternative solutions [*21*].

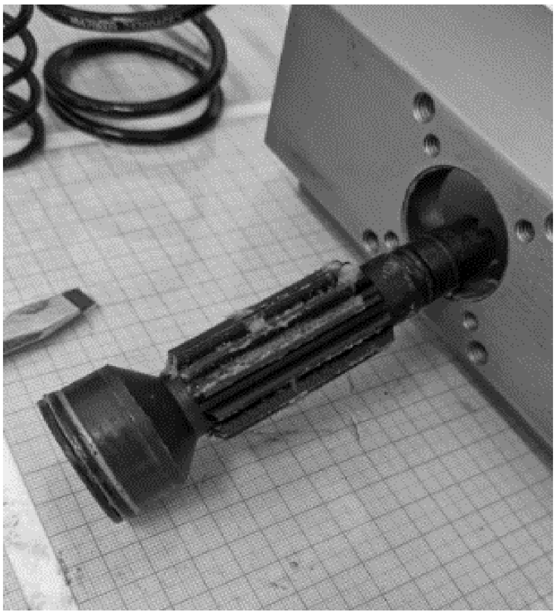
During the actuator re-design project, contemporarily to other activities for idea generation, a “teardown” of an actuator sample having old design has been implemented by the team. The activity has been carried out with enthusiasm because it is in some way original and dealing with physical parts in a manual way it is something that usually is not part of the day-by-tasks of many of the team members.

During the activity, after having completely pulled apart a sample of actuator, the main components have been placed in front of their construction drawing, as shown in figure Figure 29. They have been weighed, and measurements have been taken to evaluate whether the actual dimensions and tolerances corresponded to those in the drawing.

The following main features have been analyzed:

- the material chosen for construction,
- the production process (milling, casting, etc.),
- the heat treatment or surface treatment,
- the dimensional and geometric tolerances,
- the surface roughness,
- the presence and value of draft angles in case of casted components.





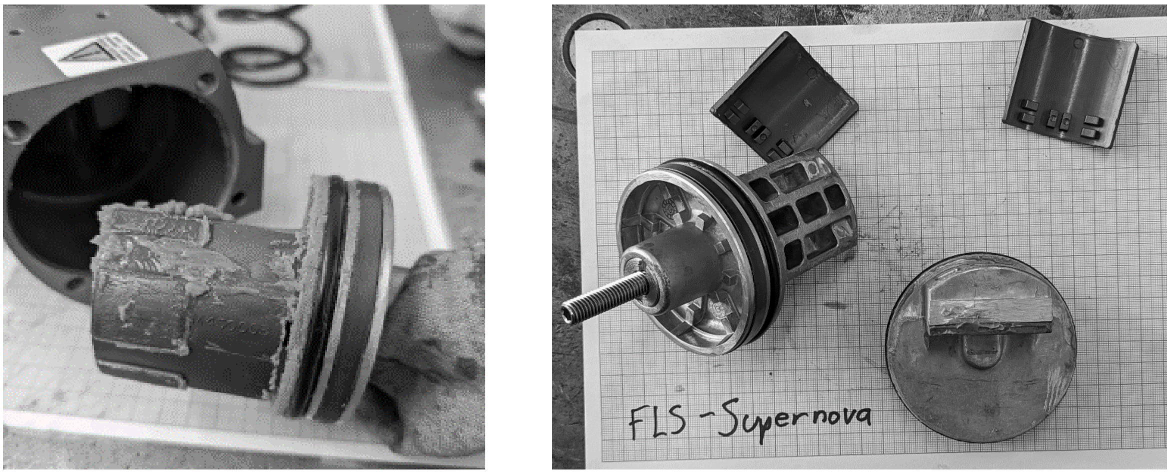


Figure 28. Moments from the teardown Analysis, during in-depth study of each component.

By directly observing and discussing in group the above features, different opportunities for improving the component more easily emerge, and it is possible to formalize many improvement proposals. Ideas can be proposed about new production processes or new materials previously not taken into consideration. In the case of the actuator, for example, a proposal emerged about the replacement of small, machined components with new versions obtained by investigating alternative and new manufacturing process, like for example stamping, or sintering of metal powders or fast metal 3d printing.

Furthermore, during teardown it is possible to study all the actions to be performed during the procedures for assembling/disassembling, in search for design changes that could make them faster and easier.

In the context of the actuator project, the teardown has been an opportunity to review the most delicate phases of the assembling process, studying the steps that have been reported as most complicated by the team members from production department during their presentation, as described in paragraph 5.1.2 “Production – Analysis of assembling procedure”. For example, Figure 38 shows a series of alternative concepts, developed with the aim of improving the fixing system of a bushing, following a need highlighted by the production department. These proposals have been developed thanks to the ideas and observations performed born during teardown.

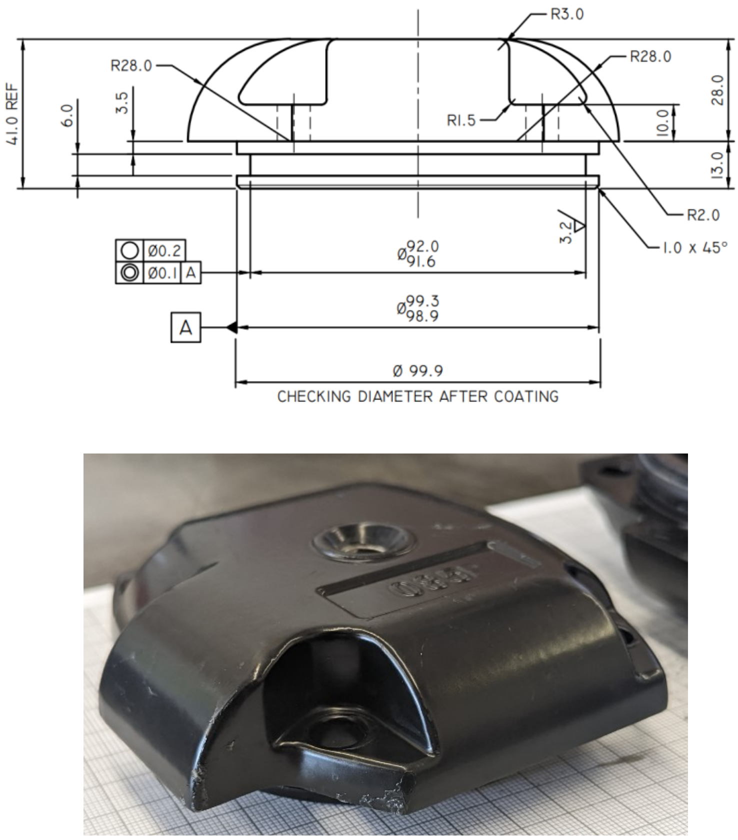


Figure 29.Analysis of actuator components in front of their detailed construction drawings.

6.2 Function Analysis

In conjunction with “teardown” analysis, it is possible to take advantage of the moment when the team comes into contact with the individual parts and mechanisms of the product, for performing another group of effective techniques aimed to support product design / re-design and developed in the field of Value Engineering / Value Analysis [*22*], defined as "*Function Analysis*".

6.2.1 “Function Analysis” definition and procedure

During Function analysis the focus is shifted from the item itself to its function, and to its role in the context of the whole assembly. This type of reasoning allows team member belonging to different working fields to develop new insights on the components, discovering aspects maybe not evident to everyone [*23*].

Through Function analysis the importance of each component is better understood, and the reason of its presence in the assembly and the presence of its features becomes clearer [*24*].

The function of a component is defined as its specific purpose of use. Describing a function is a way to describe a "need", and therefore, during workshop, the description of these "needs" stimulates creativity, pushing towards the proposal of alternative solutions. Function analysis can then represent a useful passage during DtV, providing inputs for the "idea Generation Phase", as schematized in Figure 30 (Value Analysis Canada©).

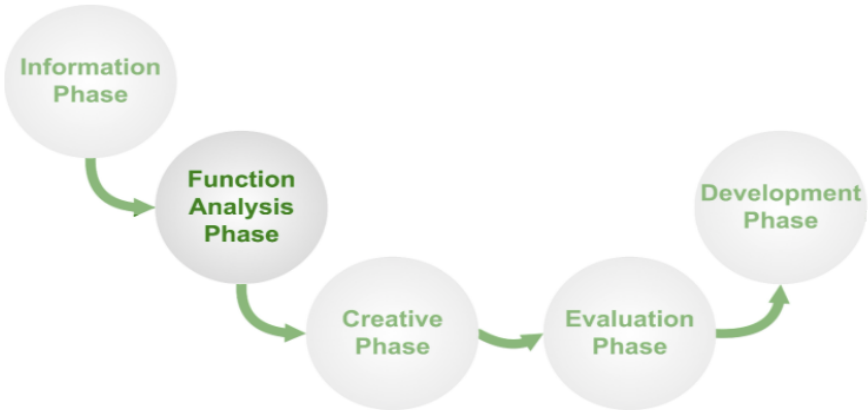


Figure 30. Position of the Function Analysis phase within a Value Analysis / Value Engineering Study (image courtesy of Value Analysis Canada© 2023)

When combined with analytical techniques, Function Analysis provides very useful information, that can be used in the context of creative workshops, for developing alternatives to achieve the desired functions [*25*]. In fact, understanding and quantifying the maximum resources that it is possible to dedicate to each function is very important, as in this way it is possible to set constraints for the definition of alternative solutions, that must be feasible. For this reason, this information is obtained by performing dedicated quantitative analyses, based on activities like the "costing" or "ranking" of the functions, as described in next sub-paragraph 6.2.2.

During the meeting for performing the "Function Analysis" the team members are asked to describe the functions by using "two-word" definitions, composed by "verb-noun" sentences, and describing the "need" satisfied by the function [*26*]. The two words used to describe a function must in fact include an active verb and a noun, identifying something that can be quantified and measurable. The final outputs are a series of concise descriptions, helping to immediately focus on the needs, both the ones necessary for the functioning of the product and the other most important ones, satisfied by means of the product. For example, considering a pencil, the main function can be described as "marking a Surface". Going into detail, each one of its features can be described by the function it performs, described by a short verb-noun sentence, as shown in Figure 31 (Value Analysis Canada©). Using the same approach, after the teardown of the actuator, when the team is in front of a component like the piston, it is possible to start the function analysis by defining its main function, described as "make the pinion rotate".

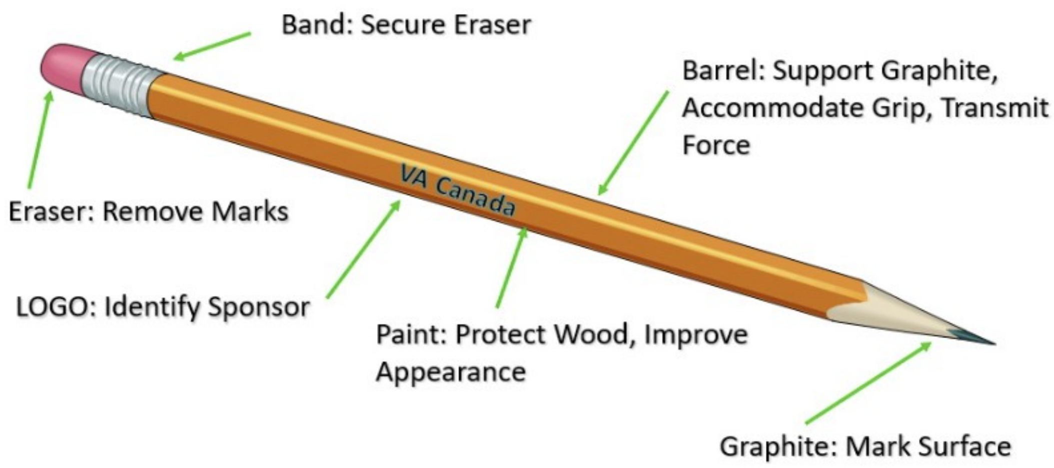


Figure 31. Example of Function Analysis of a product: a pencil (image courtesy of Value Analysis Canada© 2023)

Function Analysis can be further developed thanks to additional related techniques, like the "*Function Analysis System Technique*" (FAST) [*27*], where the functions are connected by means of a diagram, showing the logical relationship among them [*28*]. In this way it is possible to identify changes, with the purpose to unify functions, discover missing functions or eliminating duplicated ones [*29*]. In the context of DtV project, the function analysis did not enter into this stage, as a clear enumeration and definition of the functions has been deemed as sufficient for having the necessary input for starting another important subsequent activity, aimed to their ranking and "cost definition".

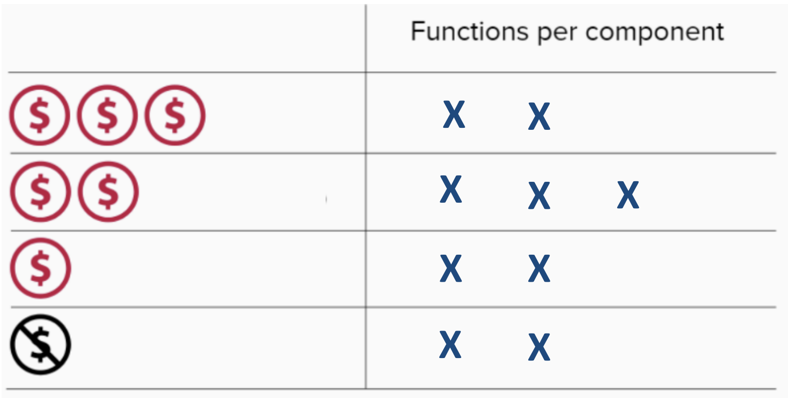


Table 3. Matrix for distributing the component cost among its functions and example of distribution of the functions.

6.2.2 Ranking and “cost definition” of the functions

In a second step of the Function Analysis, it is possible to review each function by answering the question “*which is the value of the function and the cost we can assign it?*”. Each function can be classified [*30*], assigning it a score, for example from 1 to 3, as shown in Table 3. Performing this activity, it is possible to:

1. assign priorities among the component features, understanding which are the most important ones;
2. define limits of cost for each function.

In fact, after having decided the maximum assigned cost for a component, it is possible to distribute it among its functions, according to their score. For example, let’s assume that we decide to assign a maximum cost of € 20 for a piston. Moreover, let's hypothesize that the analysis of the functions led to determining the distribution reported in Table 3:

- n°2 functions with n° 3 "$"dots,
- n°3 functions with n° 2 "$"dots,
- n°2 functions with n° 1 "$"dots,
- n°2 functions with n° 0 "$"dots.

The total number of "$ dots" amounts then to: 2x3 + 3x2 +2x1 + 2x0 = 18 dots.

The cost attributable to each dot is therefore: 20/18 = € 1.1.

For the one-dotted functions it is therefore possible to assume in the first instance to dedicate them a maximum expenditure of 1 x €1.1 = €1.1. For each one of the most important 3-dotted functions it is instead possible to use resources up to an indicative expense of 3 x € 1.1 = € 3.3.

Associate to each function its indicative maximum cost also helps to decide which are the functions where it is better to concentrate the efforts for the investigations of design enhancement, in order of achieving the biggest possible impact in terms of component functionality, quality and cost improvement. Furthermore, associating a cost to a function helps also to understand in its turn the maximum cost of possible proposed improvement alternatives. Good alternatives but exceeding by too much the assigned cost lose relevance, because they are too difficult to implement.

During the function analysis of the actuator, the just described quantitative analysis was carried out for each one of its main components, during an online group meeting. The obtained results were a useful support to generate improvement ideas during the subsequent brainstorming workshops. For example, the extruded center body of the actuator has been studied analyzing its relations with other components and about its role in the execution of the final purpose of the actuator, and the functions reported on the virtual blackboard of Figure 32 were identified. A target cost for the component has been assigned and it has been distributed among the functions, according to the just described procedure. In this way it has been possible to better understand that this component is very critic, as it must perform many functions, and many of them have high importance or "n°3 $ dots".

In Figure 33 it is also possible to notice the high number of virtual post-it created by team members while studying this component during brainstorming meetings. The cost distribution among functions allowed to notice that, considering the initial target cost, for performing secondary functions, having less importance but them also necessary, not enough expense remained available. This prediction has been confirmed once received the first offers from suppliers (the component is not produced internally but by external suppliers).

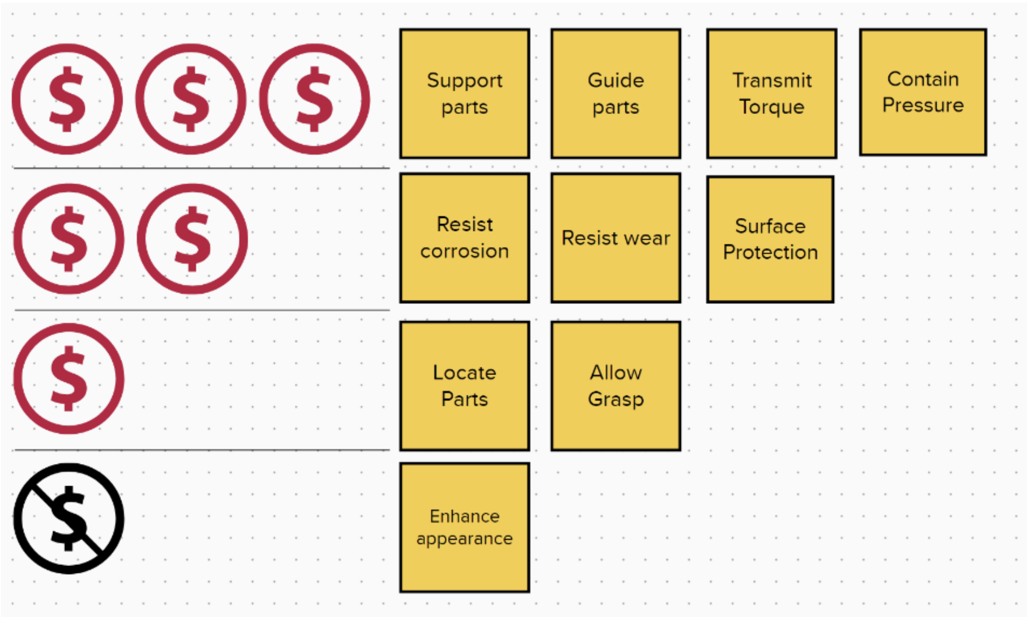


Figure 32. Matrix with the identification of center body functions and their ranking, developed during an online workshop.

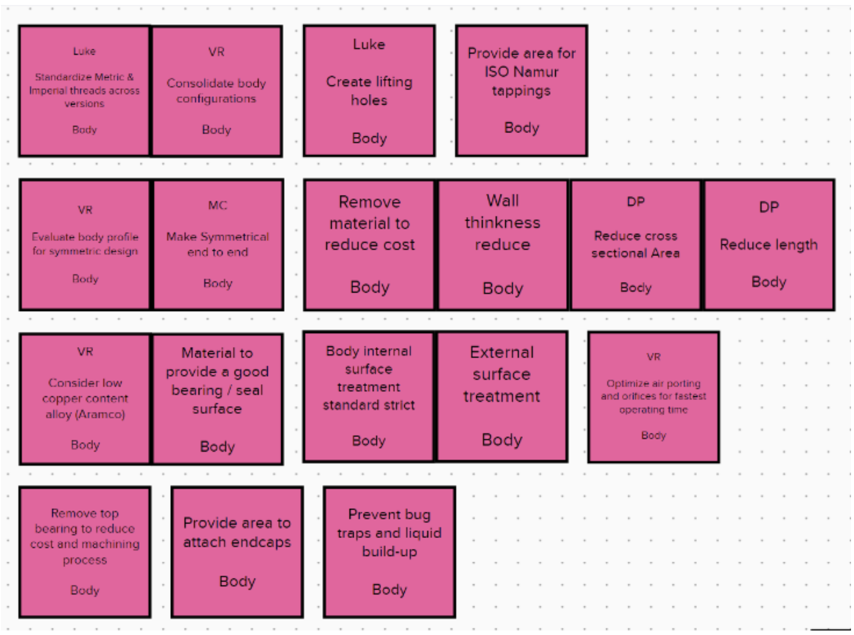


Figure 33. Virtual post-it written by the team on a virtual blackboard with the software MURAL® during the function analysis of the center body.

Therefore, it was not possible to respect the initial target cost. Nevertheless, the optimization of the center body obtained thanks to function analysis and all other investigations performed in the context of DtV must be seen as positive, considering it in the context of full actuator re-design.

In fact, in the new prototype of the actuator, functions that previously were present in other components have been transferred to the center body. In this way it has been possible to have a single component to be subjected to complex machining. In particular, the following “functions” have been moved from other components to the center body”:

- the function of housing the threaded holes for the stopper bolts of the angular stroke adjustment system, has been moved from the lateral end caps to the center body, as shown in Figure 34 and Figure 37;

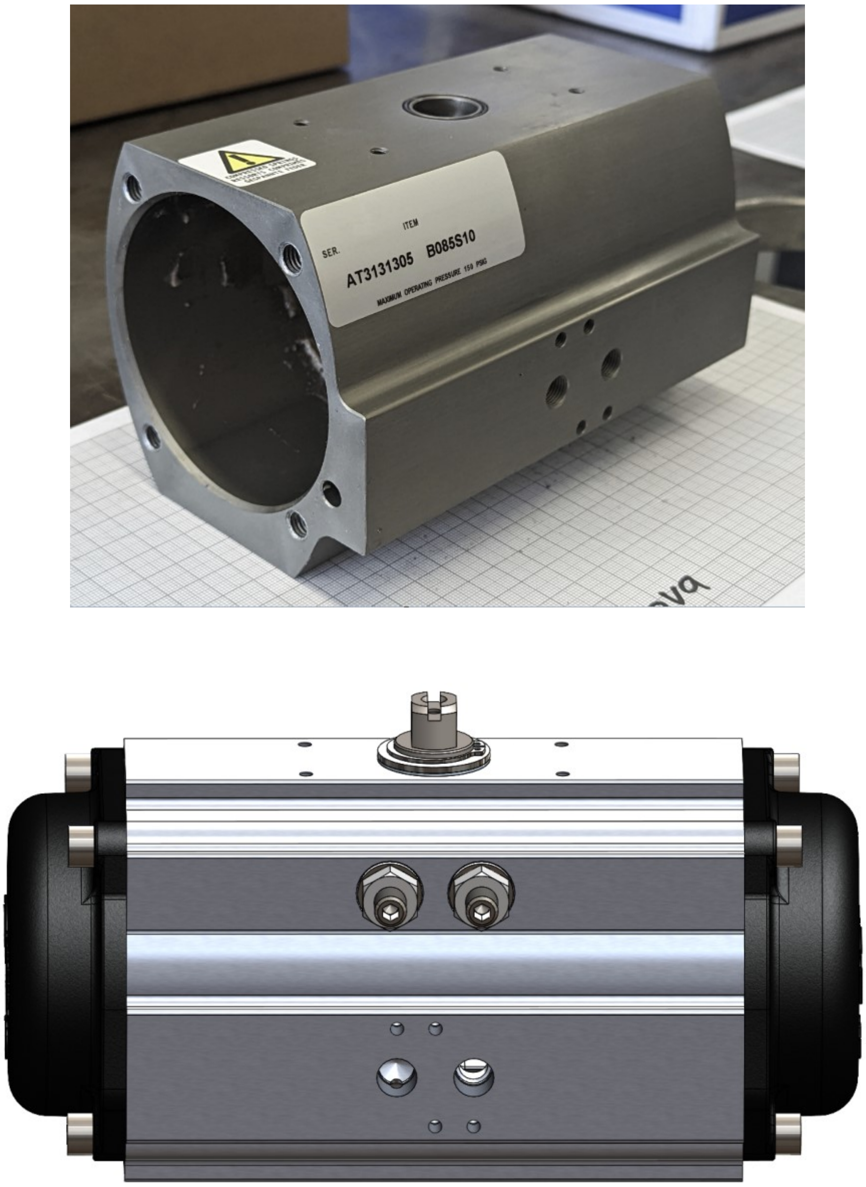


Figure 34. Comparison between old and new version of actuator extruded center body. In new version it is possible to notice the presence of stroke stopper bolts.

- the function of housing the channels funneling the pneumatic pressure into actuator external chambers (the ones pressurized for moving the pistons towards the pinion) have been moved from the lateral end caps to the center body, as shown in Figure 35.

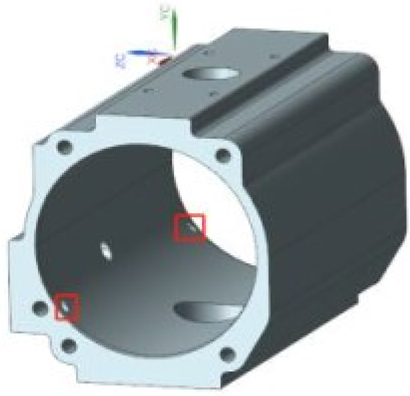


Figure 35. Position of machined holes for pressurizing outer chambers in the new concept of extruded center body.

These choices were taken as a part of the activities of re-design of the angular stroke regulation mechanism. Further details about the benefits of the new design of this mechanism will be provided in next paragraphs.

Furthermore, the actions on the center body reported above greatly concurred to the optimization of the End Cap topology. As shown in Figure 37, by moving machining to center body the end cap topology has been greatly "cleaned up", and mechanical machining has been largely eliminated.

Conversely, the execution of additional processes on the center body creates fewer impacts, as for this component several machining were already foreseen, requiring in any case different positionings of the component on CNC (computer numerical control) machines, by means of dedicated jigs, as shown in Figure 36.

Figure 36. Positioning of center bodies on jigs for machining with CNC machines.

In conclusion, considering the beneficial effects of the center body changes on the design of other components and actuator mechanisms, also if, as predicted by function analysis, a reduction in cost of the component is not achievable, the most important result is that thanks to these changes the final balance at actuator level in terms of costs has been positive. In fact:

- despite the increase in machining and time for processing, thanks to a detailed analysis of the topology, the weight of the center body has been reduced by 6%. Therefore, the final cost increase of the component has been limited to +3%. This data is not in line with the target cost reduction of -10%. Nevertheless, a complete picture of the positive impact of these changes is provided by considering the following bullet points also;
- most of the machining to be performed on the end caps have been eliminated, as shown in Figure 37. As it will be explained in the next chapters, for these components also, a detailed analysis of the topology by FEA has been performed and it has been possible to obtain a weight reduction of 15%. All these changes led to a corresponding cost reduction of -10%;

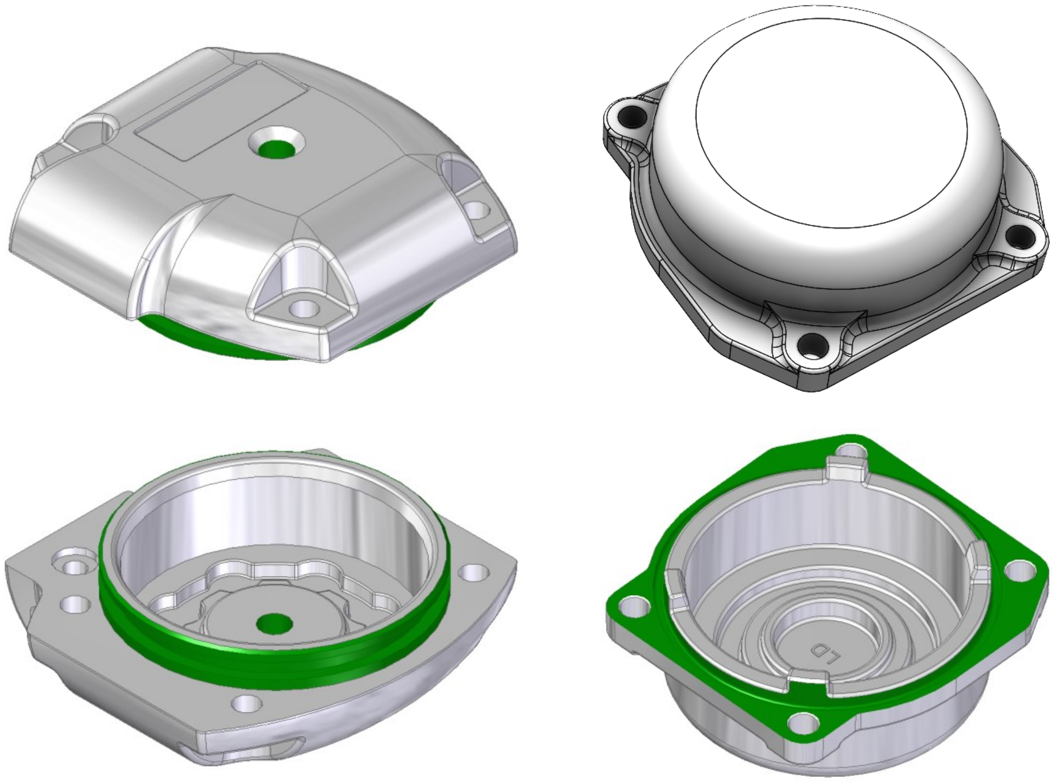


Figure 37. Comparison between the topology of the old and the new end caps.
Green surfaces are machined ones. A significant reduction in number and complexity has been obtained in the new version.

- the transfer of some functions to the center body is occurred in the context of the re-design of angular stroke adjustment system, as it will be better explained in next sub-paragraph 6.2.3. The new design, if on one side complicates the center body, on the other one brings more benefits to the assembly as a whole. In fact, in addition to benefits to end caps. a reduction in pistons cost by 8% and the elimination of other small components has been also achieved, as will be further explained in next paragraphs.

Therefore, the final balance of the complex of the changes described above and performed thanks to function analysis and to all other tools of DtV is positive.

It is exactly thanks to actions like the ones described above that it has been possible to achieve a total cost reduction of the actuator by approximately 8%, as will be set out in Chapter 12 “*Final* Considerations”.

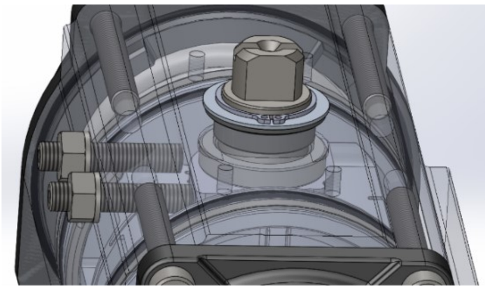
6.2.3 Examples of application of Function analysis for re-designing actuator functions – Pinion bushing fixing system and Angular stroke adjustment mechanism

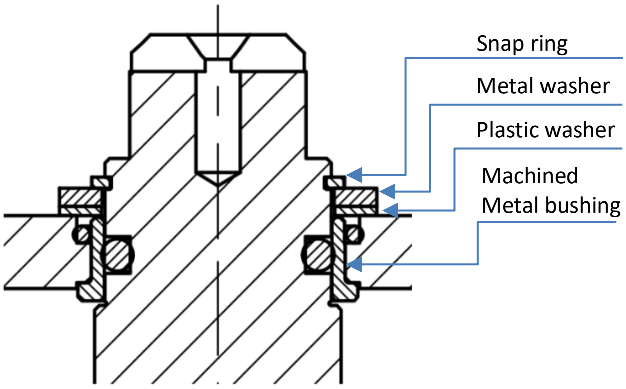
By means of Function analysis, in addition to the study of single components, the study of the functioning of whole mechanisms can be performed also, in search of more efficient construction solutions. Two examples related to the development of the new actuator could clarify this point.

1) System for fixing the upper pinion bushing

Upon suggestion of the production department, during the tear-down activities, the design of the upper pinion bushing and the system for fixing it in position was analyzed, in order to find a solution that would facilitate the assembly activities. In fact, As shown in Figure 38, the current design requires the use of a dedicated press. During the assembly the actuator must be appropriately positioned and oriented under the press, and a metal stem connected to the press allows to fit a metal bushing into its seat. This process requires many steps and consequent assembling time. For this reason, the elementary functions of the system have been analyzed with the technique of the function analysis.

OLD DESIGN





OLD DESIGN - EQUIPMENT NECESSARY FOR INSTALLATION

ALTERNATIVE PROPOSALS FOR NEW DESIGN ELINIMATING SPECIAL INSTALLATION EQUIPMENT

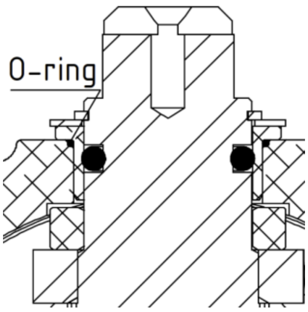
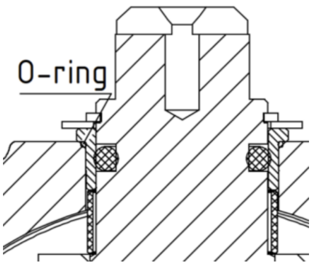
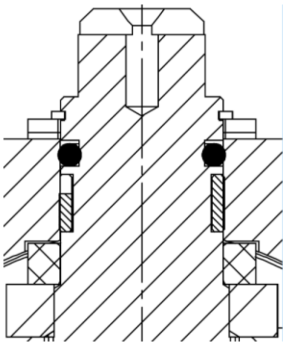
CONCEPT 1	***CONCEPT 2***	***CONCEPT 3***
		

Figure 38. Alternative versions developed during the studies for the re-design aimed to simplification of the system for fixing the upper bushing of the pinion.

In particular, among the main functions there are:

1. *Avoid wear of the pinion;*
2. *Avoid the pinion falls, slipping into the actuator body;*
3. *Contribute to avoid the entry of dirt and water.*

Function analysis has encouraged and facilitated the development of the alternative design solutions reported in Figure 38. The new versions avoid the use a press and replace the metal bushing with less expensive plastic ones. Proposals have been analyzed until one of them has been assessed as the best one to be included in final prototype.

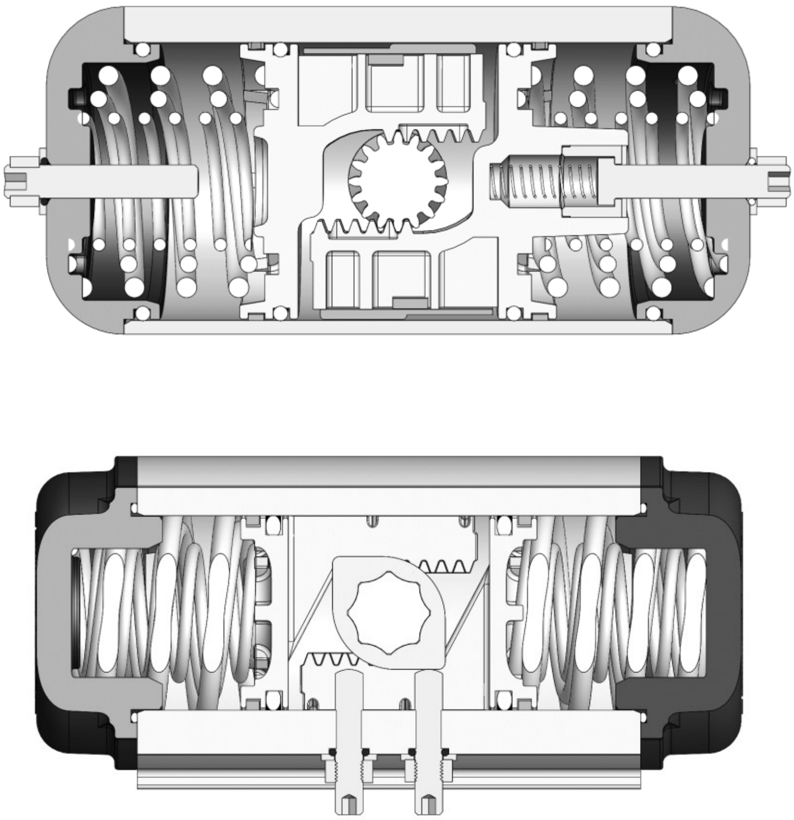


Figure 39. Details of the old and of the new proposed angular Strokes Adjustment systems. The old design is based on lateral screws and complex machining. New system replaced it with a system based on a cam and simplified components.

2) Angular stroke adjustment system

During teardown it has been possible to analyze in depth the mechanism used for the angular adjustment of the strokes. In the old version of the actuator this process is based on two long screws located on the lateral closing flanges, acting on the frontal surface of the pistons, and stopping in this way their linear path. The old system is shown in Figure 40. This solution is functional; however, it involves using two different models of pistons, with complex machining, and additional secondary components like bushings and a small spring. Considering that one of the main objectives of the DtV is the search for design simplification, one of the first improvement proposals that emerged since first DtV activities was to evaluate alternative solutions, simplifying as much as possible the architecture required for performing this function.

For this reason, during teardown the functioning of the old system and of the single components were accurately analyzed. Following, the technique of function analysis has been very useful in order to resume not only the main functions, for example, to obtain fine regulation of angular positions in opening and closing direction, but also for having insights about secondary functions that components must guarantee. For example, regulation screws must be long enough to “allow regulation in extra-stroke conditions also, up to -5° and 95°.

Thanks to the information collected with teardown and function analysis, it has been possible to develop an alternative solution, based on a cam and on two frontal screws. The construction solution of the new proposed system is shown in Figure 40. The cam is machined featuring an inner connection that matches a corresponding male machining on the pinion, so that it could be easily fitted and fixed.

The cam makes it possible to stop pinion angular travel, when it goes into contact with two grub screws, located frontally in the center body. By screwing or unscrewing them it is possible to stop the cam travel in different positions, and then precisely regulate the strokes of the actuator, guaranteeing a correct and complete opening and closing of the connected valve.

The verification of this new system with the necessary structural checks will be presented in depth in paragraph 10.7 “Structural verification of angular strokes regulation system”.

Teardown analysis and Function Analysis demonstrated to be extremely effective tools for helping DtV team. Collected information has been at the basis for generating a lot of Improvement ideas. These ideas are added to the “bucket” containing all the ideas identified during all other DtV steps, and the best one will become official “design Change proposals”, as it will be set out in Chapter 7 “Design Change Proposals”.

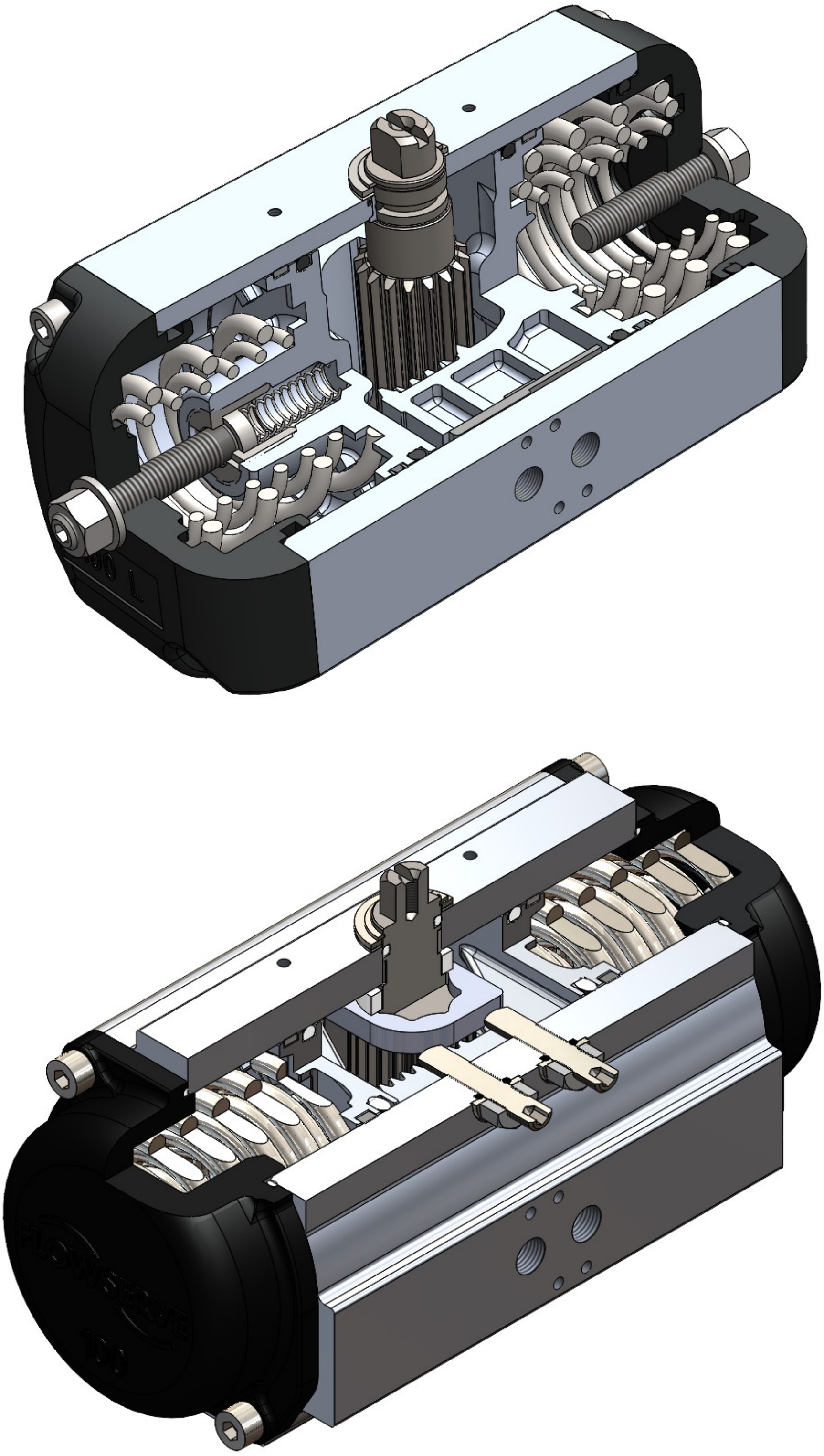


Figure 40. Section assemblies showing the differences between the old and the new proposal of angular stroke adjustment system.

7 “Design Change Proposals”

The proposals emerged thanks to all the activities performed during the phases of Design-to-value cross-functional process constitute a large pool, from which to draw the best ideas to be included in the final plan of the design improvement initiatives [13].

7.1 Preparation of the Proposal Cards

The activities described in previous chapters allowed to obtain a high number of proposals aimed to increase the value of the product. In particular, very interesting proposals were made thanks to:

- the ideas emerged from outputs of customer surveys,
- the ideas generated during teamwork workshops,
- the hints obtained by performing "teardown analysis" and “function analysis”.

Each proposal deserving an in-depth study, is assigned to a team member, who will draw up a short report. A series of simple cards are then prepared, based on a “word” format, as show in Table 4. Each report resumes a brief description of the proposal, about what is expected, and the preliminary studies that were carried out for confirming the effectiveness of the change. These cards are used during the discussions for choosing the official Design Change Proposals, as described here below. Furthermore, they represent the reference documents for providing all the necessary information to the team that will implement the proposal during detailed re-design phase.

At the end of DtV analyses, final meetings are organized, during which the cards containing the salient collected ideas are presented to the whole team for discussing them one by one. For each idea, during the discussion the team members highlight the pros and cons, and ideas that after the review everybody agrees to be critical are eliminated. It is possible, in fact, that an idea is very good in terms of satisfying some of the customer's wishes, or is very innovative, but after having listened to everybody’s suggestions it is possible to discover that it is not feasible with the available resources.

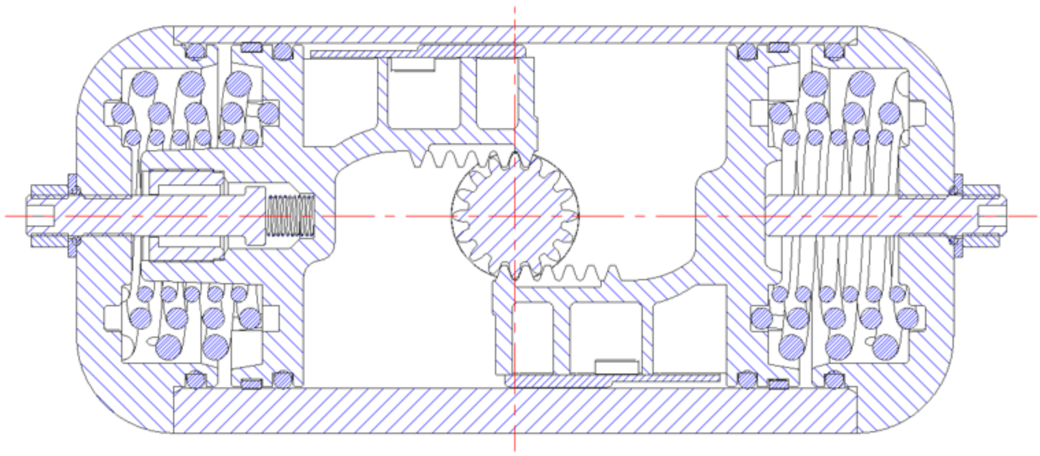
CARD FOR DESIGN CHANGE PROPOSAL

	Design Change Proposal – DCP22 **Optimize pinion geometry**			
ORIGINATION DATE:	PROJECT TITLE:	Supernova DtV		
REVISION DATE:	PROJECT ID:	SER12190	DOCUMENT OWNER:	
REVSED BY:				

1. **Current Design State**
   - Concerning the pinion, it is not anticipated there will be any direct material reduction or at least not enough to make a notable cost saving. Instead, this DCP reviews the starting tooth position which then as an impact on other features.

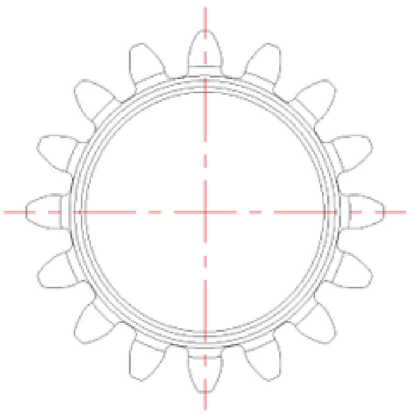
Sketch of existing pinion (shown assembled with pistons apart)

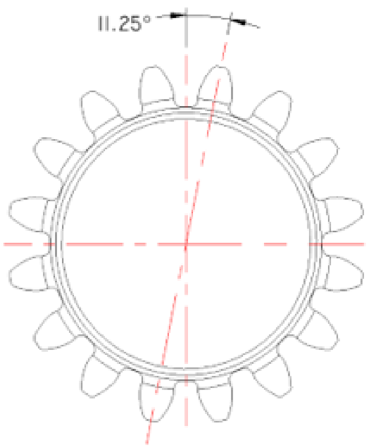
Of particular note in the image below, is the rotation of the pinion and position of the 1st tooth is directly on the vertical centreline. If the pinion teeth are rotated by half a tooth this affects the starting position of the piston rack which leads to an interesting observation.



2. **New Design / Options**

The starting tooth on the existing pinion is at zero degrees however it's possible to rotate the gear by half a tooth (11.25 degrees for the S100) as shown in the second image below.





Adjusting the starting tooth on the pinion to the off - center position, means each piston can be shortened by half a tooth and the body can be shortened by 1 tooth.

The PCD of the S100 pinion gear is 32mm and has 16 teeth. Each tooth has a diametral pitch of 32mm x pi / 16 teeth = 6.283mm. Half a tooth is 3.14mm.

So, this is a saving of 3.14mm on each piston and 6.28mm on the body.

Shorter by half a tooth

Piston		
Current	152667	mm^3
New	148659	mm^3
Saving	-2.63%	

Shorter by 1 tooth

Body		
Current	861643	mm^3
New	834201	mm^3
Saving	-3.18%	

3. **Summary / Conclusions**
   - In order to establish the financial impact of this change it will be necessary to know the costs for the raw material and machining separately. The weight savings above are based on the raw material and do not currently factor in the machining cost.

Pro's and Con's

Pro's	Con's
Reduced physical weight and lower raw material cost.	The material reduction percent is fairly low compared to the implementation time.
Short actuator profile.	Need to modify multiple components to achieve this namely the main body extrusion and the cast patterns for the pistons.

Table 4. Example of Card for presenting a Design Change Proposal DCP to DtV team. The presented Improvement Idea concerns the angular shifting of the pinion teeth, in order to obtain a reduction of the length of actuator body.

During the meetings, it is in fact possible that some members of the team, for example from design or supply chain departments, immediately indicate that an idea, even if very good, entails excessive costs for materials or machining, or leads to complications that it is not possible to manage at level of mass production. For example, the introduction of operations for O-ring assembling requiring excessive precision with high risk of errors by assemblers, or the elimination of millings for flattering coupling surfaces in favor of leaving raw surfaces, causing possible a high number of Quality Assurance non-conformities due to leakages.

A practical example of a positive idea that it has been necessary to eliminate concerns the proposal to change the design concept for the springs contained in the actuator. Proposal was aimed to offer a wider range of torques and to simplify maintenance by introducing a modular system, in which each spring is pre-compressed up to initial working position in a small stand-alone cartridge. In this way it is possible to obtain many torque configurations and to facilitate the removal and replacement. This system is used in other actuators model present in the industry and is shown in Figure 41. Nevertheless, despite these very positive aspects are increasing the value for the customer, during the team discussions it was possible to define that this proposal has lower priority with respect to two other important sources of value found thanks to DtV process, consisting in the simplification of the design and in the search for high economic efficiency.

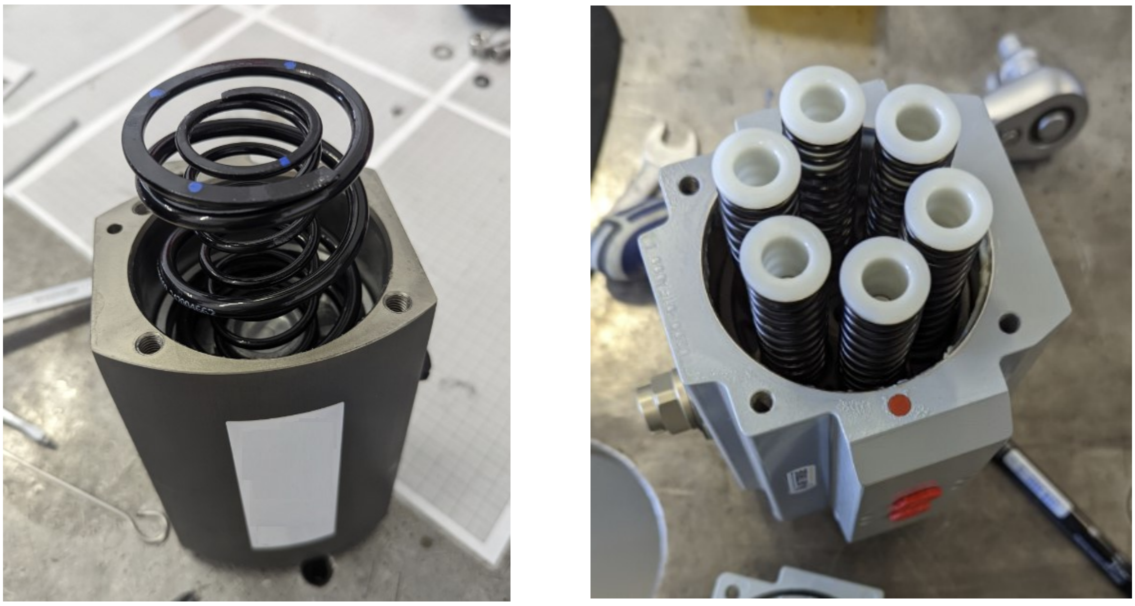


Figure 41. Design Concepts for Actuator springs.
On the left, system used in the first design of the studied actuator, and maintained in the new optimized version. On the right, alternative design concept used by some competitors and based on stand-alone cartridges.

Considering the complexity related to the construction of the small cartridges, after some checks by production and Supply chain team members, the springs system already in use in the original design, consisting of 3 concentric springs of increasing diameter, has been confirmed as the simplest and most efficient solution, even if less “elegant”. In the global balance of pros and cons, it was then decided to maintain the current approach.

Nevertheless, the springs present in the first design will be upgraded, by changing their parameters so as to best adapt to new upgraded Rack & Pinion connection, in the context of the activities for improving the actuator efficiency, in terms of increase of output torque, as it will be described in paragraph 9.2 "Torque Improvement".

7.2 Classification of the Proposals

During the review meetings the team analyzes the ideas with group discussion and must face the task of classifying them in order to find the ones producing the greatest impact in terms of increase in product value. For helping the team in performing a ranking of the proposals, it is possible to introduce the adoption of tools belonging to methodologies of "function analysis" and "quality function deployment".

First of all, as described in paragraph 6.2 "Function Analysis", by applying the principles of this methodology has been possible to understand which are the most valuable functions of each component and also of the main actuator mechanism. This information allows to understand where it is better to focus for proposing ideas of change having a high positive impact. The hints that the team obtained during function analysis oriented then the decisions of the team members during the final review of the proposals also.

7.2.1 Quality Function Deployment

For supporting the activities during the choice of the best value increase proposals, the use of tools developed by the methodology of "Quality Function Deployment" (QFD) can be introduced [*31*]. In particular, the construction of the design tool called "House of Quality".
"Quality Function Deployment" is consolidated method that is very near and strictly correlated to DtV, so much so that it can be seen as its predecessor or "mother" [*32*].

QFD is a method developed in the 60s in Japan by Yoji Akao [*33*]. The aim of QFD is to help transforming the voice of the customer into engineering characteristics of product maximizing its quality. It provides a procedure for quantifying and classifying the user demands, correlating them to product features and functions, helping in this way to deploy the features and the functions that maximize these desires and then the product quality. By means of the tools provided by QFD, it is possible to obtain hints for achieving the maximum perceived design quality at level of components, sub-systems and manufacturing process of the product [*34*].

The main tool provided by QFD is called "House of Quality" and it has been introduced for the first time in the occasion of the design of an oil tanker by Mitsubishi Heavy Industries.

The house of quality is a matrix that allows to classify the importance of customer values, also called "What's", and correlate these values to the engineering characteristics of the product, also called the "How's". The matrix helps identifying the existing correlations, and then helps also assigning priorities to engineering requirements to be achieved in order to maximize customer values.

This process can be applied at any level during the design of a product, that is at component, mechanism, or whole product level, and allows for defining the most important features a product must be provided with in order to maximize its value for the customer.

If we get back to have a look at the definition of Design to Value process provided in paragraph 4 "Design-to-Value (DtV): introduction to the process", it appears clear how these two processes are closely related, so much so that DtV can be seen as a further development of Quality Function Deployment. In particular, DtV addresses the problem of the design / re-design of a product in a harmonious manner thanks to the involvement of many company departments, evolving in this way into a very cross-functional process.

7.2.2 Actuator House of Quality for definition of main Design Change Proposals

In the context of the actuator design enhancement project, the house of quality found application for having a clear vision of the areas in which it is best to invest efforts, with the purpose of making changes to the design producing the highest possible increase in product value in the eyes of the customers.

Thanks to all the activities carried out in the previous phases of the DtV process, from the group workshops to Teardown, the main sources of value of the product were gradually identified, as well as the correlation between each one of them and the improvement proposals that could allow to maximize it. A first attempt to monitor the link between design changes and the source of value taking benefit was made by preparing the Table 5.

A further development of this table could occur thanks to the application of the house of quality technique. The House of Quality that has been prepared for identifying the best design changes of the actuator is shown in the matrix of Table 6.

Priority	Attribute	Function	Design Change proposal
High	Safety	Good strength in front of Pressure tests	Constraint for proposals A, B, C
High	Cost	Constraint to other functions	A. optimization of the topology of main components (extruded central body, closing flanges and cast pistons); B. simplification of construction solutions and reduction of the number of codes and components (example: redesign of the angular stroke adjustment system, introducing a new more streamlined solution); C. simplification of assembly activities (redesign of the fixing system for a critical component).
High	Performances	To Guarantee nominal delivered torques	Constraint for proposals A, B, C
High	Reliability	To positively pass endurance cyclic tests	Constraint for proposals A, B, C
Medium	Ease of Maintenance	To feature Simple adjustment and disassembly operations and procedures	B, C

Table 5. First Matrix prepared for representing the priorities given to the different sources of value and for correlating each design change proposal one to the affected sources of value.

The house of Quality matrix reports the sources of value for the customer on the rows and correlated topics of design changes on the columns. For each improvement proposal, symbols (triangles and rhombus) help to understand if the target is to “maximize” or “minimize” the quantity [*35*].

The cells of the matrix are filled with symbols (•, ◦, upside down triangle) representing the strength of the relationship between each design change and the affected sources of value. When a design change proposal is not correlated to a customer value the cell is left blank, indicating that the source of value is not addressed by the design features improved by the proposal. On the contrary, a black dot (•) suggests that the re-design activity has a large impact on the source of value.

Correlations	
Positive	+
Negative	–
No Correlation	

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

Correlations (roof)	1	2	3	4
1		+	+	
2			+	+
3				+

	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Design Change Proposals / Sources of Value	1 Topology Optimization of main Components	2 Simplification of Construction solutions	3 Reduction of number of part codes composing the assembly	4 Simplification of assembling/disassembling procedures
					Direction of Improvement	◇	▲	▲	▲
1		28%	10	3	Actuator Safety	○	○		○
2		17%	6	9	Actuator Cost	●	●	●	●
3		22%	8	9	Actuator Performances	●	▽		
4		25%	9	3	Actuator Reliability	○	○	○	▽
5		8%	3	9	Ease of Maintenance	▽	●	●	●
					Max Relationship	9	9	9	9
					Technical Importance Rating	517	406	300	333
					Relative Weight	33%	26%	19%	21%
					Weight Chart				

Relationships	
Strong	●
Moderate	○
Weak	▽

Table 6. House of Quality used for prioritizing the design change proposals according to sources of value.

At the top of the matrix, each "tile" of the roof is filled with symbols (**+**, **-**, **" "**) helping to understand if, inside each couple of design change proposals, the ideas can reinforce each other. At the side of the matrix the importance assigned by the customer to each source of value is classified, according to the information collected during DtV.

At the bottom of the matrix, the total impact of each design change is evaluated and weighted with respect to all the other ones. In this way it possible to identify and classify the design changes having the overall biggest positive impact on all the sources of value of the product [*37*]. For this reason, this technique has been very useful to the team for establishing which improvement actions to approve for the execution in the detailed design phase.

7.3 Selection of the final official Design Change Proposals

During the discussions where the improvement ideas were presented by means of cards, the coherence and potential usefulness of each proposal have been definitively verified and confirmed. After that, all the proposals have been classified thanks to the techniques provided by Quality Function Deployment exposed in previous sub-paragraph.

Once having at disposal a full picture of the proposed improvements, with a ranking of the ideas most impacting on the product sources of value, the team can agree to formalize the best ones in the form of final official "Design Change Proposals" (DCPs). DCPs represent the ideas that received a final positive "OK to proceed", and constitute the list of all changes to the product design that will be implemented in the following phase of the project, dedicated to detailed design activities.

The main agreed DCPs concerning the enhancement of the actuator design are the following ones:

1. Re-design of the angular stroke adjustment system, by implementing a solution based on a cam. This DCP has already been presented in sub-paragraph 6.2.3. A comparison between the old and the new design concepts are presented in Figure 39 and Figure 40.

2. Optimization of the geometry, also indicated as topology, and features of the casted lateral closing flanges. A comparison between the old and the new design concepts are presented in Figure 37.

3. Optimization of the topology and features of the extruded central body. A comparison between the old and the new design concepts are presented in Figure 34.

4. 3. Optimization of the topology and features of the casted pistons. A progression of the optimization of piston design concept is presented in Figure 52.

5. Re-design of piston guide pads, that is the plastic pads allowing the pistons to be well aligned within center body inner body and sliding without any jamming. A comparison between the old and the new design concepts are presented in Figure 42.

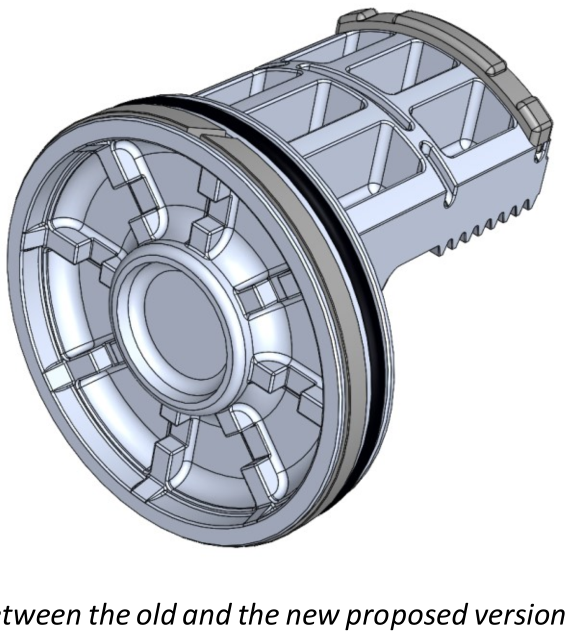


Figure 42. Comparison between the old and the new proposed version of the piston sliding pad. During the validation tests, prototypes of the new pads were created to be installed on the Mockup prototype of the actuator.

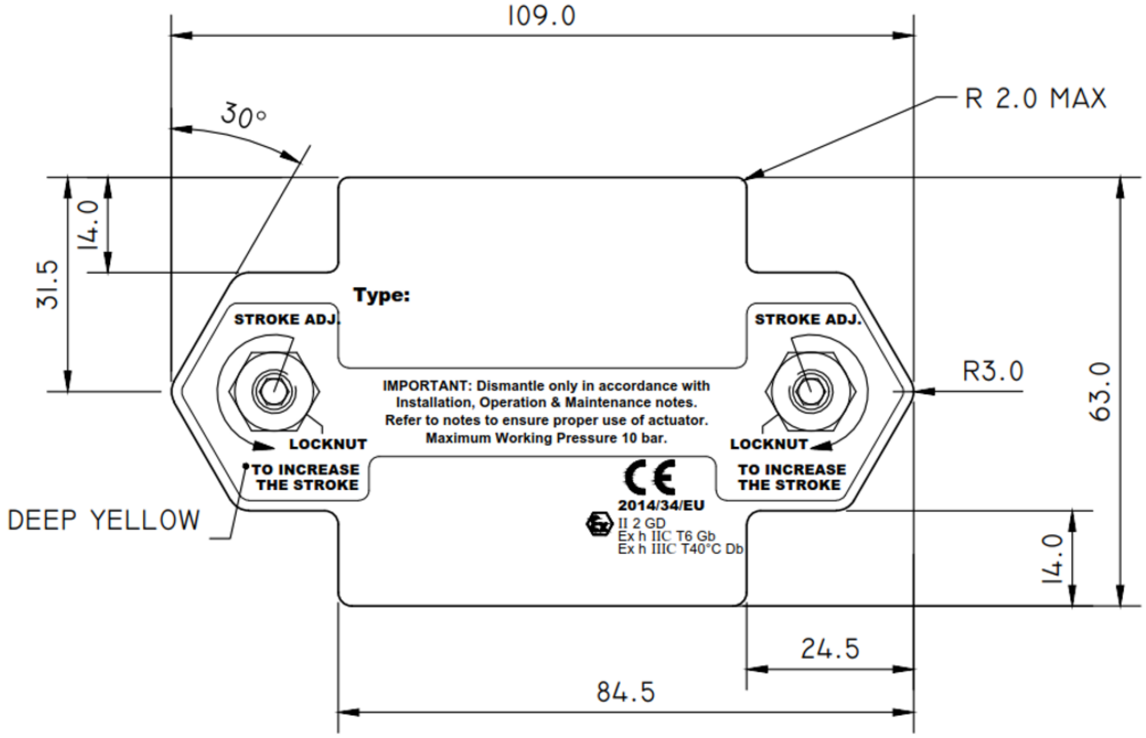
6. Re-design of pinion upper bushings and simplification of the system for fastening the pinion to the center body. The studies performed for the definition of a new design concept upgrading all these features are presented in Figure 38.

7. Introduction of a new nameplate. The new version must be provided with features providing new sources of value. In particular, it must contain new fields so as to be aligned with requirements of updated versions of main actuator standards, like ISO12490 and EN15714-3. Furthermore, it must exploit QR code technology, for providing in-field maintenance technicians with a link to important documentation like Safety Manuals and IOM. A comparison between the old and the new design concepts is presented in Figure 43. Further information about the new proposed nameplate is reported in paragraph 10.9 “Other activities performed during detailed design phase”.

With the definition of the final list of "Design Change Proposals", the initial phase of the project dedicated to the application of the DtV process ends.

The second part of the project, dedicated to the application of advanced design techniques, at this point begins. No less important will be also the third and final phase of the project, dedicated to the validation of the design improvement activities by means of experimental tests carried out on prototypes.

OLD NAMEPLATE



NEW NAMEPLATE

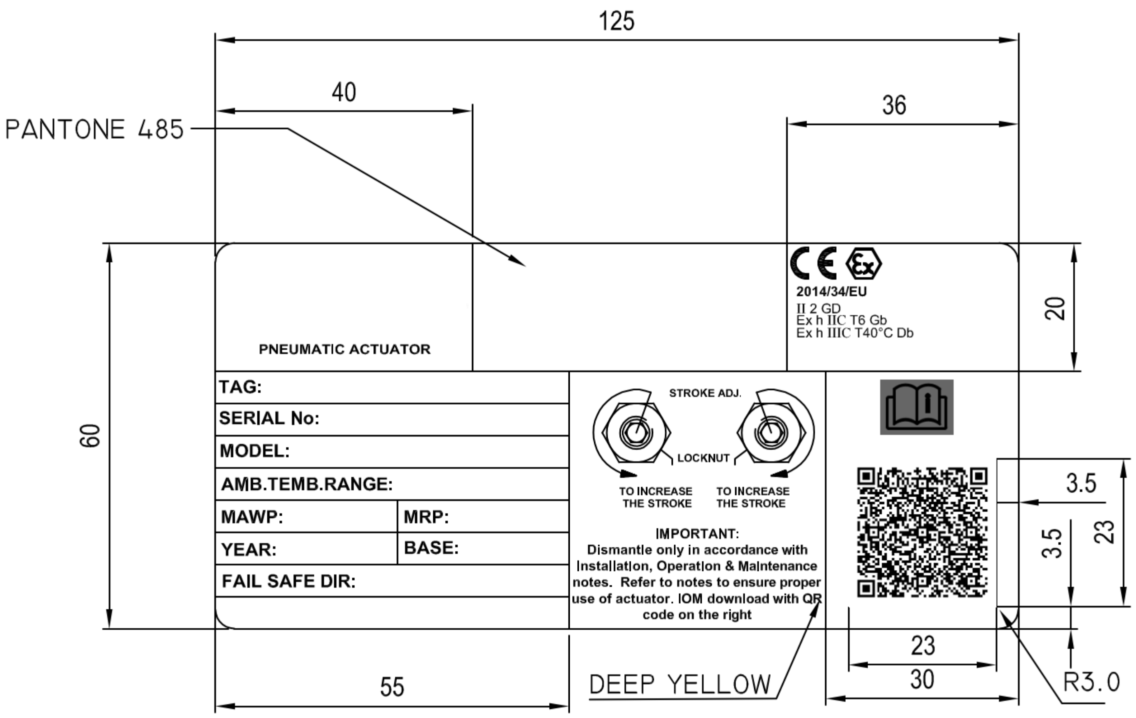


Figure 43. Comparison between the old actuator nameplate and the new proposed one. The new version introduces the QR technology for a rapid access to IOM and Safety Manuals.

8 Detailed design phase

One of the aims of the investigation activities developed in the context of this thesis is to demonstrate that also for a manufacturing company of medium or small size, it is extremely important to introduce advanced design techniques and innovative software design tools during the development of the activities for the design and re-design of a product.

8.1 Tools for an integrated design and re-design process

For innovating the process of design and re-design of a product an initial investment can be required to the company, but the cost will be compensated by the benefits that design enhancement techniques can bring to the product to de designed or renewed. Furthermore, the initial investment can be associated to costs not very high in absolute terms. In particular, these costs may consist in introducing the innovations reported in following sub-paragraphs.

8.1.1 Training in Value Engineering and Principles and Methods of Industrial Design

A training program on these topics for the staff involved into design and re-design projects can bring tangible benefits. With the contribution of trained people the plan for the execution of a design/re-design project can in fact be sketched out in such a way to include a study aimed to Value Optimization. For example, In the studied case of actuator re-design project, the central element of the first part of the activities has been the implementation of the cross-functional process of the Design-to-Value.

8.1.2 Software for FEA simulations for Structural verifications

The introduction of the use of softwares for the execution of Finite Element Simulations (FEA) is essential for enriching the design activities. These softwares are nowadays available also in versions with prices affordable for small companies also, and the skills for performing these activities can be developed internally, with a proper training program of the involved staff. Considering also that nowadays almost all the companies introduced the use of 3D cad, the available 3d models, in addition to simplifying the classic design activities linked to the issuing of construction drawings, can be used as input for simulations based on finite element analyses.

Simulations can be performed with several levels of complexity, and allows for accurate predictions about a wide range of mechanical checks. A fundamental first step to be implemented consists in having the possibility of carrying out static structural verifications, considering a linear behavior of the materials. By Introducing these first activities it is already possible to make a tangible step forward in design activities. In fact, classic checks based on formulas can be integrated with simulations validating the hypotheses made and strengthen the results obtained. Linear static simulations can then be expanded with more accurate options, by including for example the use of material models including the non-linear behavior beyond the yield point.

8.1.3 Software for FEA simulations for complex verifications

This level of application of FEA may be not mandatory for a small company interested in introducing in the market products with a good value for the customers and at the same respecting strict cost constraints for development process. Nevertheless, if it is possible to implement complex FEA, they allow to simulate the behavior of the product in specific working conditions, difficult to predict otherwise, and then improving greatly the level of reliability of the design choices. Among the possibilities that it is possible to investigate with FEA, the most important to be taken into consideration for improving the design of the product are:

- ✓ FEA Simulations for analyzing the behavior in case of extremely high loads, leading to big plastic deformations or to the failure of components of the product, thanks to explicit dynamic techniques.

  In the context of the actuator renewal project, in the near future will be investigated the benefits of introducing the use of explicit dynamic analyzes, to study the behavior of the pressure retaining parts during the initial acceptance tests, when the actuator is brought to a pressure equal to 1,5 times the design pressure (Pd):

$$1{,}5 \times Pd = 1{,}5 \times 10{,}5 \ barg = 15{,}75 \ barg \tag{4}$$

The final objective will be to apply this type of FEA to study the behavior of the actuator when it is mistakenly powered at pressure levels that can lead to the explosion of some component. These tests are usually performed using prototypes, and are called "burst tests". The use of FEA would allow to reduce the extent of these tests, with significant benefits in terms of time and costs. One of the first simulations on actuator components performed with explicit dynamics FEA is shown in Figure 44.

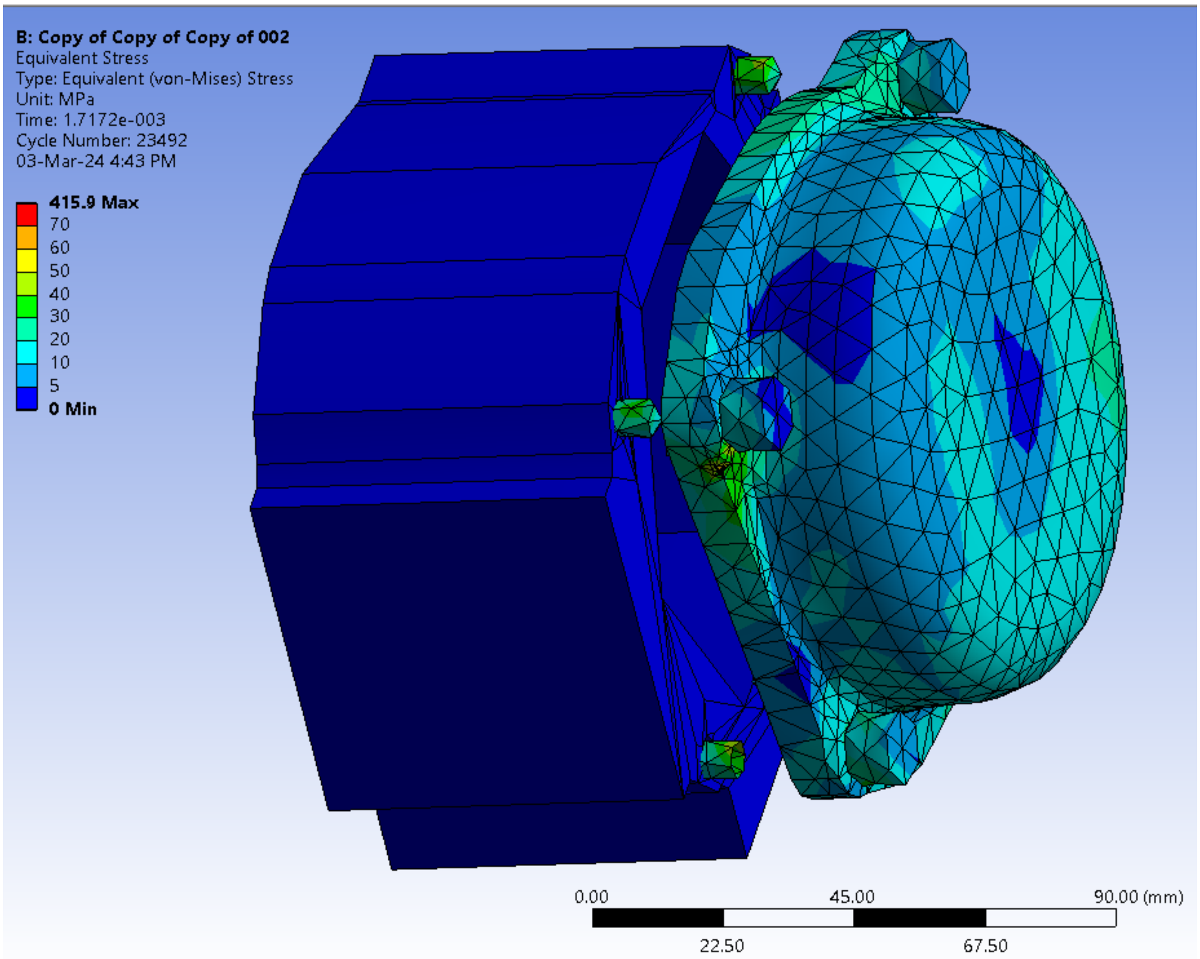


Figure 44. FEA Simulation on Actuator components using an Explicit Dynamics solver. The simulation investigates the behavior of the end cap and of connection bolts when subjected to an extremely high value of pressure, bringing the components to failure (Burst Test).

✓FEA Simulations for investigating the Fatigue behavior. Exactly like for the case of the explicit dynamic simulations, the use of fatigue analyses in also envisaged subsequent steps of the investigations on the actuator is also for the. One of the first fatigue simulation tests is shown in Figure 48.

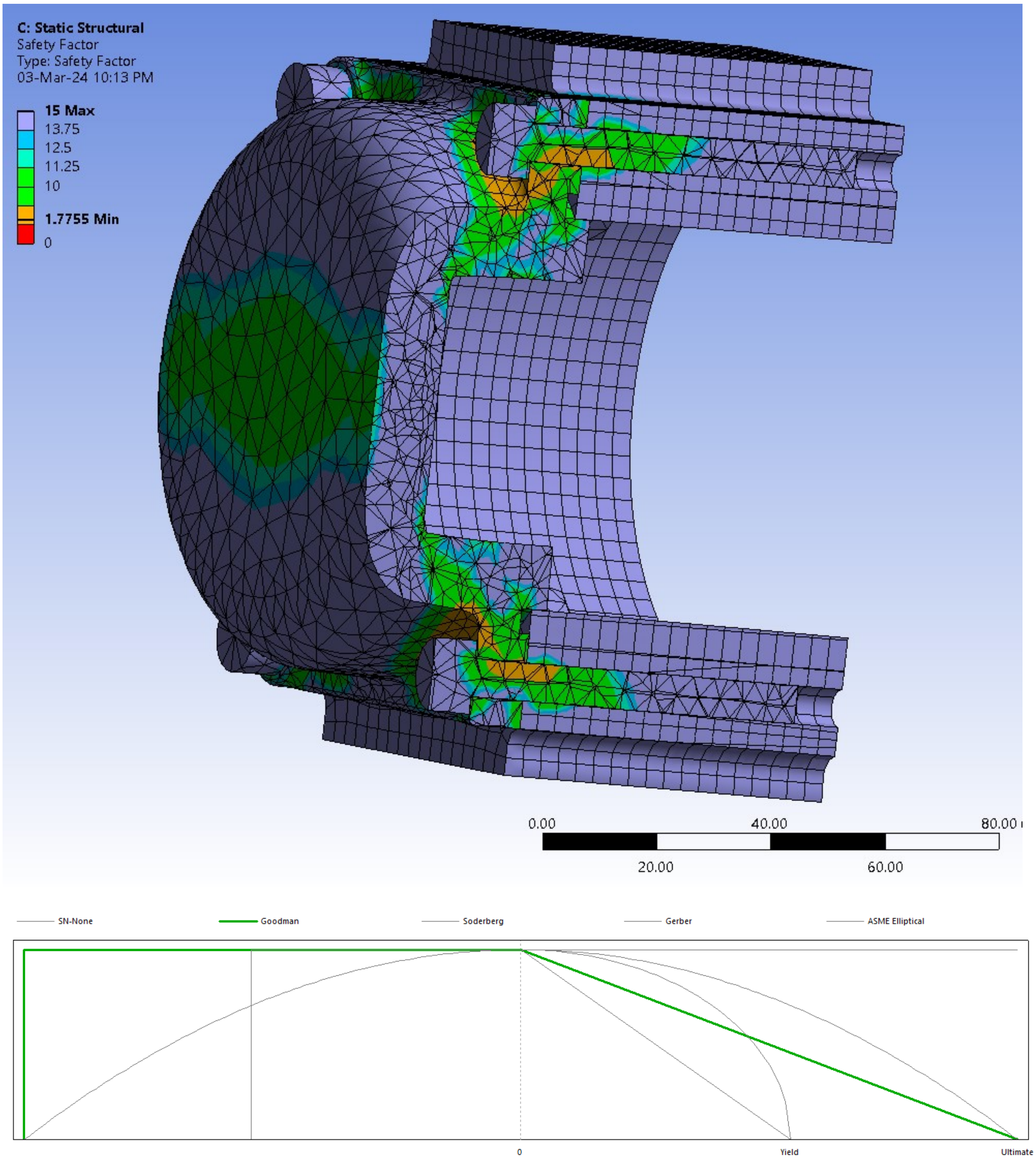


Figure 45. Fatigue assessment of actuator components using a FEA Fatigue Tool.
The end cap and connection bolts have been subjected to zero-based constant amplitude pressure loads equal to design pressure (10,5 barg). The simulation allowed to obtain a first estimation of the safety factor with respect to infinite fatigue life, by using Goodman model.

- ✓FEA Simulations for analyzing the kinematics of the mechanisms present in the product, by precisely defining the values of forces and reactions, thanks to dynamics of rigid bodies.

A design approach based on simulations is therefore a key factor that strongly contributes to the success of a project. The main purposes of the investigations presented in this Thesis consists exactly in demonstrating that the benefits deriving from an extensive application of FEA during the detailed design phase can be multiplied by inserting this phase into a multi-methodology harmonizing the full development of a project for the improvement of the design of a product. In fact, for the actuator project, according to the new proposed integrated methodology, simulation-based design phase has been associated to an initial phase dedicated to value analysis, and to a way of working that maximizes collaboration, information exchange and group work. During the activities this new proposed methodology has been called **TEAM-VAL-FEA** for simplicity.

8.2 The plan for detailed design activities for actuator value-oriented re-design

As described in previous Chapter 7 ““Design Change Proposals”, the main part of the DtV process ends with the whole DtV Team formally delivering to team members belonging to Engineering department a series of detailed proposal, called “DCPs”, for implementing enhancements to actuator design.

The new proposed methodology provides that the path for executing the detailed design activities is based on two successive and complementary phases. The peculiarity of actuator project has been then to combine into the detailed design plan the “classical” approach for structural verifications, based on formulas, with advanced FEA simulations, aimed to stress, deformation, and topology optimization [*38*].

The first phase of the activities has been named "design by Formulas", borrowing this term from a standard for pressure vessels, EN 13445-3 “Unfired pressure vessels - part 3: design”. This phase includes the verifications performed by issuing electronic spreadsheets with structural verifications. These analyses are used to make the first choices regarding the structural characteristics of each component, such as manufacturing process and material, first estimation of the overall dimensions and thicknesses of the load bearing sections.

The second phase of the detailed design plan focuses on the use of simulation techniques, based on Finite Element Method (FEM). During this phase different design concepts are simulated, so that it is possible to define the best one and arrive to experimental validation phase with design solutions that proved to be the most promising, after a careful design enhancement based on "topology optimization" concept [*38*].

Considering the case where a product launched on the market years ago needs a design update, like for the studied rack & pinion actuator, it is possible to exploit all the benefits that can be introduced by the new design techniques that are now available but were not present at the time of the initial design. For example, FEA simulations, with all the possibilities of improvement that they offer in the fields of static structural verifications and topology optimization, at the time of the first design of the studied actuator, in 1984, were accessible only to few companies operating in very specific fields, like aerospace and military industries.

On the contrary, they are now accessible to medium small companies also and must then be used, with the purpose of maximizing the value of the product, by trying to achieve the most efficient use of materials, guaranteeing at the same time safety and reliability.

In the next two paragraphs each one of the two approaches used for verifying in a complete and accurate way the design of the new version of the actuator will be described, discussing some examples, and highlighting the results that has been possible to achieve.

Finally, during the detailed design phase, an important part of the activities has been dedicated to perform the verifications finalized to check the compliance of the design of pressure containing parts with respect to an international standard for pressure vessels (EN13445-3), as required by the main actuator product standards (EN15714, ISO12490, API 6DX).

9 “Design by Formulas”

The design plan implemented during the actuator meliorative re-design project provides that, during the first phase of the detailed design activities, the verifications of the safety and reliability of the components rely on the issue of electronic spreadsheets based on formulas for structural verifications. This phase, on which in 1984 the design of the first version of the actuator first was entirely based, becomes with the new approach a first one of two steps, during which initial choices are made. The output design of this phase will be then refined and optimized thanks to the simulation techniques provided for the second design phase.

The safety of the actuator against the risks due to pneumatic pressure is an absolute priority, and for this reason the main actuator product standards (EN15714-3, ISO 12490, API6DX) require verifications in accordance with an international standard for pressure vessels. For the studied project, EN13445-3 has been the chosen as reference standard. This standard contemplates the use of FEA analyses, defined as "Design by Analysis", as an integration or as an alternative to "Design by Formulas".

Formulas constitute the basic tool for choosing the minimum dimensions and thicknesses guaranteeing that components have the proper mechanical strength under the mechanical and pressure solicitations present during the initial testing and in normal service conditions for all actuator working life. It is possible through the formulas to have a first confirmation about a suitable response of the components when they are subject to traction, compression, torsion and bending loads. Starting shapes verified by formulas could then be refined and optimized thanks to simulation techniques, in the subsequent design phase.

For the actuator verifications the spreadsheet containing structural calculations have been elaborated by using the formulas present in the mechanical manuals like "Roark's Formulas for stress and strain" [*39*]. During the verifications the components have been simplified, by schematizing them with simple geometric shapes and by dividing them into sections. Then for each analyzed section the central activity consisted in finding a suitable formula for representing with the best possible approximation the actual load case. In addition, pressure containing parts have been verified with dedicated formulas, as detailed in next sub-paragraph.

9.1 Verifications of Pressure containing Parts according to EN13445-3

Being powered by pneumatic pressure, a rack and pinion actuator also represents a pressure vessel, even if its main function is delivering a torque. The safety of the design in presence of pressure loads is an absolute priority. For this reason, main industry standards for actuators require that pressure containing parts are designed in compliance with recognized international standard for pressure vessels.

9.1.1 Main Reference Standards

Among the standards indicating the requirements that an actuator must satisfy for guaranteeing good manufacturing practices, regarding design, safety of "pressure containing parts", reliability, operative life, quality controls and testing, it is possible to mention:

- EN15714-3:2022. *“Industrial valves - Actuators - Part 3: Pneumatic part-turn actuators for industrial valves - Basic requirements”*
- ISO12490:2011. *“Petroleum and natural gas industries — Mechanical integrity and sizing of actuators and mounting kits for pipeline valves”*
- API 6DX:2020 “*Standard for Actuators and Mounting Kits for Valves*”

All these standards ask for design compliance to standard like the following two. Below are in fact listed the two main internationally recognized standards establishing the requirements for the design, construction, quality inspection and testing of pressure vessel, that is possible to use for the verification of actuator components retaining the supply pneumatic pressure toward external environment:

- EN13445-3:2021. *“Unfired pressure vessels - Part 3: Design”*
- ASME BPVC - Sec. VIII - Div.1 2023. *“ASME Boiler & Pressure Vessel Code - Section VIII - Rules for construction of pressure vessels - Division 1”*

9.1.2 The spreadsheet with EN13445-3 formulas

The parts of the actuator containing the supply pressure avoiding that is leaked toward the external are the extruded central body, the lateral closing flanges, called end caps, and the screws for connecting the center body to end caps. Pistons are housed inside the central body, and therefore do not contain the pressure towards the external environment.

These parts ensure the safety of the operation of the actuator with respect to the external environment and to the operators interfacing with it when pressurized. The failure of one of these components could cause in fact an explosion or in any case the expulsion of fragments of materials at extreme high speed, reason why the conformity of these components to accurate design rules reported in dedicated standards has become an absolute priority in the design of a fluid actuator.

A spreadsheet complying with formulas of EN13445-3 standard has then been issued. Since the formulas of the standard take into consideration typical components of pressure vessels, like shells, flanges, flat ends, which in many cases do not exactly coincide with the geometric characteristics of the designed component of the actuator, it is necessary to use the same technique valid in general and described in previous sub-paragraph, when speaking about verifications in front of mechanical loads by using mechanical design manuals.

This technique consists in schematizing the component by dividing it into simple sections. The sections have simple shapes, and it is then possible to associate them to the existing formulas. For example, the lateral closing end cap of the actuator has an articulated geometry that cannot be associated to existing load cases present in EN13445-3. Therefore, it has been necessary to divide it into three sections, each one suitable to be verified through formulas available in the standard. The technique just described applied to the calculations of the end cap of the actuator has been reported in full in "Appendix 1 – Verification of End Cap according to EN13445-3 Design by Formulas rules".

9.1.3 Introduction to EN13445-3 "Annex B - Design by Analysis - Direct Route"

In addition to pressure load, pressure containing parts can simultaneously be subjected to loads of a different nature, for which no formulas are provided by the standards, as, for example, concentrated loads or earthquake solicitations. For these situations, main pressure vessel standards provide for the possibility to use FEA, defined as "design by analysis". In the case of the actuator, this situation occurs for central body and for the lateral closing flanges, as shown in Figure 46. For FEA set up and results analysis the rules of EN13445-3 “Annex B - Design by Analysis - Direct Route" have been followed. Further details about the performed simulations will be described in Chapter 10 “Design by Analysis”.

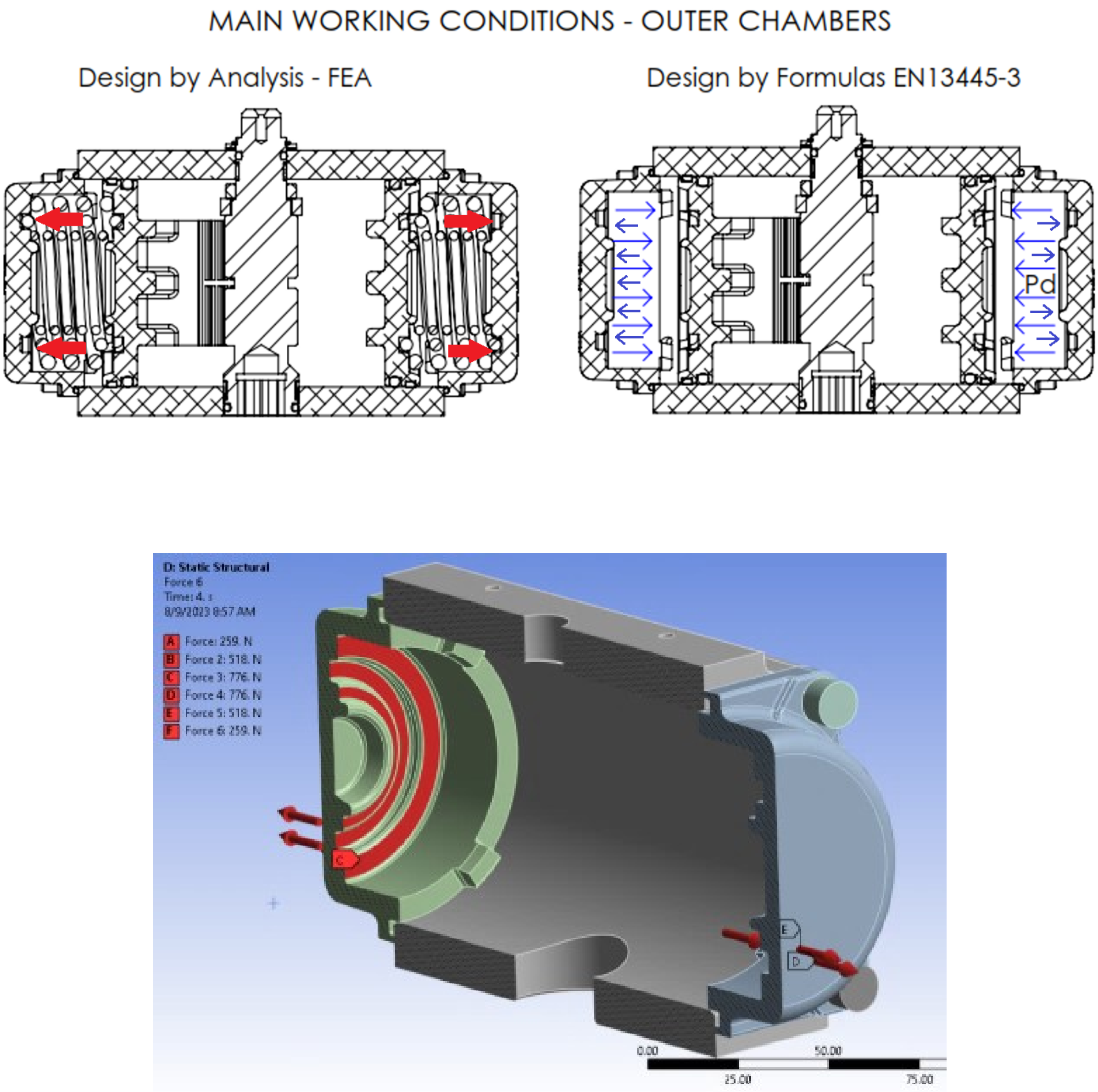


Figure 46. Scheme summarizing the integration of calculations with FEA for end caps verification.
Lateral closing flanges are subjected to both pressure and spring loads. According to EN13445-3, for this load cases a verification by means of “Design by analysis” is possible.

Resuming, to confirm the compliance of the actuator with the requirements of EN13445-3:2021 standard, a dual approach has been applied:

- for pressure loads, the formulas present in the different sections of the standard has been adopted, grouped into a dedicated electronic spreadsheet.
- for special loads not covered by formulas, the "design by Analysis" route has been used.

The opportunity of integrating formulas with simulations for demonstrating the compliance to design rules of EN13445-3 is in line with the new studied design approach, aimed to maximize the use of FEA, and then has been exploited to integrate the checks on all actuator components that are contemporarily subject to pressure and to additional loads, as shown for example also in Figure 49 and in Figure 57.

9.2 Torque Improvement

One of the most important Design Change Proposals presented as at the end of the design to values process concerned increasing the value of the actuator thanks to the improvement of actuator performances, expressed as delivered torque at parity of pneumatic pressure and piston diameter. In this context it has been extremely useful to integrate initial structural verifications of rack & pinion gear, based on Lewis theory, with dedicated simulations. As show in Figure 50, FEA confirmed the results of formula (5), allowing to enter in validation phase with a much higher level of confidence on positive tests completion.

$$\sigma = \frac{1}{mY}\frac{F_t}{b}k = \frac{1}{2 \cdot 0.296}\frac{6283}{60}1.5 = 265\ Mpa \tag{5}$$

In the formula above:

σ is bending Stress at base of the pinion tooth,

m is the module of the pinion gear,

Y is the Lewis factor,

b is the tooth length,

k is the stress concentration factor.

This value is very near to the values identified with FEA, presenting a peak stress of 276 MPa, as shown in Figure 50.

The design change proposal about rack & pinion geometry optimization has been implemented because it concurs in maximizing the actuator efficiency in terms of torque performance, one of most important sources of value. Thanks to the design improvement study, the Maximum Operating Torque (MOT) has been increased of about 18%.

A related KPI represented by the cost per each Nm of produced torque and expressed in [$/Nm] decreased of about -22%, as show in Figure 73.

The geometry update consisted in the increase of the diameter of the pinion and in consequent adjustment of the module of the gear present on both pinion and rack. In this way, as exposed in paragraph 3.1 “Description of torque generation mechanism”, it has been possible to increase the "moment arm" producing the torque, equal to the radius of the pitch diameter of the pinion. The increase in moment arm has as a direct consequence the increase in the delivered torque at parity of the force exerted by the pistons.

Furthermore, in order to improve the performance of the actuator and make it capable of being used to operate the greatest possible number of valves, a review of the characteristics of the springs was also carried out.

In particular, modifications to the loads exerted by the springs in their working positions at the two ends of the strokes have been proposed. By remodulating these characteristic quantities, explained in paragraph 3.1, it is possible to improve the balancing between the torques delivered by the air and those delivered by the springs at the ends of the angular stroke of the actuator. As shown in Figure 47, in the first series an imbalance was present, for almost all possible spring combinations to be used for covering the torque range of the actuator.

With the new proposed changes to spring load this imbalance has been realigned, allowing the actuator to be used also for valves requiring higher torques at the end of the air stroke.

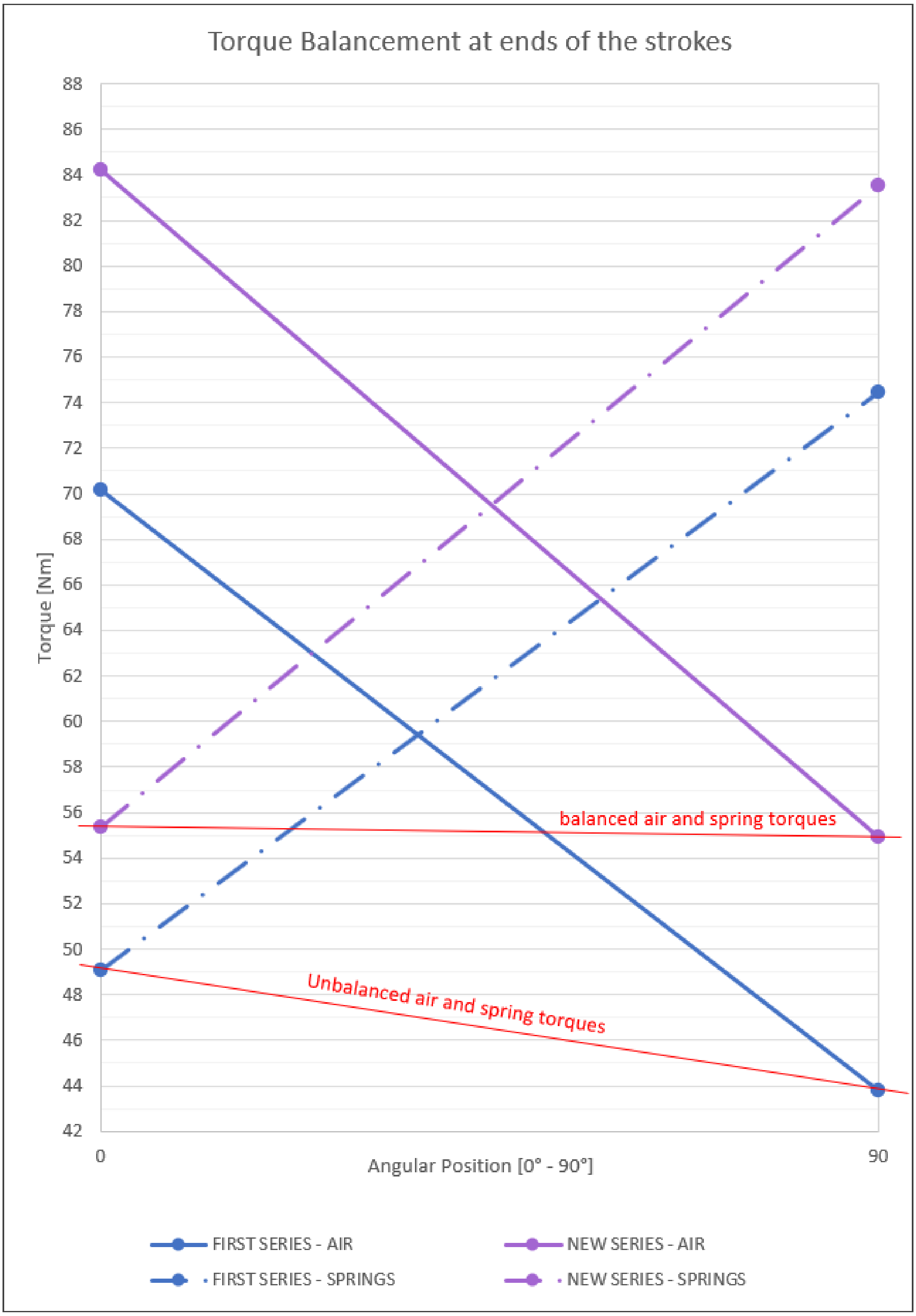


Figure 47. Torque graph resuming the actuator efficiency improvement in terms of air and spring torques.
The red lines show how the balancing between the torques at the ends of the strokes has been improved in the context of DtV proposals.

The study about torque improvement has been extended to other models belonging to the same actuator series of the studied model, as shown in Figure 48. The results confirmed that the improvement idea proposed in the context of DtV allows for an average torque improvement of about 14%.

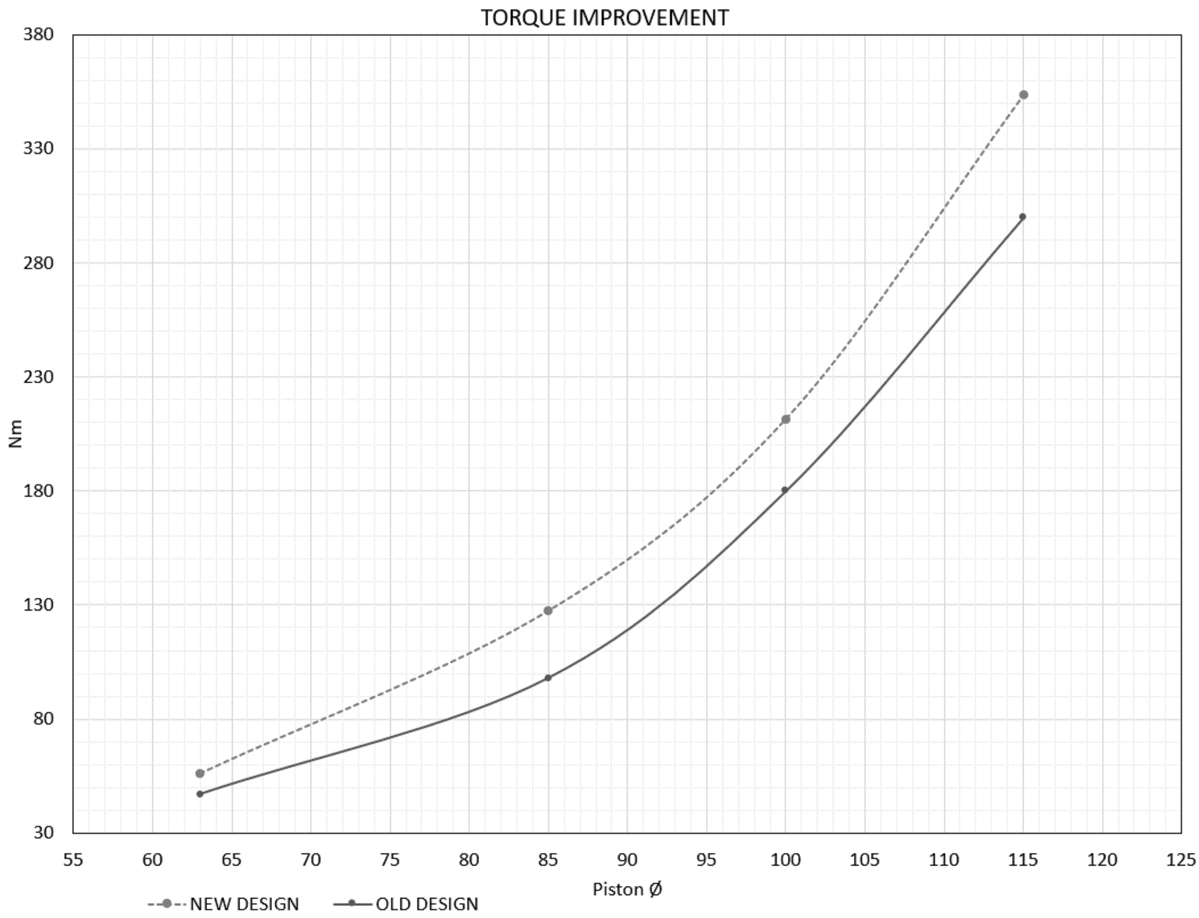
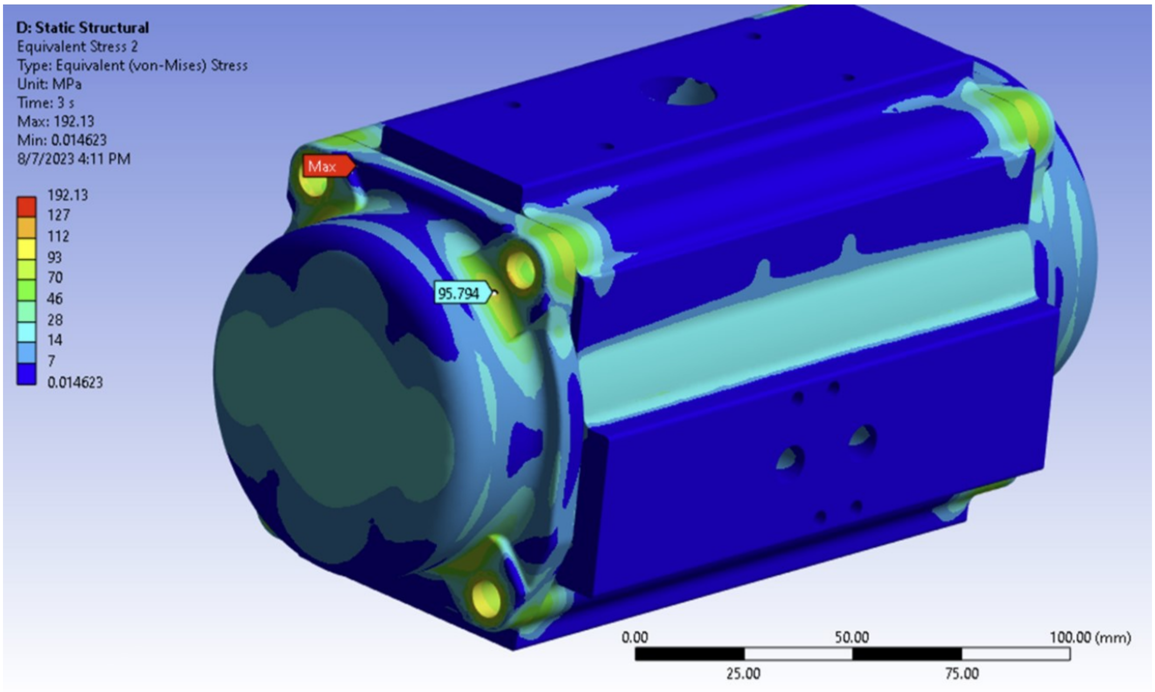


Figure 48. Increase in Maximum operating torque achievable over the entire series of actuators thanks to the improvement idea proposed through DtV.

At the end of the "Design by Formulas" phase of the design plan, the output that is possible to obtain is a prototype, consisting of a detailed 3D model, where all the parts have been preliminary verified using the procedures just described.

This 3D model enters then in the next phase of design activities, called “Design by Analysis”, that will be described in detail in next paragraph. During the second phase its components will be further checked by means of verifications based on FEM simulations, and its final aspect will "refined" thanks to the "topology optimization" techniques applied to its components.



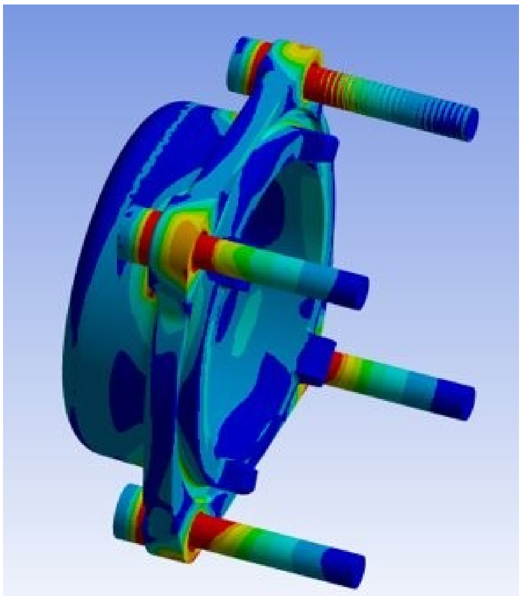
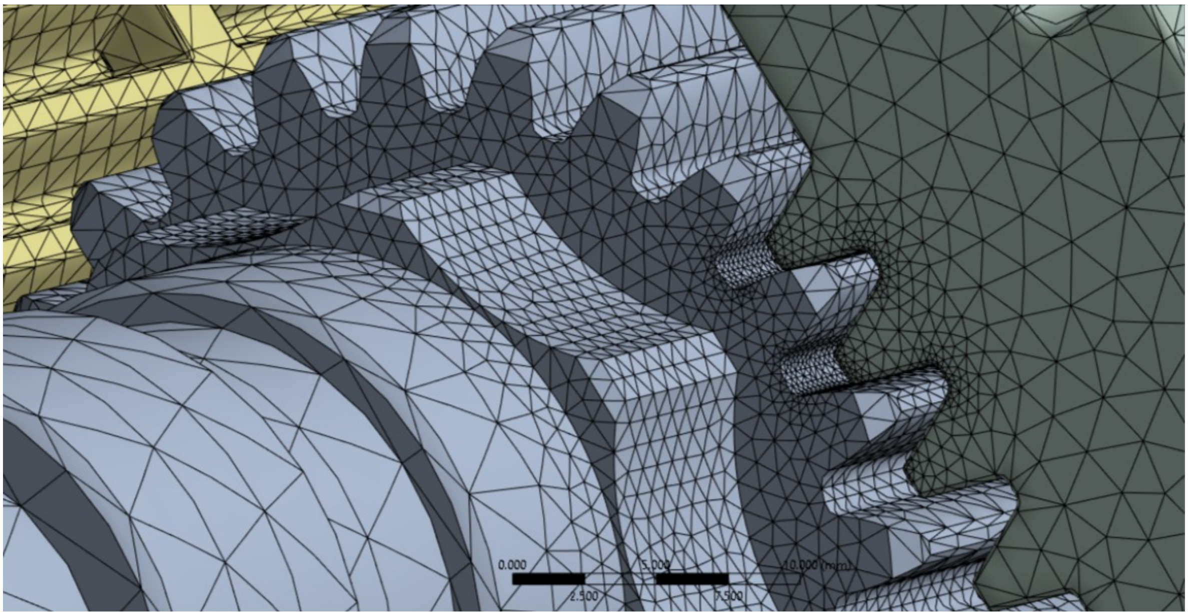
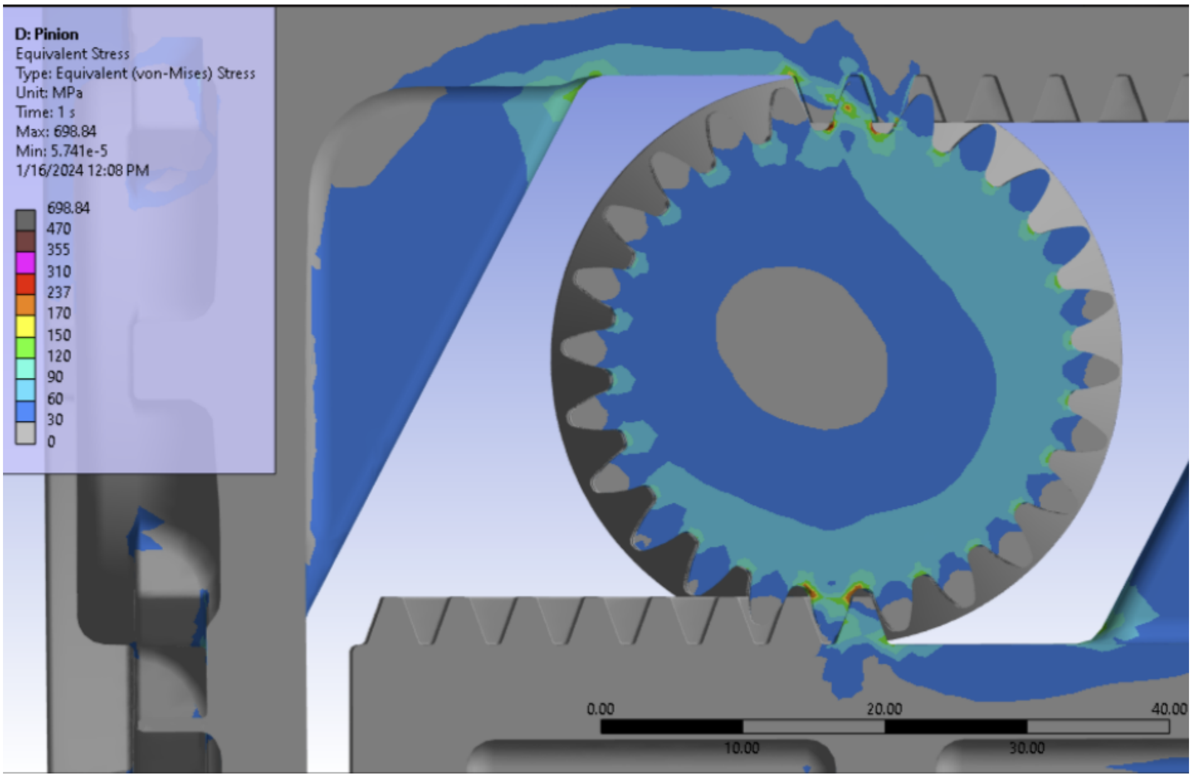


Figure 49. Checks on pressure containing parts according to rules of EN13445-3 “Annex B - Design by Analysis - Direct Route”.




D: Pinion
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1 s
Max: 698.84
Min: 5.741e-5
1/16/2024 12:08 PM
698.84
470
355
310
237
170
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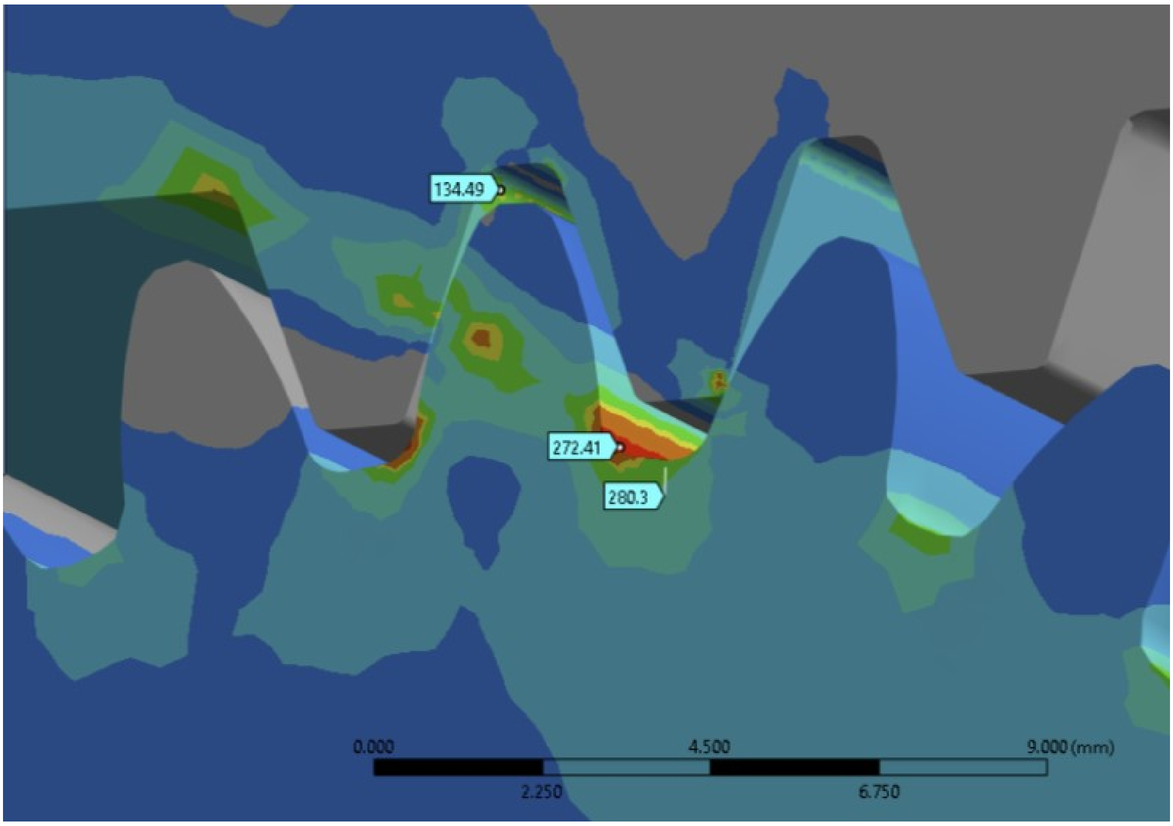


Figure 50. Correspondence of FEA results with results design by formulas about the stress in pinion teeth base.
The VON Mises stress value found with simulation at the base of the tooth (276 MPa) is aligned with the average value found with formulas (265 MPa).

10 “Design by Analysis”

During the design activities carried out for the actuator design enhancement project, a second step, following the first one based on formulas, has been of fundamental importance. This second phase is based on FEM simulations. Finite Element Analyses (FEA) are a very powerful tool, and for this project they have been used for two concomitant purposes: on one side, to carry out a further in-depth verification of the design choices, on the other one, to achieve an accurate design enhancement. Going into details:

1. A first function of FEA is to obtain a further confirmation of the safety and reliability of the results obtained with "Design by Formulas", integrating the checks performed through calculations. In fact, as a first step, simulations allow to verify that stress levels in the components are aligned with the ones found by means of formulas [*40*].

2. A second function of the "design by Analysis" has already been described in previous paragraph 9.1 “Verifications of Pressure containing Parts according to EN13445-3”, and consists in being a fundament help during the verifications of pressure containing parts, for compliance to international standards of pressure vessel sector [*41*]. As exposed, in this case study FEA have been applied according to the procedure described in “*Annex B - Design by Analysis - Direct Route*" of EN13445-3:2021.

3. In a third and last extremely important function, FEA are used to perform an optimization of the shape and dimensions of each component, a set of characteristics often defined as "*topology*" [*42*]. In fact, with FEA is possible to achieve a higher precision than formulas about the distribution in the space of stresses and deformations, arriving to have at disposal detailed maps of the areas where these quantities are intense. For achieving this situation is necessary that the model correctly captures the salient information about the material of the component, and its loads and constraints, requiring a high care. Nevertheless, if the simulation is accurately performed, it is possible to obtain a good approximation of the component real behavior, and consequently to “shape” its geometry, so at to reinforce the areas where a high strength is needed and lightening other ones where reinforcing material is not necessary [*43*] [*44*].

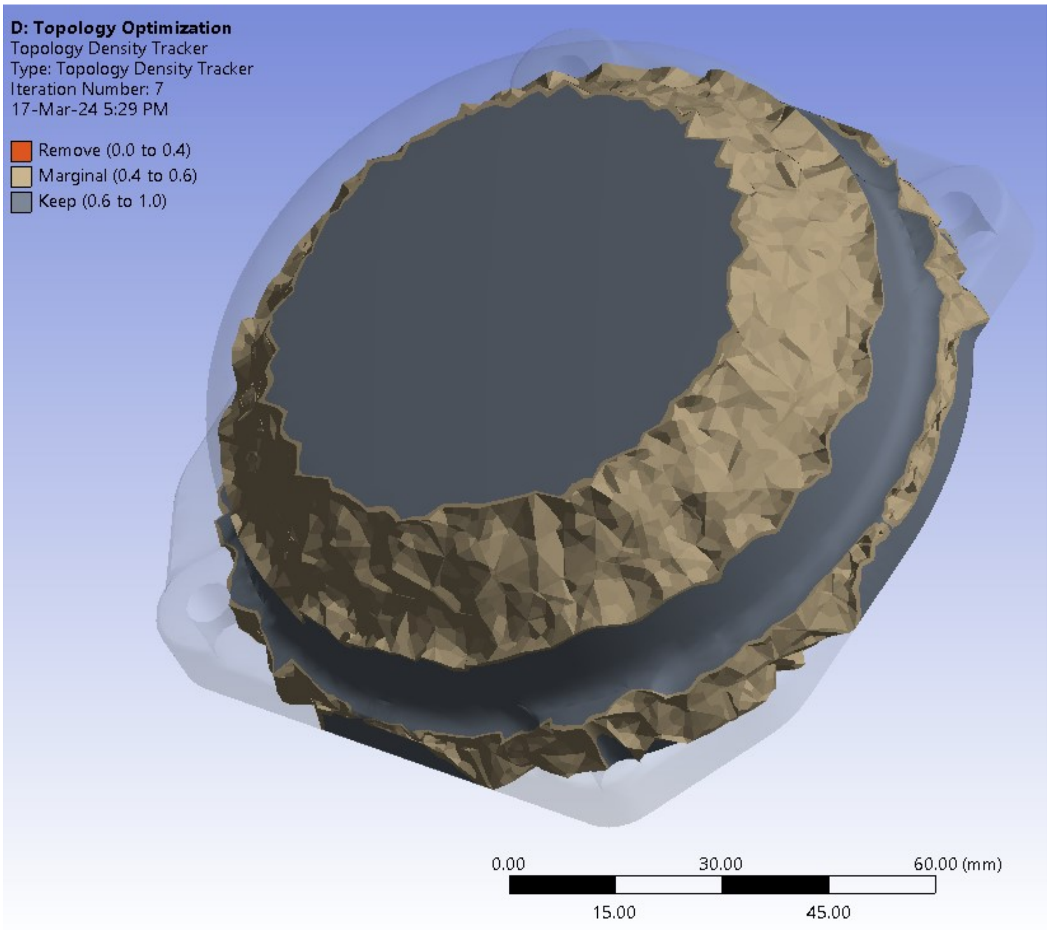


Figure 51. Intermediate step of a topology optimization study performed with the topology Optimization tool present in Ansys Mechanical®.

As shown, for example, in Figure 62, the second step of the detailed re-design phase contemplates an accurate use of FEA, with the purpose of achieving an extensive optimization of the component topology [*38*], as well as u further confirmation of safety and reliability of components. Topological Optimization of com-ponents is necessary for improving as much as possible weight efficiency and component simplification, that in their turn are main factors affecting some of main sources of value identified by DtV, as cost efficiency and ease of use.

Thanks to a detailed model of the product, it has been possible to study and optimize the stress and strain maps present in subsequent versions of the fundamental components.

The applied methodology consisted in performing a series of static analyses with non-linear material models and non-linear contacts formulations. Topology optimization has been performed by choosing as methodology a double approach, on one side by directly changing the geometry of the components according to static FEA clues, and on the other, in order to increase accuracy of possible weight improvements, by performing topology optimization simulations downstream to static simulations, thanks to a special software present in Ansys Mechanical®, as shown in Figure 51.

For each component, a detailed analysis of the stress and of the deformation has been performed. New optimized version must respect the admissible stress limits and have deformations aligned with the baseline given by original version.

For example, as it will be described in detail in next sub-paragraph, the geometry of the pistons has been improved by means of a series of intermediate concepts, redistributing each time its material so as to reinforce areas where necessary, and to lighten others [*40*], according to FEA clues, achieving in this way a final weight reduction of approximately 6%.

Some examples are reported in following sub-paragraphs, for describing more clearly how an approach based on an extensive use of FEA has been effective for the achievement of the objectives of actuator value oriented re-design.

10.1 Topology optimization of a component - Piston

An integrated approach with joint application of structural calculations and FEA was extensively used for one of most important actuator components, the piston.
Structural checks by formulas are very difficult for this component, having a complex shape, and connected to other components through constraints in different points. Verification by formulas is then possible only by schematizing it in a simplified way. For example, it is possible to break it down into two simple geometric parts, represented by a beam and a squared plate, connected to each other.

This approach is functional, anyway, simplifications introduced in the calculations do not allow for a precise evaluation of the distributions of deformations and stresses in the different sections, and consequently it is not possible to precisely evaluate if, with hypothesized thicknesses, the material is used in the best way. For this reason, the most appropriate choice, according to good design rules for preserving Safety, is to adopt quite high safety factors.

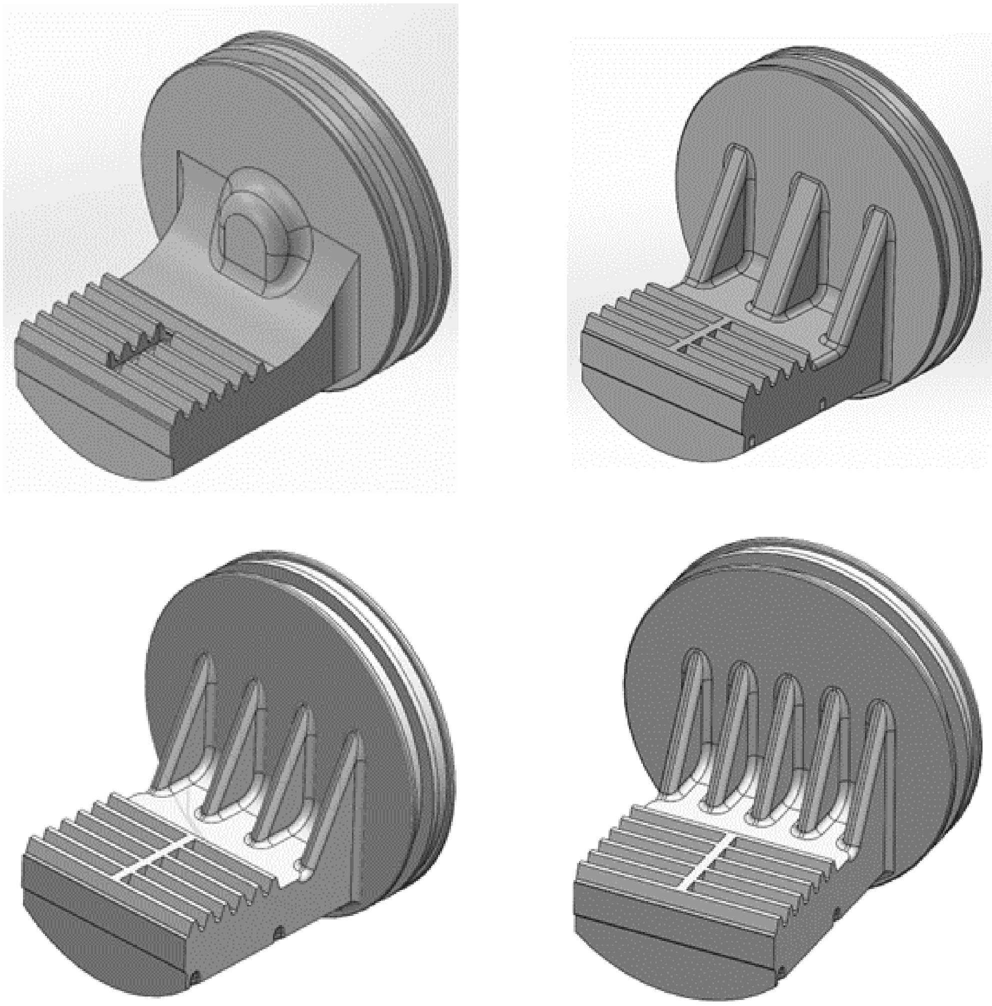


Figure 52. Subsequent steps of the topology optimization analysis of a piston.

Alternatively, accepting to have lower safety factors in calculations and then lower thicknesses, could lead to increase the probability to revise the design during the experimental validation. To complement these weak points of calculation-based method, it is therefore possible to use FEA. During the design of actuator pistons, thanks to FEA it has been possible:

- to model and verify the actual shape of the component, the real constraints and real existing contacts with surrounding components;

- to identify areas subject to high stress concentrations and verify the possibility to accept some small local plasticization under special conditions;
- to study the detailed maps and trends of deformation and stress along the component. A detailed representation of the distribution of these quantities makes it possible:
  a) to strengthen weak areas, if present,
  b) vice versa to identify less stressed areas, and, if possible, remove or redistribute material.

This shape improvement process is also called "topology optimization” and is a very effective tool for increasing the weight efficiency, while maintaining the functionality and respecting the constraints given by connections with other components [*45*]. For the piston the topology optimization methodology followed the process of directly changing step by step the geometry of the component according to the “clues” on low stressed and deformed areas offered by a series of static FEA.

The deformation levels present in the old piston were used as a "baseline" to define levels of acceptability, causing not excessive stress and then wear on the sliding ring guiding the piston inside the center body. The old piston did not present problems of this type and therefore the hypothesis was to maintain in the new prototype aligned values of deformations.

In a first phase then simulations were therefore carried out on old piston, to find reference values to compare with the new ones. The model for the simulations was initially a subassembly, where interactions with other components through different types of contacts (“bonded”, “frictionless”, “frictional”) are possible, to have a detailed representation of the stresses in the region. In a second phase, FEA on a model of the single piston, with constraints calibrated by means of the results of the complex model, allowed to speed up the analyzes. This second model was developed with the purpose to facilitate the verifications of the new geometry, giving the possibility to perform many simulations, each one associated to small geometry improvements, without expending excessive time. In addition to alignment with deformation levels of old piston, also limitations about maximum acceptable stresses were taken into consideration.

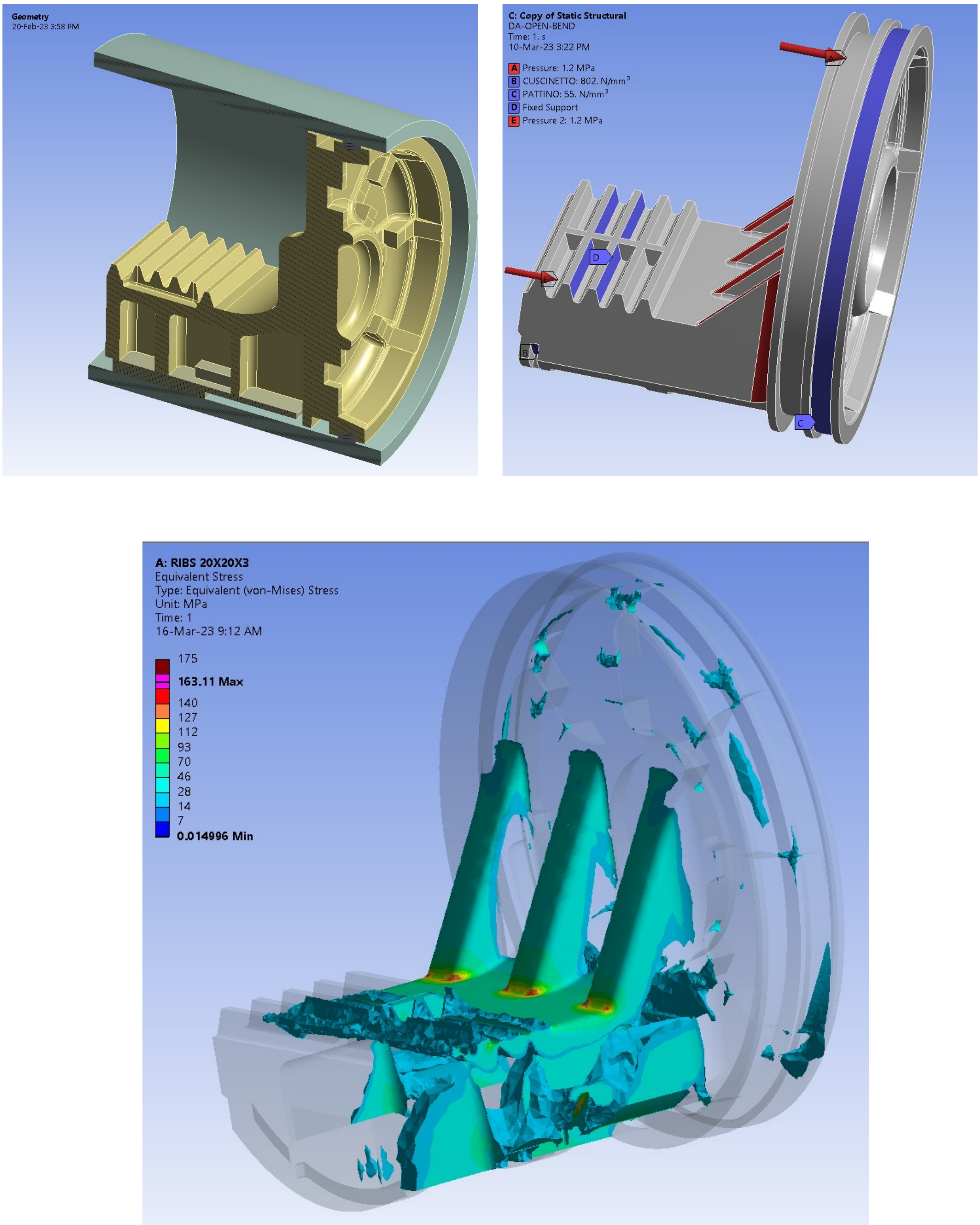


Figure 53. Set up and post-processing form a topology optimization FEA simulation of an actuator piston.

When the component is subject to design pressure (10,5 barg), stress values with a minimum safety factor of 1.5 with respect to yield value have been imposed as acceptable, with exception of small surface areas considered as "peak stress". In this way, the expected average stress, when the supply pressure is about half of the design pressure, can be predicted to have values below of the fatigue limit.

For the topology optimization activity, a first concept for the new piston geometry was modelled, in which first geometric optimizations were implemented, based on an accurate study of actuator strokes, with the aim of eliminating every millimeter of superfluous length in the rack and reducing thus the total length of the component as much as possible.

In this first concept it was also tried an initial optimization of the shapes, according to the opportunities given process chosen for the new piston, which will be die casting. In detail, it was decided to lighten the area between the rack and the piston disc, by introducing ribs to replace a single large reinforcement present in the old model.

With the results of the simulations on this first new model, it has been possible to make a comparative analysis of the obtained deformation and stress levels with respect to the ones of the old piston. The geometry has been then modified with a second iteration, optimizing each area by adding, removing, or redistributing the material where more necessary. Several iterations have been carried out, as shown in Figure 52, gradually optimizing the use of the material, and checking to remain within acceptable stress and deformation limits [*46*] [*47*]. At the end of the improvement process, it has been possible to achieve a total weight reduction equal to 6%.

It would have been possible to further reduce piston mass by replacing the triangular reinforcements between the rack and the central disc by introducing lightened reinforcements, having central cavities, as shown in Figure 54.

However, this possibility was unfortunately set aside due to limitations linked to the chosen production technology, that is die casting. In fact, an attempt was made to propose this solution to foundry engineers taking care of the production of the mold. The cavities in the reinforcement ribs have unfortunately been confirmed as not achievable, neither by providing special "cores" in the mold.

This limitation would not have been present with other production processes, such as 3D printing with metal powders, but after preliminary investigations, for the studied application, considering the production volumes, die casting was confirmed as the most economically efficient technology.

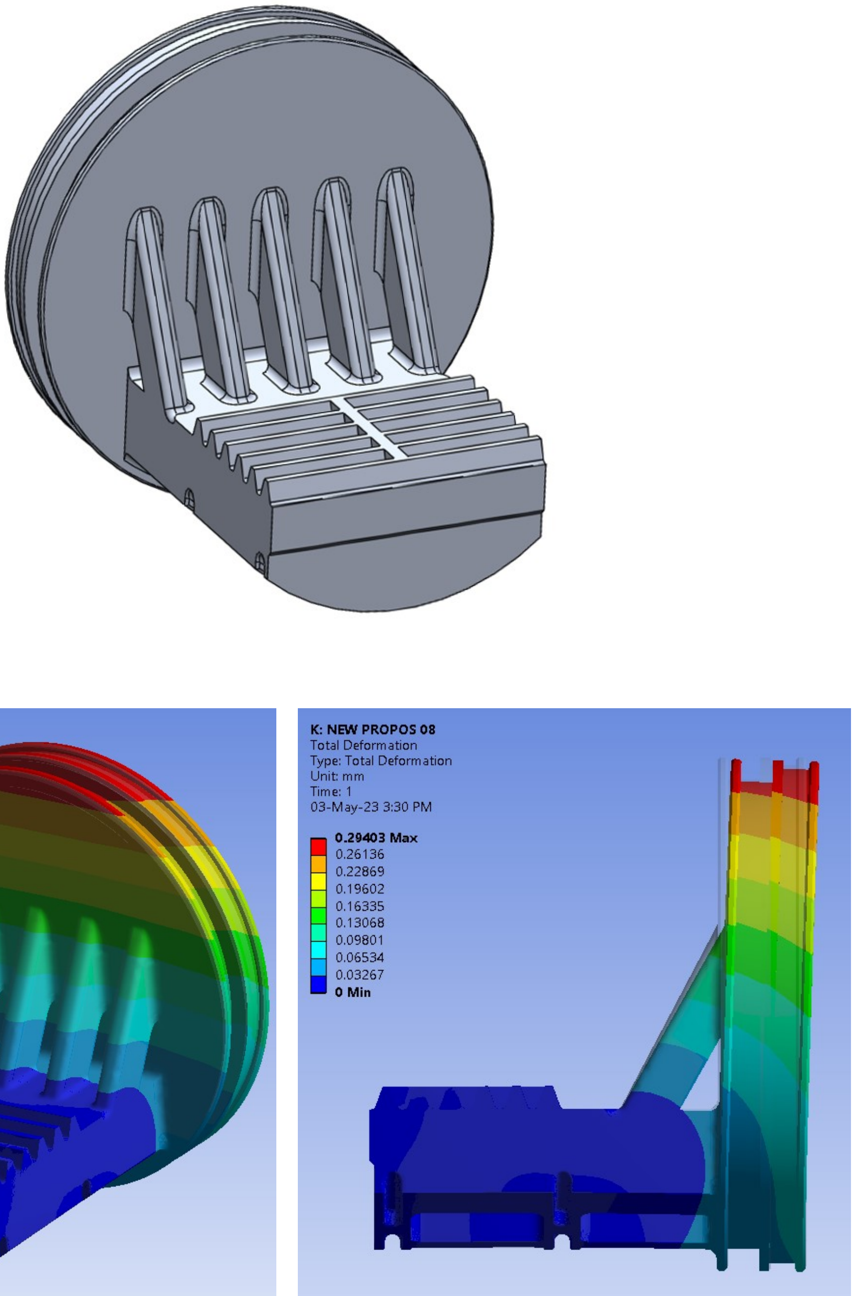


Figure 54. Study for a piston version with lightened ribs.
This version was not chosen as definitive one due to limitations relating to the production process.

10.2 EN13445-3 “Design by Analysis” Annexes

As anticipated in the previous paragraph 9.1 “Verifications of Pressure containing Parts according to EN13445-3”, FEA simulations are an official instrument foreseen for integrating the verifications performed to guarantee the conformity to the requirements of the main sector standards dedicated to pressure vessels. In fact, these standards provide for the opportunity that for pure pressure and temperature loads, but also in presence of unconventional loads, such as wind, snow, earthquakes, and concentrated loads of different nature, it is possible to resort to the different techniques classified as "Design by Analysis" (DBA) [48].

The Design By Analysis route is provided by the standards so as to have an additional tool that could be used as a complement to the Design By Formulae route, for cases not covered by the formulas, but also as an allowed valid alternative. With the help of FEA analyses, complex geometries and load conditions that deviate from the most common ones faced by the formulas present in the standard can be examined and verified. For example, design by analysis can be used as a complement for cases where superposition of pressure load with additional load of other nature is necessary (for example in presence of environmental actions like wind and earthquake).

As already exposed, for the actuator project, the pressure retaining components shall conform to the EN13445-3 standard. Among the reasons of the choice of this standard there is also the fact the conformity to this standard is accepted by the other important European standard EN15714-3, dedicated to the general requirements and good practices for a reliable actuator design.

Within Design by Analysis route, there are two possible strategies available for performing the analyses:

- The “Direct Route”, presented in ANNEX B of EN13445-3
- The “Stress Categorization Route, presented in ANNEX C of EN13445-3

The method based on stress categorization, described in “*Annex C - Design by analysis - Method based on stress categories*” involves a detailed procedure, where several sections of the component presenting stress concentrations are analyzed. Linear paths crossing them are chosen and studied. The stresses present in the sections are divided into the ones having local ranges (secondary stresses) and global ranges (primary stresses). The total stress found in each point of the path is divided and catalogued into different stress categories, called “membranes”, “bending”, “peak”, each one having specific maximum limits not to be exceeded.

Stress Categorization Route is proposed by many national standards and technical regulations. It presents many positive aspects and some drawbacks also, like problems associated with non-uniqueness of the determination of stress classification [49]. Among positive aspects of Stress Categorization Route there are, for example, that it requires only linear-elastic analyses, and it offers the possibility of linear superposition of the results for different actions.

The method instead indicated as "direct route" allows for the use of non-linear FEA, associated with criteria to evaluate the acceptability of the intensity of the found results, as described in more detail in next paragraph.

The "Direct route" approach described in “*Annex B - Design by Analysis - Direct Route*" has been applied in actuator re-design project. This method has been used to perform design checks, evaluate the behavior, and check the absence of ductile ruptures nor excessive deformations for two important actuator pressurized components, that, due to construction needs, are at the same time subject to pressure and to other loads of a concentrated type, defined as variable actions. These two components are the extruded central body and the side closing flanges and the peculiarities of their verifications are reported in the following paragraphs.

10.3 Application of Annex B of EN13445-3 “DBA - Direct Route”

Direct route takes into considerations different types of actions, representing the quantities imposed on the structure of the part to be analyzed and causing its stresses or strains. These actions can be pressure, forces, imposed displacements and temperature variations, in case of thermomechanical problems. Actions are classified according to their variation in time:

- Permanent actions,

- Variable actions,
- Exceptional actions,
- Operating pressures and temperatures.

Table 7 reports the types of actions considered for actuator pressure containing components. Design values of the actions have been increased by the relevant partial safety factors (γ_A) reported in Annex B. In the case of the actuator, no exceptional actions have been deemed as applicable (for example, failure of primary containment systems, …). Verifications against creep also are not applicable to the conditions of use of the actuator.

Unlike Annex C, according to the procedure of Annex B of EN 13445-3, the proof of strength is not based on stress categorization but is provided by means of a series of verifications that must be fulfilled. These checks allow to define the permissible loads that a structure can withstand. The verifications to be performed listed by Annex B are the following ones:

- Design check for Gross plastic deformation
- Design check for Progressive plastic deformation
- Design check for instability
- Design check for fatigue
- Design check for static equilibrium

<table>
<tr><th>Component</th><th>Operating Pressure</th><th>Variable actions</th></tr>
<tr><td>Lateral Closure Caps</td><td rowspan="2">Design Pressure Load (Pd)</td><td>Springs Load in compressed and released positions</td></tr>
<tr><td>Extruded Center body</td><td>Load of stopper bolts of angular stroke regulation system. Bolts are threaded into frontal wall of the body.</td></tr>
</table>

Table 7. Actions applied to Pressure Containing parts of the actuator analysed with DBA

For actuator components each one of the checks has been analyzed and it was assessed its applicability and then to perform it or not, according to the considerations reported below.

Design check for Gross plastic deformation - This check has been performed, to verify the behavior of pressure containing parts when they are subjected to the maximum allowable loads, consisting in the test pressure (1,5 times the design pressure) and the maximum localized variable loads intrinsic of actuator design (loads of springs in compressed condition and load of stopper bolts of angular stroke regulation system). Details about this design check are reported in next paragraph.

Design check for Progressive plastic deformation – This check has been deemed as not necessary. In fact, for the actuator components there is not the possibility that, on repeated application of specified action cycles, progressive plastic deformation shall occur. For the applications where the actuator will be employed, considering the range of operative pressures, there is not in fact the risk that the components could be subject to phenomena of progressive plastic deformation under cyclic actions.

Design check for instability - This check has been deemed as not necessary. In fact, actuator components shall not be subject to design value of an action or of a combination of actions that could be greater than the buckling strength. In other terms there is no risk for some of the pressure containing parts of the actuator to be subject to phenomena of buckling.

Design check for fatigue – The check of the behavior of pressure containing parts when subject to fatigue loads has been performed by using the Design by Formulas route, by applying the procedure of Chapter 17 of standard EN13445-3 “simplified assessment of fatigue life”. The formulas for assessing the maximum allowable number of full pressure cycles the components can be subjected to (from 0 barg to Design Pressure, according to formula EN 13445-3:2021, 17.6.6.1 eq. 17.6-18) have been then applied. The reference maximum stresses that have been chosen to be inserted in the formulas are the peak values found with DBA while performing the design check for Gross plastic deformation.

Design check for static equilibrium - This check has been deemed as not necessary. In fact, due to the small dimension of actuator and its pressure containing parts, there is no need of checks due to the self-weight of the structure. In addition, the sizing of the hole pattern for connecting the base of the actuator to other components and in particular to the brackets for connection to valve is performed according to dedicated standards, as for example ISO 5211 “Industrial valves. Part-turn actuator attachments”.

10.4 Implementation of Design check for Gross plastic deformation

This check has been performed in accordance with the rules described in Annex B “*Design by Analysis – Direct Route*” of standard En13445-3 on the following pressure containing parts of the actuator: lateral closure caps and extruded center body.

For performing this design check the following assumptions have been made during the preparation of the model and for the definition of the applied actions, according to the procedure indicated at paragraph B.8.2 “Gross Plastic Deformation (GPD)” of Annex B of EN13445-3:2021.

• the material models used for the components of the assembly studied with FEA have a linear-elastic ideal-plastic constitutive law. The analyzes have been also repeated using linear-elastic linear-plastic material models.

• The design strength parameters of the materials have been obtained by starting from the minimum guaranteed values of the yield strength from material standards, and by dividing them by the appropriate partial safety factors (γ_R), according to Annex B gross plastic deformation check’s rules.

• The finite elements used in the model are of first-order. The analyzes have been repeated using also second order elements for comparing the differences of the obtained results.

• Annex B indicates to use Tresca's yield criterion as first option for assessing the stress distribution in the component. Anyway, in alternative to Tresca’s criterion, it is allowed to use the Von Mises’ criterion also. For the analyzes on actuator components this last one was used, since softwares allowing for Tresca's yield criterion are not easily available. According to Annex B indications, by using Von Mises' yield criterion, the design strength of the materials must be decreased by a *sqrt(3)/2* factor, that is a reduction factor of

15.5% must be used.

• All the actions (pressure, variable concentrated loads) considered in the design load cases under investigation have been applied with a proportional increase.

The results obtained from FEA simulations confirmed that the maximum deformation of each one of the analyzed parts of the actuator is lower than the admissible value indicated in paragraph B.8.2.1 of Annex B, equal to **5%**. The studied pressure containing components of the actuator are therefore verified.

	Stress Categories				
	Primary stress			Secondary membrane + bending stress	Peak stress
	General membrane stress	Local membrane stress	Bending stress		
Description (For practical examples, see Table C-2)	Primary mean stress calculated across the wall thickness without taking into account discontinuities and stress concentrations. Caused only by mechanical loads.	Primary mean stress calculated across the wall thickness taking into account large discontinuities, but not stress concentrations. Caused only by mechanical loads.	Primary stress component proportional to the distance from the centroid of the solid wall section. Does not include discontinuities and stress concentrations. Caused only by mechanical loads	Self-equilibrating stress necessary to satisfy the continuity of the structure. Occurs at large discontinuities, but does not include stress concentrations. Can be caused by both mechanical loads and thermal effects.	a) Addition to primary or secondary stress because of stress concentration. b) Certain thermal stresses which may cause fatigue, but not distortion.
Symbol	P_m	P_L 1)	P_b	Q $(= Q_m + Q_b)$	F

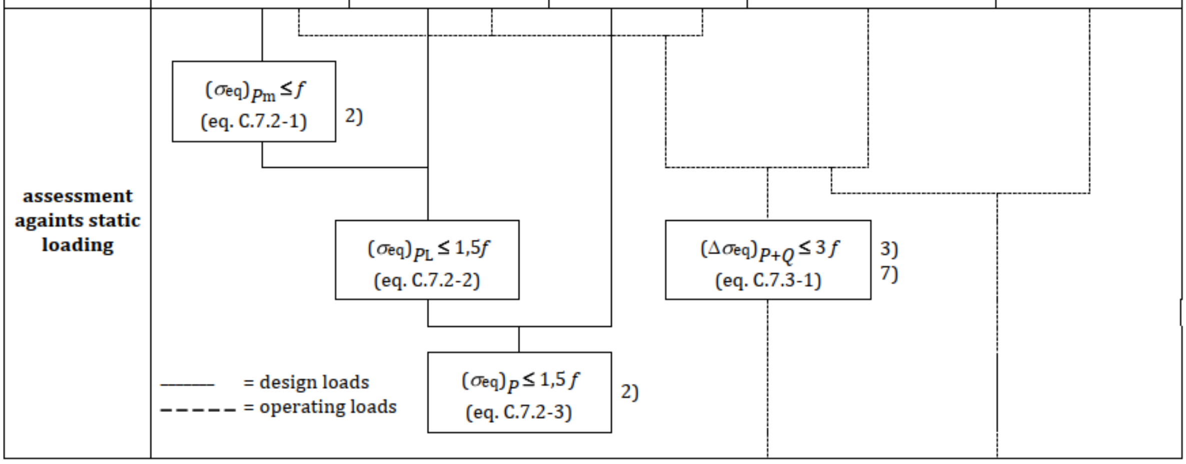


Figure 55. Summary Table resuming the assessment criteria for acceptability of stress values according to stress categorization method proposed by Annex C of En13445-3.
A supplementary check according to this table has been performed on results of FEA on pressure containing parts of the actuator.

Furthermore, in order to have an additional evaluation criterion regarding the acceptability of the stress values present in the components, when they are subjected to the maximum admissible loads, in accordance with the indications in paragraph B.5.1.1 of Annex B, which allows for the use of alternative or additional "application rules", a further additional check has been introduced, without affecting the main design check procedure.

It has been in fact decided to carry out a check of the distribution of the stress values present in the models also recurring to the stress categorization method provided by Annex C "Annex C - Design by analysis - Method based on stress categories", by analyzing the primary, secondary and peak stresses. It was verified that stresses present in the stress maps of the models respected the values provided by table C-3 of Annex C, as reported in Figure 55 . In particular, it was verified that the peak stress values were always lower than 3 times the allowable design stresses "f" used for the checks of Design by Formulas.

10.5 Design Checks on Lateral Closure End Caps

As shown for example in Figure 39, in single-acting "spring return" actuators it is necessary to install one or more springs inside each of the two outer chambers, delimited by piston and lateral closing flange, here called end cap. During the actuator opening maneuver these springs are compressed, and subsequently they allow the closing maneuver to be carried out in the absence of pressure, thanks to the potential energy accumulated inside the springs that they release during decompression. If springs perform the closing stroke, the actuator is called "fail close", but it is also possible to obtain the "fail open" function, for situation where the valve must be opened in case of fail of power and control systems, only by inverting the position of the pistons with respect to the pinion.

The closing end caps can therefore be subject to different load types, depending on actuator movements:

1) double-acting actuator: pressure load at operating pressures, during one of the two maneuvers;

2) double-acting actuator: pressure load at test pressure, during initial structural integrity test;

3) single-acting actuator: springs load at varying lengths from extended to compressed, during one of the two maneuvers;

4) single-acting actuator: pressure load at test pressure plus springs load at extended length, during initial structural integrity test.

The most severe of the four previous situations is represented by case 4.

FEA have been then applied for evaluating the flange behavior during the initial pressure test of a single acting actuator. In this phase the actuator is powered at a pressure equal to 1.5 times the design pressure, and, in the case of single acting actuators, all the inner components and the closing flanges are also subject to the load of the springs, that, even if they are in a rest condition, exert an action equal to their precompression.

FEA analyzes performed on the flanges allowed to confirm that the chosen component dimensions are suitable to resist the force exerted by the springs, acting in addition to pneumatic load, already verified with formulas of EN13445-3. Thanks to FEA it has been possible to identify areas with high concentration of stress and change the component geometry for redistributing in a better way the lines of stress.

Concentrations mainly occur in correspondence of fillets connecting the three main sections composing the closure flange: the external annular flange, the cylindrical shell, and the final flat end.

It has therefore been possible to obtain an optimization of the component and to reduce the peak stresses by finding correct values for these fillets. Regarding the central areas of the final flat end, the simulations confirmed compliance with required safety factors even in the presence of springs acting on it. This example makes it very clear how thanks to the FEA it has been possible to clearly identify and face problems that could limit the efficiency of the component, as the formulas could not capture details about areas with stress concentrations. The improvement is important especially regarding the fatigue life of the component, since stress concentrations, also if they don’t reach levels causing failure of the component, they often coincide with areas where possible fatigue cracks originate.

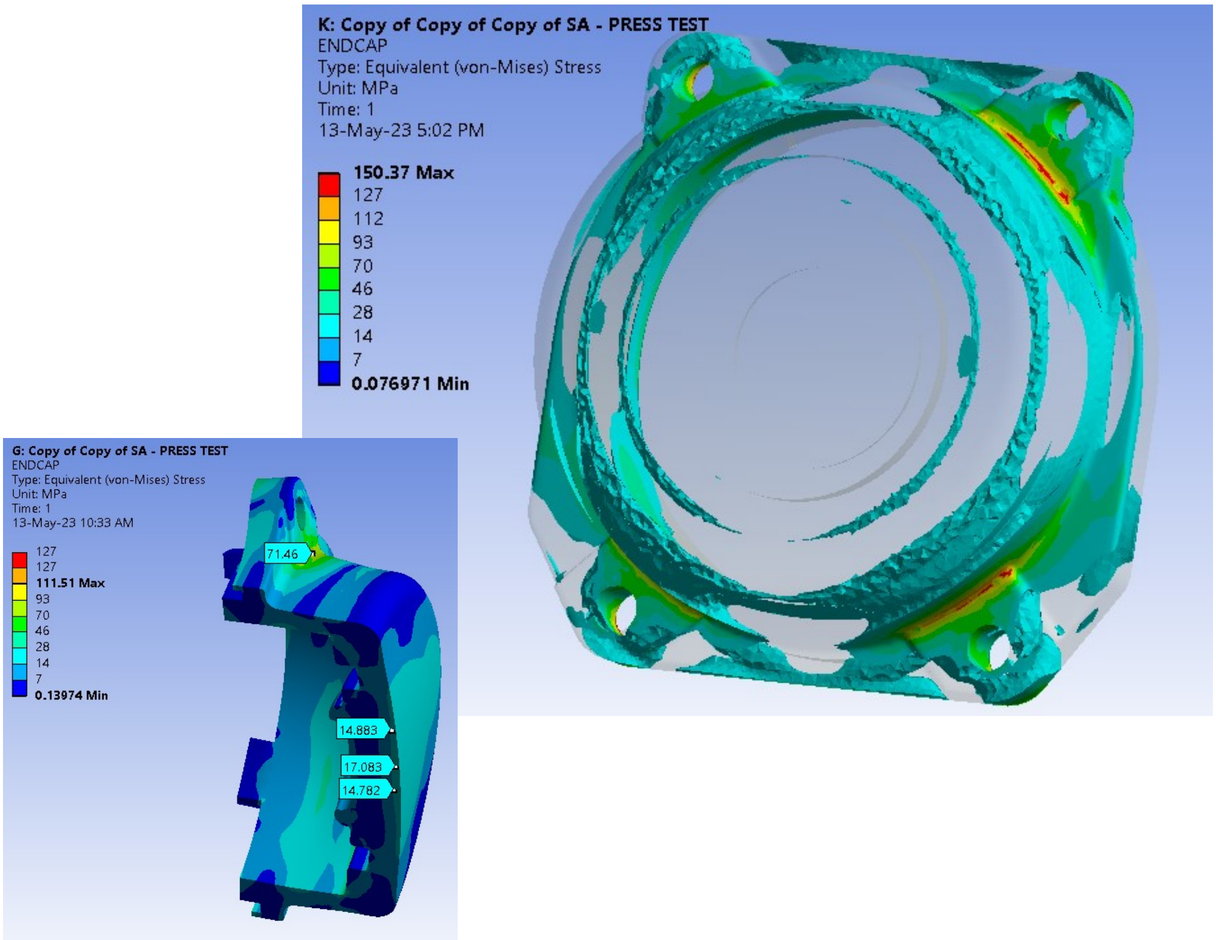


Figure 56.Images from post-processing of topology optimization FEA of actuator End Cap. It is possible to notice the stress concentration areas near the bolt holes. Peak values have been reduced by optimizing the fillet radius.

10.6 Design Checks on Extruded Center Body

Another component that thanks to FEA simulations has been possible to verify accurately, and in accordance with the requirements of the EN134445-3 standard, is the extruded center body. This component faces load conditions similar to lateral closing flanges, as it is also subjected to an additional concentrated load with respect to pressure, for which "Design by Analysis" has been adopted [*50*].

This component contains in fact the threaded holes for the grub screws belonging to the angular strokes adjustment system, as it will be described also next paragraph, dedicated to the verification of this system. The adjustment screws transmit a load to the actuator body, causing its deformation.

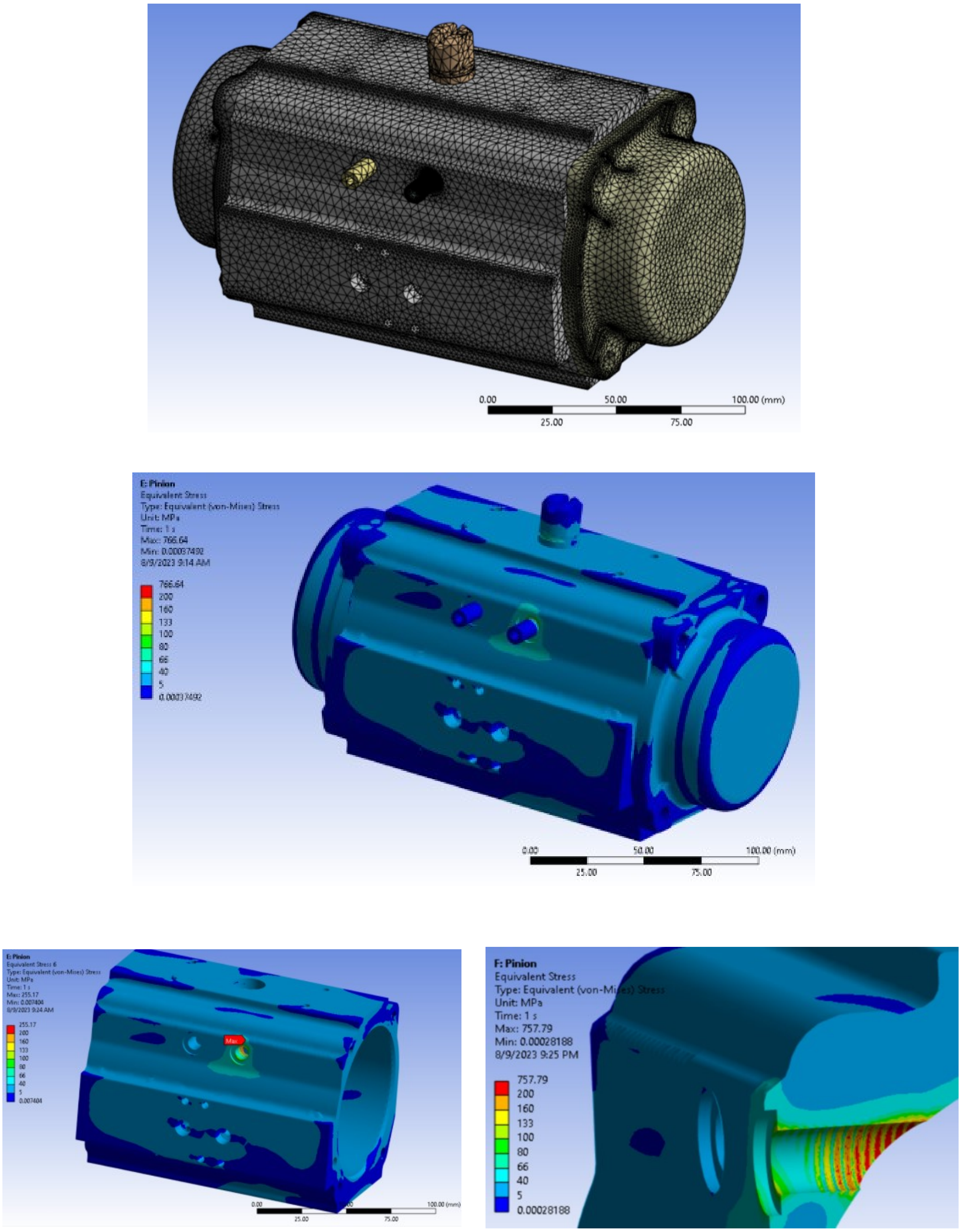


Figure 57.Images from post-processing of topology optimization FEA of actuator Center Body. In the images below it is possible to notice the effect on body of the concentrated load transmitted by the grub screws for stroke regulation.

As described in previous sub-paragraph for the lateral closure end caps, also in the case of the center body, all the activities for verifying the compliance of the component to direct route of EN13455-3 design by analysis were carried out. A verification has been done for ensuring that the average and peak stress values are below maximum allowable values [*51*]. Furthermore, it has been verified that the stress values in the center body when the actuator must withstand the design pressure have sufficient safety factors for deducing that when the actuator is powered at low pressures, typically present in the plants, stress values can be below the fatigue limit.

Further details about the model used for FEA will be described in next paragraph, as the center body interact with angular stroke adjustment system, and a single model were prepared for verifying all these components interacting with each other.

During FEA execution, the obtained results allowed to optimize the use of the material for the center body also, searching for the best topology of this component. By analyzing the stress maps, a search has been made to identify all the possible areas where the material does not contribute to the component strength, and where then a possible reduction in mass is possible.

All the protuberances present in the profile of the central body were analyzed, and a study was made to find ways to reduce them as much as possible. Even in this case, however, like for example for pistons, a compromise had to be found, linked to the construction technology used for producing the center body, that is the extrusion.

This process requires that the section of the component is constant. Therefore, it has been possible to optimize the profile of the section, but all the protuberances that was not possible to eliminate or furtherly reduce are present for the entire extension of the component.

If the chosen production technology had been die-casting, the shape of the component could have been further optimized, as the constraint of the constant profile along the entire length would have been eliminated. However, extruded center bodies were chosen, according to parallel analyses performed by supply chain, as the component made by extrusion were confirmed by suppliers to have the best economic efficiency.

10.7 Structural verification of angular strokes regulation system

One of the principal “design change proposals” emerged thanks to DtV process concerns the re-design of the actuator “angular strokes regulation system”, skipping to a solution that could simplify the actuator design. The detailed description of the functioning of this system has been presented in paragraph 6.2.3, when speaking about how the function analysis positively impacted the definition of the new proposal.

For performing an accurate verification of this system by means of FEA, a model of the complete actuator assembly was prepared, where the contacts and reactions among all the components were simulated, as shown in Figure 58. By applying a pressure load to the pistons, it has been possible to evaluate the entities and directions of the forces exchanged among the components, as shown in Figure 59, also following possible deformations, and in particular at the contact between cam and grub screw, as shown in Figure 59.

A special function provided by the simulation software was also included, allowing to simulate the presence of a real threaded connection between grub screw and center body, even if, from a 3D point of view, components are modeled as smooth cylindrical surfaces, as shown in Figure 57.

A first verification of the validity of FEA results has been possible by analytically estimating the load acting on the grub screws, and then comparing it with the value found through FEA, obtained by inserting a force probe in cam-screw contact area of the model. The heaviest load situation occurs for a double-acting actuator, when the opening or closing maneuvers are carried out at the design pressure, equal to 10.5 barg.

In this situation the pistons generate the actuator maximum achievable torque, called MOT (Maximum Operating Torque). Inside the mechanism, the pneumatic load is transmitted from the pistons to the pinion, and, in absence of valve counter-torque, the torque is then fully transmitted to the center body via cam and grub screw. By dividing the MOT torque value by the "moment arm", represented by the distance between the center of rotation of the pinion and the straight line parallel to the axis of the grub screw screwed into the body, it is possible to determine the force compressing the screw that is then discharged in the central body threaded hole, as shown in Figure 59.

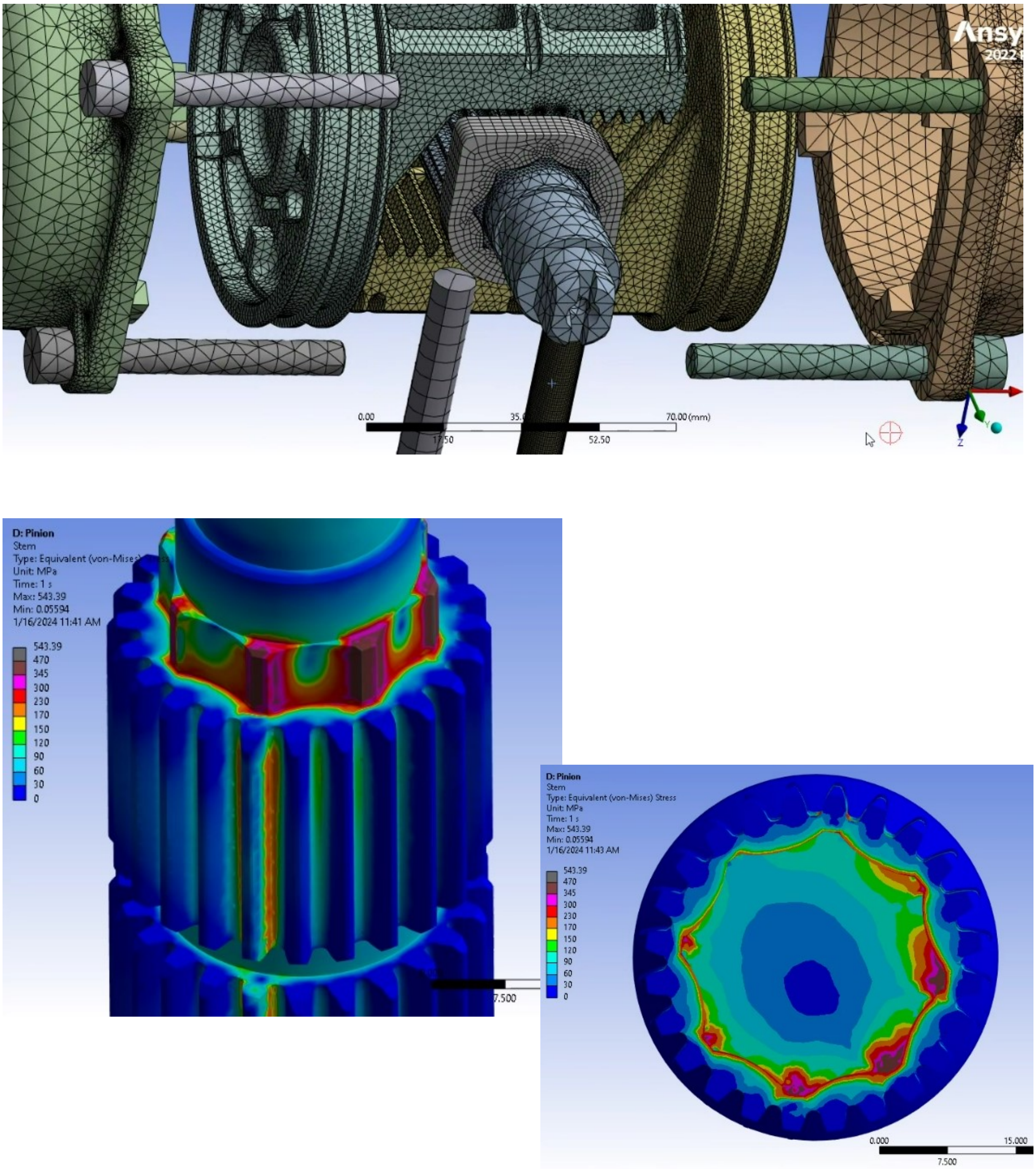


Figure 58.Model of the whole actuator for static structural FEA and stress map of a component. By simulating the whole mechanism it is possible to check the stress and deformation maps of all its components, like the pinion, as shown in the lower images.

A good correspondence between the force and compression stress obtained with FEA and the values obtained analytically has been found.

This correspondence confirms that the full model has been properly set, correctly simulating the transmission of the pressures and forces among all the components of the kinematic system, from pistons up to grub screws and body.

This is then a first validation of FEA results, confirming the high effectiveness of the approach also, because in addition to force and stress values, with FEA it has been possible to also have an immediate estimation of the directions and entity of deformations of each component.

Thanks to FEA, the new cam system has been thoroughly verified and the geometry of the center body has been verified following topology optimization principles [*52*], guaranteeing at same time compliance with EN13445-3 requirements.

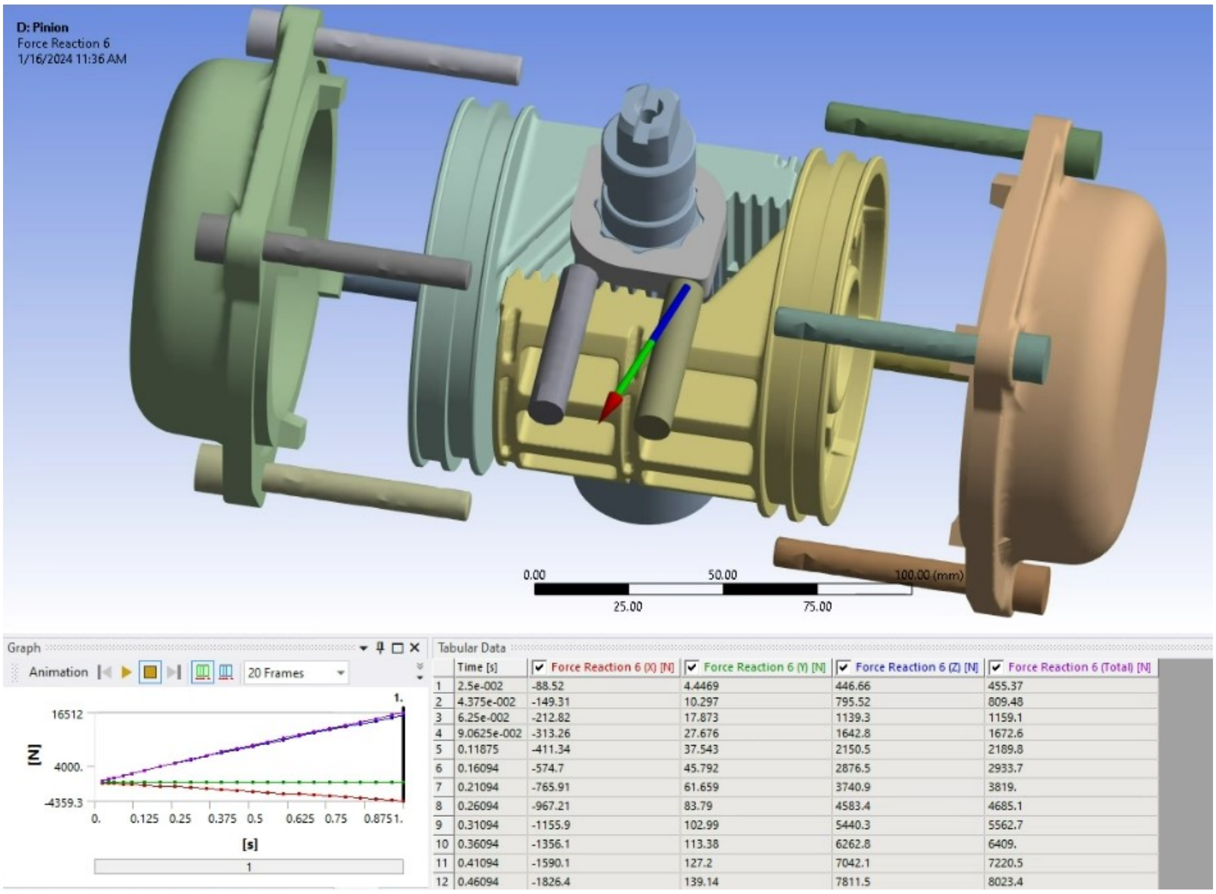
10.8 Summary of the benefits obtained thanks to FEA

In summary, accurate FEAs on critical components are a big help to confirm and optimize the design choices, and for correcting situations that could present criticalities. For example, they allowed to update fillet radii and other areas subjected to high peak stresses in many of the components.

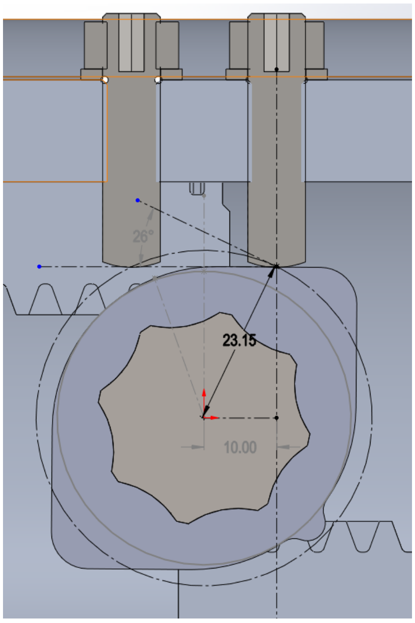
The investigations carried out during the FEA analyzes confirmed that the adopted constructive choices are correct and that the chosen solutions are efficient.

Thanks to FEA and to all the checks just described and carried out "upstream", during the detailed design phase, it is expected to encounter a lower number of situations requiring modifications to the design in the subsequent phase of the project, dedicated to experimental tests on prototypes. Also in case some changes will be necessary, it will be much more probable to deal with minor changes.

It must be nevertheless underlined that, despite the efforts made during the detailed design phases, and the consequent detailed forecasts obtained thanks to calculations and simulations, the validation phase by means of prototypes remains an extremely important activity, which must be in any case performed with care and meticulousness, as it will be described and analyzed in detail in next Chapter.



	Time [s]	Force Reaction 6 (X) [N]	Force Reaction 6 (Y) [N]	Force Reaction 6 (Z) [N]	Force Reaction 6 (Total) [N]
1	2.5e-002	-88.52	4.4469	446.66	455.37
2	4.375e-002	-149.31	10.297	795.52	809.48
3	6.25e-002	-212.82	17.873	1139.3	1159.1
4	9.0625e-002	-313.26	27.676	1642.8	1672.6
5	0.11875	-411.34	37.543	2150.5	2189.8
6	0.16094	-574.7	45.792	2876.5	2933.7
7	0.21094	-765.91	61.659	3740.9	3819.
8	0.26094	-967.21	83.79	4583.4	4685.1
9	0.31094	-1155.9	102.99	5440.3	5562.7
10	0.36094	-1356.1	113.38	6262.8	6409.
11	0.41094	-1590.1	127.2	7042.1	7220.5
12	0.46094	-1826.4	139.14	7811.5	8023.4



Main Data				
Piston diameter			[mm]	100
MAWP - Design pneumatic pressure			[barg]	12
Test Presure			[barg]	17.16
Design pneumatic load at full piston area			[N]	9425
Test pneumatic load at full piston area			[N]	13477
Pinion data				
Pinion gear External Diameter	*de*		[mm]	36
number of teeths of pinion gear	*z*			16
module of pinion gear	*m*	*de / (z+2)*	[mm]	2.0
pitch diameter of pinion gear	*d*	*de - 2*m*	[mm]	32.0
Torques				
ARM - Distance pinion-piston	*b*	*d/2*	[mm]	16
number of pistons generating toque	*np*			2
Efficiency (η)				0.9
Torque at design pneumatic load	*Td*		[Nm]	271
Torque at test pneumatic load	*Tt*		[Nm]	388
Verification of stopper stud bolts				
Contact radius cam-bolt at 0° / 90°	*dc1*		[mm]	23.15
Contact radius cam-bolt at 45°	*dc2*		[mm]	20.25
Full cam force on bolt at 0° / 90° - Design Pressure	*Fc*	*Td / dc1*	[N]	11725
Full cam force on bolt at 0° / 90° - Test Pressure	*Fc*	*Tt / dc1*	[N]	16767

Figure 59.Estimations of the force transmitted between cam and stopper stub bolt via FEA and via calculations.

A first check for ensuring that the models have been properly set up consisted in comparing the reaction force between components with respect to the result found by means of formulas.

10.9 Other activities performed during detailed design phase

To conclude the section dedicated to detailed design, it is important to mention that the re-design phase also included further activities, not strictly connected to structural checks, but having nevertheless great importance for the purpose of optimizing the product.

The first one of these activities concerns the study regarding possible alternative surface treatments and coatings of the components. Considering the actuator design enhancement project, the final decision taken has been to not modify the surface treatments that are used in the original version for parts exposed to outdoor environment. These treatments are:

1. anodizing of the aluminum central body,
2. nitriding of the pinion,
3. painting of the lateral closing aluminum end caps.

These anti-corrosion protective treatments have been analyzed and, after a comparison with alternative solutions, they have been confirmed as the most economically efficient among alternatives having same corrosion resistance.

Another activity promoted by a “design change proposal” has been the complete update of the actuator nameplate, as already anticipated in paragraph 7.3. Thanks to this useful proposal a totally new version has been developed.

The new nameplate is reported in Figure 43. This updated version is more complete than the previous one, as it includes additional fields for indicating information by last versions of actuator international standards (ISO 12490, API 6DX, EN15714-3). These standards include in fact chapters entirely dedicated to the requirement of the nameplate, as it is a very important feature of the actuator, a real identity document resuming main information to be considered for a safe use.

Furthermore, in the new nameplate version a very useful innovation has been introduced, by adding a QR code. In this way it is possible to include a link for downloading the safety and use and maintenance manuals, making these extremely important documents available in a very short time to technicians in the field. This design change represents another example of how, by using new technologies not available at the time of the first design, it is possible to increase the overall value of the product, without making large investments in modifications.

11 Experimental validation

FEA analyses cannot be seen as a panacea but as a valid instrument for increasing the detail and precision of verifications. Their accuracy must in any case be verified with experimental studies. For this reason, once fully defined the final proposal for the new actuator design, the next step of the studied approach consists in adopting a validation plan aligned with the FEA investigations, that is, oriented to verify first the components that require greater attention, according to the clues emerged during the analysis of FEA results.

In this perspective a partial prototype called "mockup" has been created, composed of detailed versions of the components to be validated with first tests, and simplified versions, machined from solid or recycled from the old design, for the other ones to be analyzes in a second step.

In this way it is possible to reduce the probability of having to modify the final detailed prototype, due to changes in dimensions of these critical components, influencing the dimensions of many adjacent components, obtained by casting or extrusion also, then requiring the modification of patterns. The final prototype will be then produced only in a second step.

The observations performed after the execution of the tests confirmed some behaviors predicted by the simulations with good approximation. The comparison shown in Figure 62 is a useful example. On the surface of a cam used for shaft stroke adjustment, in correspondence with the contact area with a stopper stud bolt, a small plasticization was detected, as expected by FEA.

The second phase of the validation, focused on a prototype identical to the actuator intended for production, includes fundamental tests to confirm the safety and reliability of the product (pressure tests, cyclic tests, ...), as required by product standards and by SIL certification (SIL = Safety Integrity Level) according to EN61508 [*54*].

The detailed re-design phase of the product has been completed with the issue of a proposal of new prototype, composed by a 3d model, where all the components have been verified thanks to all the techniques and tools described in previous paragraph. Final output of the detailed design phase are also the construction drawings of all the actuator components, with tolerances, roughness, and all other parameters defined according to the performed verifications.

11.1 Validation Plan

The first activity that has been organized in the phase dedicated to design validation has been a meeting, where the project team discussed, agreed, and drew up a detailed validation plan.

The plan contains all the tests necessary to discover and fix all possible critical points present in the prototypes, before proceeding with mass production [*53*].

Prototypes are essential for multiple purposes, each one extremely important:

I. to validate the safety of the pressure containing parts, by performing the pressure tests required by the standards, and additional test, for confirming the safety of the design also in case of possible misuses. These additional tests are called “Burst Tests” and are finalized to bring the pressure containing components up to failure;

II. to confirm the good reliability of the product, ensuring that it can perform the emergency functions, when required, with a very low probability of failure. The actuator must in fact be certified as "SIL 3 Capable" (SIL = Safety Integrity Level), according to standard EN61508 “*Functional safety of electrical / electronic / programmable electronic safety related systems*”. For confirming that the product has low failure rates, compatible with SIL 3 applications, it is necessary to carry out a series of reliability analyses. These analyzes focus on the examination of product design, but also on quality, production and testing procedures. Reliability calculations are performed, using the failure rates of each single component available in international database, for returning as a result hourly failure rates, divided among safe and dangerous, detected and undetected, of the complete actuator. Finally, to integrate the analyzes and calculations, experimental tests must be run, for verifying the actuator behavior when subjected to very high loads and a very number of cycles. The positive execution of these tests, together with the results of all other validation tests, are taken into consideration by the inspectors who certify the product for assessing its suitability to SIL 3.

III. to validate good fatigue life of all the components subjected to pressure and mechanical loads. The actuator must in fact be suitable for special applications, requiring performing up to 500,000 cycles during its operational life [*54*]. For this purpose it is planned the execution of a cyclic test, valid also, as described, for obtainment of SIL certification, during which the components subject to wear, like bushings and O-rings, at regular cycles intervals are checked. During the test the status of all other components subjected to mechanical and pressure loads are checked, for verifying the absence of possible cracks due to fatigue.

IV. to check actuator assembling procedures. During prototype assembling all the studied and defined procedures are verified, for checking the difficulty of the operations for to be performed by assemblers and the required time.

V. to confirm the chosen dimensional and geometric tolerances. Some connections between components remained unchanged with respect to old design, so tolerance problems are not expected, for example regarding the distance between the piston and the inner cylinder of the central body, or the tolerances of the gears in the rack-pinion connection. Nevertheless, other connections are new, so it is necessary to carry out an accurate analysis regarding the chosen values, for confirming they are suitable and obtainable, thanks to measurements of the ones found in prototype machined pieces. During the measurements also the choice of the correct dimensions of the O-ring grooves is verified, to obtain a correct O-ring compression. These validation activities are then an indispensable tool for checking the construction drawings, confirming or modifying reported dimensions of and other contained indications about tolerances, surfaces roughness and other special notes.

VI. For the studied actuator, no new heat treatments or new surface treatments were introduced with re-design, so validation of these aspects was not necessary. Nevertheless, any introduced changes would have required a validation through tests and nondestructive examinations (NDE).

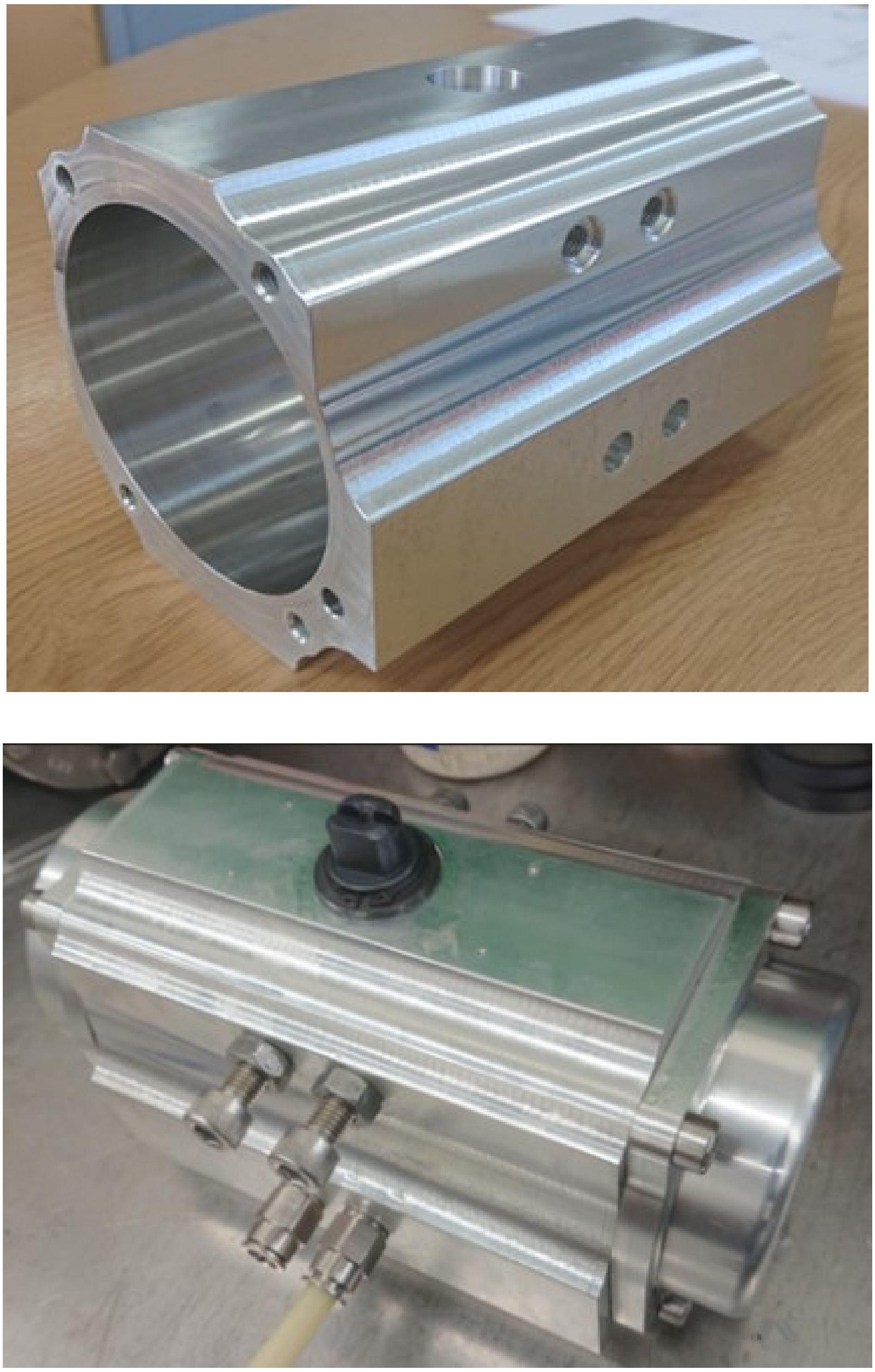


Figure 60.Moments of the validation by means of a "mockup" prototype.
From above: (a) center body obtained by machining of a solid block, (b) assembling of the prototype, where it is possible to notice two different versions of limit grub screws, installed on the two sides of the body.

One of the first topic that immediately attracted the attention and has been discussed during the meetings for the definition of the validation plan, as possible source of complications, is the fact that some of the actuator parts are obtained by casting and extrusion. For both production processes, for obtaining the final pieces, it is necessary to prepare special equipment, having significant production costs and that are not reversible.

For producing the extruded body by extrusion, it is necessary to machine an extrusion stamp with the profile of the piece. For actuator components obtained by die casting, it is also necessary to proceed with the production of a permanent molds, with high costs and the constraint that once created, in most cases, they cannot be modified according to the need of component design changes.

These constraints take on particular importance, considering that in the new prototype, for the stroke adjustment mechanism, a totally new solution has been introduced, interacting with center body and pistons. Any need of thickening of the center body in correspondence to regulation screws threaded holes, for example, would be impossible without providing a new stamp, and, in addition, any possible lengthening of the central body due to changes in the dimensions of cam system would lead to a consequent adjustment of casted pistons length, with related need to provide a new mold.

For this reason, even if, thanks to performed verification on design, no major entity issues are expected, it has been agreed as a good solution to proceed with a special validation procedure, based on two subsequent steps:

1- a first phase is focused on the creation of a partial prototype, called "mockup", aimed at testing design features to be validated first;

2- a second phase is focused on a final prototype identical to the actuator that will go into production, and it is finalized to test all the remaining design choices.

Having defined the objectives that it is possible to pursue by means of the validation plan and the chosen approach for performing the activities, it is now possible to describe in more detail each of the two phases.

11.2 Validation based on a "Mockup" prototype

A partial prototype here called "Mockup" has been assembled with the special aim to validate actuator features to be checked first. Checks are focused on the new strokes adjustment system and on the new pinion bushings. In fact, as previously clarified, dimensions of other important components, the casted pistons and the extruded central body, depend on them. The production processes of these components require to produce stamps, making very difficult to perform changes in component shapes once produced. Then the chosen approach was to create a preliminary model, as shown in Figure 60, where the components not involved into the checks have a secondary importance for the moment. According to this principle, the mockup prototype is composed by:

1) Components in the new designed version for pinion, pinion guide bushings, stroke adjustment grub screws.

2) The new designed cam.

3) A central body machined from solid specifically for this purpose. The component features detailed machining for the areas of interest for the tests, as for example the bushings slots and the O-ring grooves in the holes for pinion, or the holes the stroke adjustment grub screws, with precise depth and dimensions, while for other sections it does not present all the details present in final version, as for example the interfaces for accessories.

4) For all other parts not directly affected by the tests, components with old design taken from old model. In particular, the old lateral closing flanges, the old pistons and related guide bearings were used.

5) the pressure sealing system of the components not subjected to the tests remained the same present in the old model. For example, the "dummy" model of the central body maintained the same internal diameter tolerances present in the old model, in order to guarantee the functioning of the seals of old pistons and old flanges.

During the assembly phases of the prototype, a problem had to be faced, regarding the assembly tolerances of the cam, a component that was never previously produced. Excessive backslash was noticed during first assembling of the prototype, requiring a design modification for indicating tighter dimensional tolerances.

Nominal dimensions		Pinion nominal dimensions	Cam nominal dimensions
Outer PCD		49.5	49.92
Radius		12	12
Inner PCD		25.5	25.92
Across distance		29.04	29.74
Chosen tolerance size (+/-)		0.03	0.1
Dimensions at their tolerance limits		Highest gap configuration	Lowest gap configuration
Cam	Outer PCD	50.02	49.82
	Radius	11.9	12.1
	Across distance	29.84	29.64
Pinion	Outer PCD	49.47	49.53
	Radius	12.03	11.97
	Across distance	29.01	29.07
Calculation of the angle of rotation motion			
Chosen arc's angle which center is described in the polar coordinate system for both parts		67.5	67.5
Pinion	Center of circle X	9.4657	9.4772
	Center of circle Y	22.8522	22.8799
	Chosen point X	0.8028	0.8956
	Chosen point Y	14.5050	14.5350
Cam	Center of circle X	9.5709	9.5326
	Center of circle Y	23.1062	23.0138
Radius which the pinion's chosen point is on		14.5272	14.5626
Cam's circle and chosen point's circle's intersection points	X1	9.2388	9.6408
	Y1	11.2109	10.9143
	X2	1.3944	0.9005
	Y2	14.4601	14.5347
Closest point to the pinion's chosen point		2nd point (X2, Y2)	2nd point (X2, Y2)
Angle of the chosen point		86.8322	86.4743
Angle of the intersection point		84.4918	86.4548
Angle of motion		**2.34038649**	**0.0195**

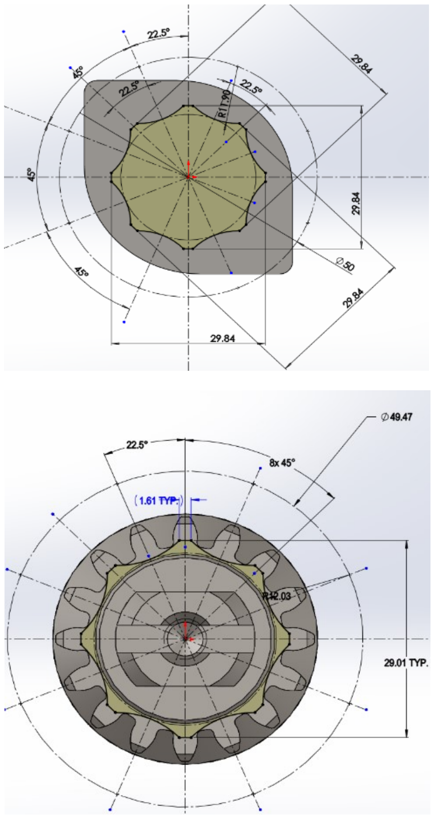


Figure 61. tool developed for the definition of the best tolerances of pinion-cam connection.

In fact, the connection of the cam with the pinion is made by means of a special grooved profile. The identical profile is machined in the internal hole of the cam and on the external profile of the pinion. To allow the assembly and the correct coupling between the two parts it is necessary to ensure the correct clearance, because an excessive one would relative movements with the possibility of damages to the profiles of the cam and piston. For this reason, investigations were carried out about the minimum and maximum acceptable tolerances, taking into consideration different cam production technologies, as laser cutting, wire cutting and sintering. During the first prototype assembly, however, a cam produced by laser cutting proposed by a supplier has been assembled excessive backslash was noticed, requiring modifying the design for indicating the need to respect tighter tolerances. For finding the best new values to be introduced and integrating the observations and the measurements done on first prototype, a small calculation tool has been developed, as shown in Figure 61, allowing to correlate the maximum dimensional tolerances of the cam and of the pinion with the maximum obtainable angular relative rotation. A second cam prototype was produced, obtained by wire cutting, a technology having high machining precision and then avoiding to introduce additional errors in dimensions, and the new proposed tolerances were confirmed as suitable.

During the assembling of the "mockup" prototype it was also possible to check the dimensions and tolerances, as well as between cam and pinion, also for all other the components of the new angular stroke adjusting system, as for example the dimensions and position of the threaded holes for the stroke adjustment grub screws, allowing for a correct positioning with respect to cam surface, and the correct sizing of their sealing, as they are screwed into pressure containing part. Finally, the ease of regulation of the angular strokes was tested.

Checks were performed about the correct assembling and functioning of the pinion bushings, completely re-designed for simplifying the assembly operations. The correct dimensions of the connections among the following new designed components were checked:

1) check of the tolerances between pinion and guide bushings, and between guide bushings and their seat in the center body;

3) check of the tolerances of the groove in the center body for the O-rings in contact with pinion, and check of the correct O-rings compression;

4) checks of the dimensions and correct fitting of the coupling elements allowing the pinion to be kept in position, composed by a washer and a Seeger.

Once these preliminary checks about dimensions, tolerances and correct assembling were completed, tests under load allowed to verify the structural resistance of the new designed parts in static and dynamic conditions. The following sub-paragraphs describe the main tests performed thanks to mockup prototype.

11.2.1 Leakage test of pinion sealing system and Actuator pressure test

This test consists in verifying the correct functioning of the new sealing systems of the pinion and of the regulation grub screws, by checking for the absence of leakages. The actuator is powered with low pressure values. Then a foaming liquid is used, sprayed or brushed on seals area, allowing to detect any leaks escaping from O-rings grooves, that in contact with the liquid creates bubbles. After the new designed seals, all other seals are also checked for possible leakages, although the design is not new. In fact, absence of leaks is necessary before proceeding with the main pressure test.

Pressure test is performed at values above the design pressure, for the specific purpose of ensuring the safety of all pressure containing parts before allowing the use of the actuator and that operators can approach it when it is powered with high pressure values. Once positively passed the pressure test, it is possible to proceed to static and dynamic verifications of the new designed components and systems.

Quantitative Analysis of Results:

The complete mock-up actuator has been pressure tested with 6.9 barg shop air and any leaks were found in the following areas:

- End caps;
- Pinion;
- Limit stop screws;
- Body extrusion through holes.

11.2.2 Functional test of the mockup prototype

The correct functioning of the prototype was checked, since before to perform tests with heavy loads it is necessary to check that the actuator is able to operate correctly, performing the opening and closing angular strokes without jamming and in a fluid manner, confirming absence of excessive friction. These checks are a further confirmation of the correct assembly and sizing of the connection between the pinion and its guide bushings, completely redesigned for making it simpler the assembly and ensuring the proper rotation of the pinion without friction.

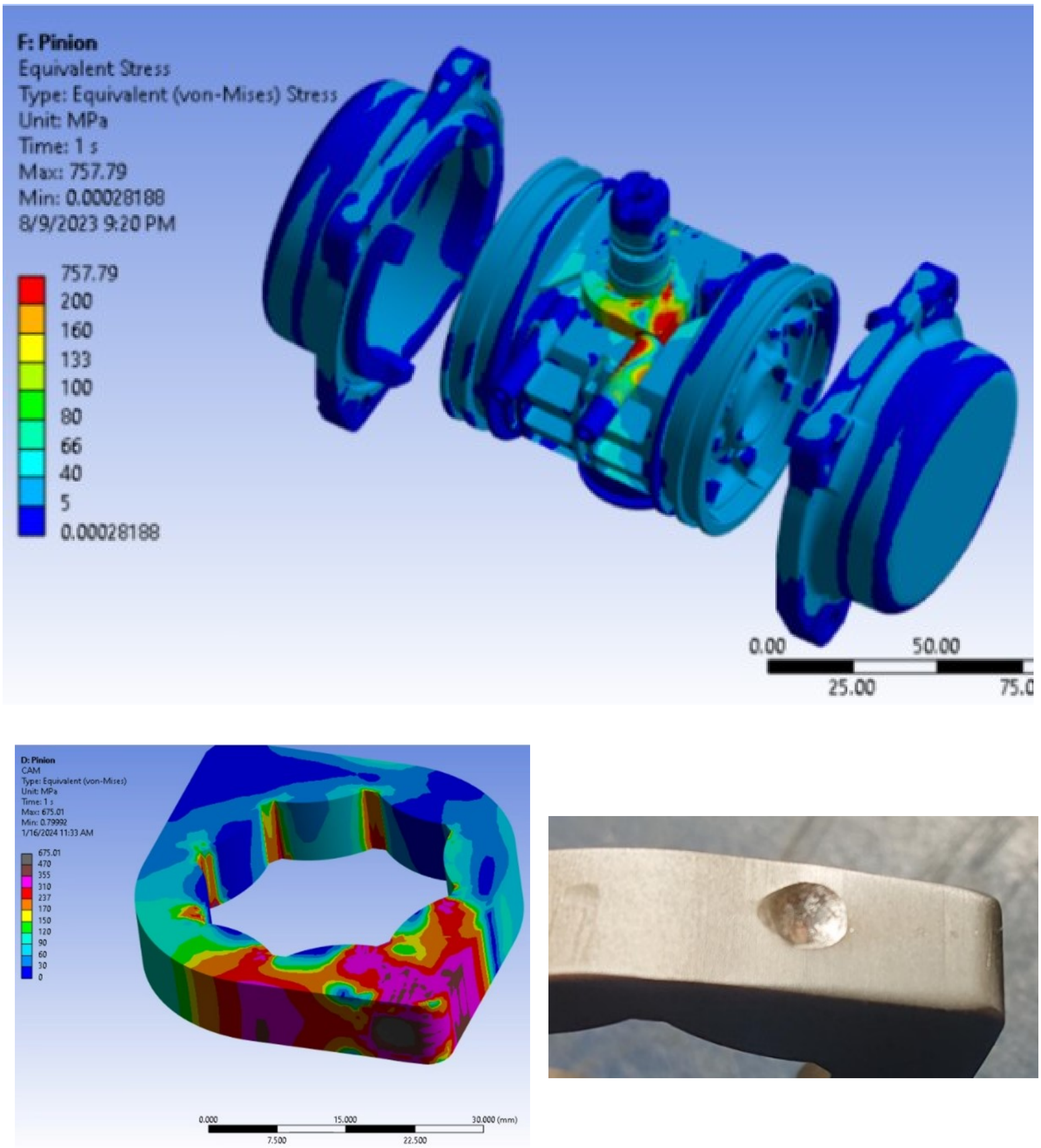


Figure 62. Simulation focused on the study of the connection between cam and grub screws of angular stroke regulation system.
The performed FEA were finalized to optimization of shape and dimensions of the studied components. The small plasticization in last image highlights the consistency between FEA results and the observations from experimental tests about the cam – grain contact area.

During functional test also the functioning of the new angular stroke adjusting system is checked, confirming that is possible regulate the strokes and stop the actuator at different angular positions without problems. Concluded functional tests at normal loads it is possible to start the ones where the behavior of the components when subjected at high loads and high speeds is investigated.

11.2.3 Static Tests at design pressure

During this test the actuator is powered both in opening and closing directions, at a pressure value equal to design pressure, for measuring the deformations of the new designed components when subjected to very high loads. In particular, the entity and effect of deformations in the following areas are verified:

- deformation of pinion and cam in correspondence of their connection;
- deformation of cam and the stroke adjustment grub screw in the area of their contact;
- possible deformations of the guide bushings between pinion and center body, following deformation of the pinion under the pneumatic load. In particular, the absence of crushing of the bushings, increasing their wear due to friction, was verified.

All the checks reported above did not bring to light specific problems with the components, confirming that the dimensions identified in the design phase are appropriate. The observations on the components after the tests confirmed some behaviors foreseen by FEA with good approximation. For example, the formation of an acceptable small denting on the cam surface, in correspondence to the contact position with grub screw, was noticed, as shown in Figure 62. This result is very important and confirms the useful predictions obtained with FEA.

Quantitative Analysis of Results:

For better evaluating the effects of pneumatic design load on the limit stop grub screw design, the option to use either 8mm or 10mm limit stop screws has been analyzed. The mock-up prototype has been then produced with both options installed, so they could both be validated. Screw holes of two different size has been then machined on each side of the extruded body, so as to have an angular stroke regulation system with M8 screws on one side and M10 screws on the other as shown in Figure 63.

The first strength test of the Cam/Pinion limit stop mechanism has been performed by using the version with 10 mm limit stop screws. The pinion angular position was set at 20° away from fully open, resting against the limit stop. The actuator has been placed in the test chamber and then air pressure of was applied. Pressure value was gradually increased from zero to 10.5barg. A digital angle sensor was then connected to the pinion. The sensor showed an angular deflection increasing from 0 to a maximum of 0.08 degrees, as shown in Figure 64.

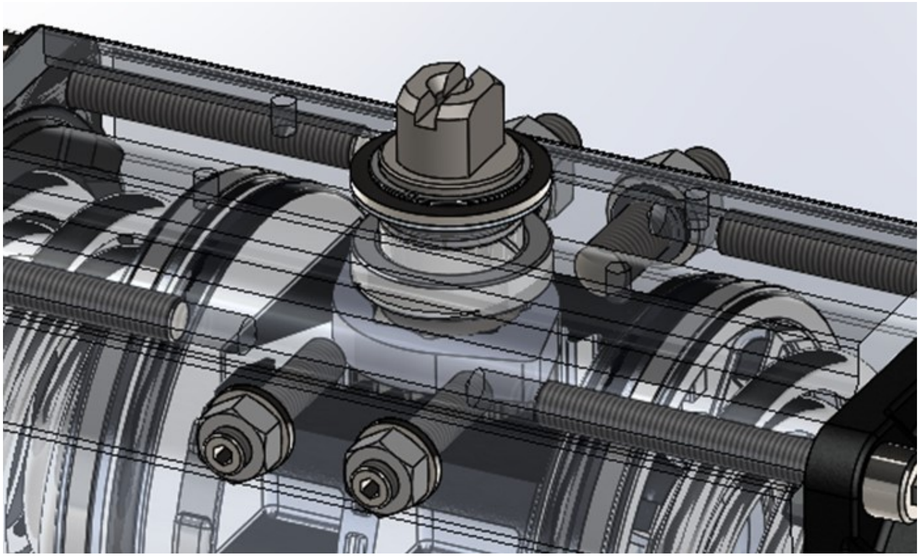


Figure 63. Two options of angular stroke regulation systems machined on each side of extruded center body.
On one side the screws have size M8 and on the other they have size M10.

Once the above testing was completed the actuator has been disassembled and checked for possible permanent deformations or damages of components. The CAM and M10 limit stop screws appeared intact. The actuator was then reconfigured to now use the M8 limit stop screws and the test described above was repeated with exactly same execution details. At 10.5 barg a total angular motion of 6.59° was measured. Once the pressure was removed the angle reduced to 4.3°, confirming the presence of plastic deformations.

At this point the actuator was opened, and the Cam and associated parts were assessed. The Cam appeared to be dented and whilst it seemed to align nicely with the limit stop screws, the dent was below the center of the CAM, as shown in Figure 66. The M8 stop screw was also slightly bent. The obtained results showed then that the M8 limit stop could be sliding along the angled surface of the CAM, as represented in Figure 67, both causing the limit stop screw to bend and the scoring / scraping of the CAM surface.

Figure 64. Validation test of the cam system with angular deformations measurement. A digital angle sensor provided with a digital display is connected to the pinion.

11.2.4 Comparison between experimental data and FEA results on pinion angular deformation

The results of the experimental tests performed on the angular stroke adjustment cam system led to a direct confirmation of the consistency of the results obtained with the FEA analyses.

As described in the quantitative analyses presented in previous sub-paragraph 11.2.3 "Static Tests at design pressure", considering an angular stroke regulation system design based on M8 size stopper bolts, by applying a pressure equal to actuator design pressure (10.5 barg), unfortunately it is not possible to guarantee that the angular position of the pinion and then of the connected valve is maintained, because of the presence of phenomena of sliding between the cam and the stopper, and also because both cam and stopper are subject to permanent plastic deformations. In particular, the pinion under load, in the conditions just described, is subjected to an unwanted angular rotation of approximately 6°.

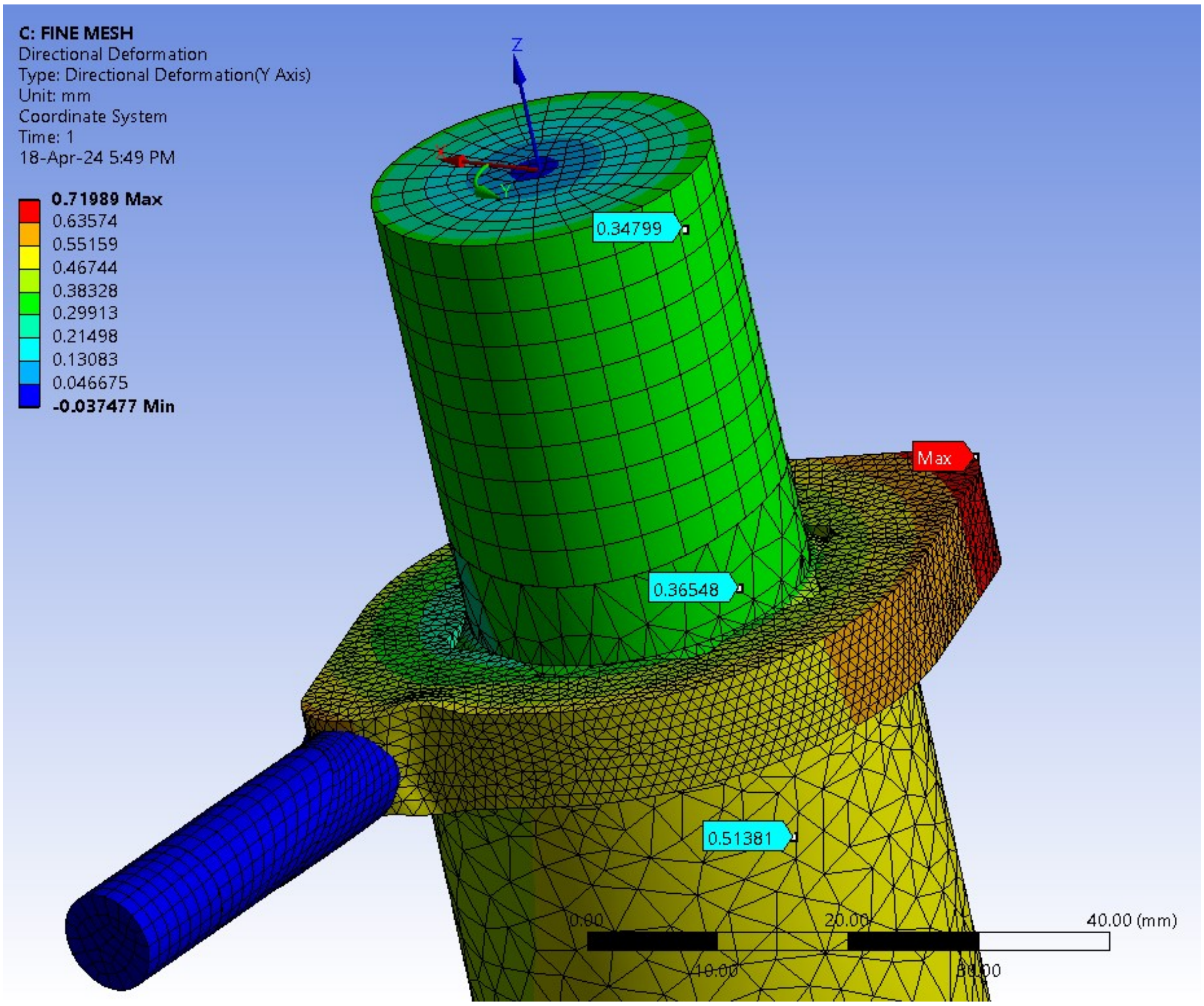


Figure 65. Tangential displacement of pinion when the cam is in in contact with the stopper bolt under the moment caused by design pressure.
FEA results are aligned with experimental data measured during tests on mock-up prototype.

The angular strokes regulation system was simulated with FEA analyzes in a condition very similar to the laboratory test, and even in FEA results it was noted that it is not possible to maintain the desired angular position with an M8 stopper bolt.

Unfortunately, the FEA analysis and the experimental test were carried out at non-identical angular positions. Nevertheless, the dynamics of the behavior of the components were the same for the experimental test and for the simulations. The FEA predicted that it was not possible to use an M8 stopper and it should be necessary to skip to an M10 size. By performing the tests and by repeating them with stoppers of both sizes, the FEA predictions have been confirmed.

Below are reported the detailed results about angular rotation of upper end of the pinion obtained with tests and with FEA.

1) angular deformation measured during the test performed in laboratory on mock-up prototype with cam set at 20° from fully open position (worse case): **6.59°**

2) average Tangential displacement measured by FEA with the cam set at 5° from fully open position: **0.35 mm**

From the average value of tangential displacement found through the graph provided by Anys Mechanical®, shown in Figure 65, it is possible to calculate angular deformation of the pinion at its end, in the area where the digital encoder for angular position measurement has been installed in mock-up prototype, as shown in Figure 64. The pinion has a diameter D_p of 25 mm at measuring point of the average displacement of 0.34 mm. The angular rotation is therefore:

$$\alpha = \frac{0,35}{\pi D_p} 360° = 1.6° \tag{6}$$

A rotation of 1.6° of the pinion under load is not acceptable and anticipates the presence of components with excessive plastic deformation. These predictions were confirmed by finding a rotation of 6.59° in similar conditions during the experimental tests, as shown in figure 66. The need for a bigger stopper was then predicted without waiting for a validation tests.

11.2.5 Dynamic tests at high pressure

Once completed the static tests, it was then possible to move on to the next type of tests, where the behaviour of new designed parts and in particular of the components of strokes adjustment system were verified no longer in static conditions but in dynamic conditions.

The “mockup” was tested by performing a cyclic test, powering it with high pressure and high flow rates, to obtain high torques and high stroke execution speeds, causing impacts between the cam and the grub screws. The actuators must in fact be suitable to applications where they must perform thousands of opening and closing cycles in these conditions. The possible cumulative damage caused by the repetition of the impacts can in this way be assessed. After completing 900 cycles, the actuator was disassembled, and components examined. The absence of permanent deformations in grub screws was verified, allowing to screw and unscrew them correctly. Pinion and cam were checked for ensuring absence of cracks. Finally, the conditions of the pinion bushings were assessed, for excluding premature deterioration. After the analyses of the results of these tests, as well as after static tests, the design choices were confirmed without the need to perform big changes to the components.

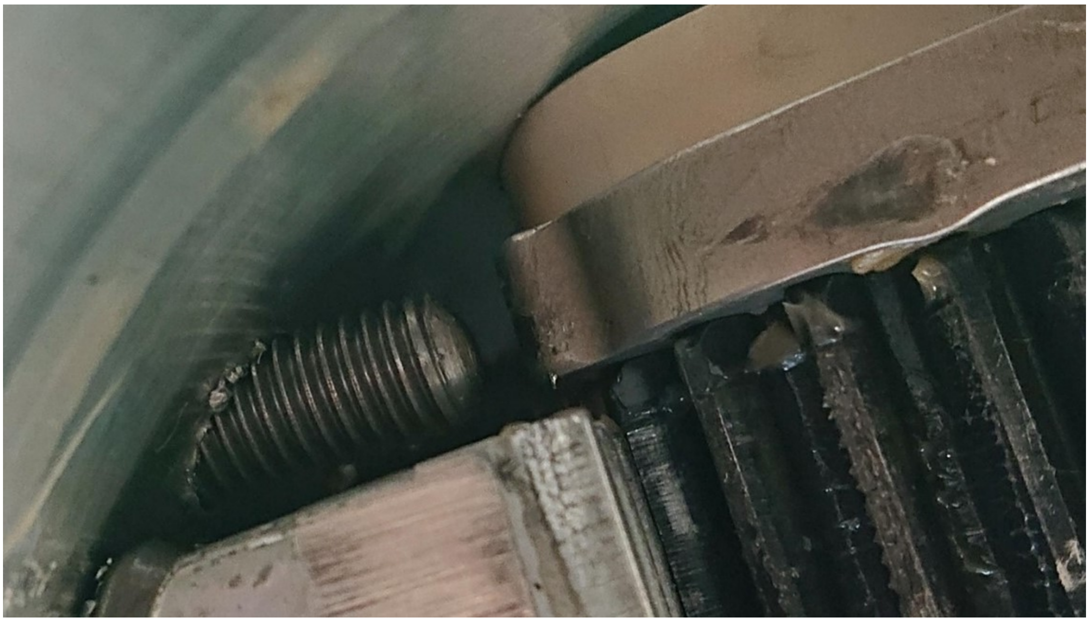


Figure 66. Check of the components of the cam – M8 stud bolts connection after testing at 10.5 barg.
It is possible to notice the local plasticization of the cam and the slight bending of the grub screw, affecting the behavior of the angular stroke adjustment system.

Quantitative Analysis of Results:

The actuator was connected to an air supply, controlled by a PLC, allowing to operate the actuator for opening and closing strokes in a range of pressure values from zero to 16 barg. For the test on the prototype the following set up as been used:

- 300 cycles at **4 barg**
- 300 cycles at **5 barg**
- 300 cycles at **6 barg**

After each 300 cycle test, the actuator was opened and inspected. The main found observations on the components are the following ones:

- As the pressure was gradually increased for each cycles batch, also the indentation of the cam grew deeper, as shown in Figure 68. This however did not affect the operation of the actuator.
- The Pinion showed no signs of wear after all the testing.
- The cam central spline has evidence of slight deformation, as shown in Figure 69.
- The M10 limit screws did have a slight polished area but again no real deformation has taken place, as shown in Figure 69.
- The body threads showed no sign of wear.

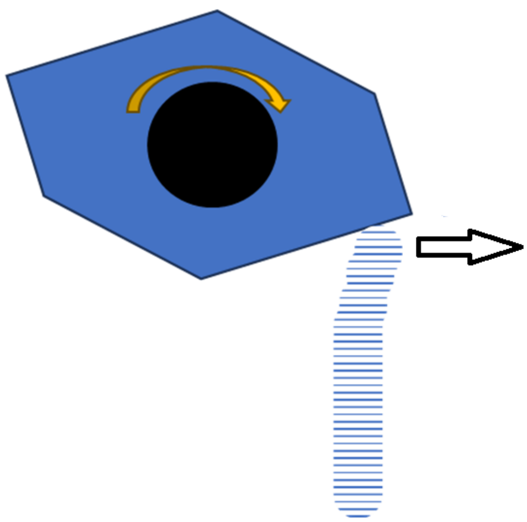


Figure 67. sketch representing the sliding of grub screw end along the angled surface of the cam, causing its bending and the denting of the cam surface.

11.2.6 Cyclic test of new piston sliding pads

For checking the operation of the new piston sliding pads design proposed with a Design Change Proposal and reported in Figure 70, an endurance test consisting in a cyclic test of over 1000 cycles was carried out at 6.9 barg with no pinion load. The prototype has been assembled with pistons and pads obtained through machining from solid parts. Two different scenarios were present in the two pistons:

- A piston with nominal fit tolerances of machining for both piston and pad;
- A piston with tolerances of piston and pads giving a worst-case loose combination.

Additionally, only extremely small amounts of grease were present representing a worst-case scenario for lubrication.

No problems were encountered, and the parts were OK after test. The new sliding pad design could then be validated.

11.2.7 Final observations after tests on mockup

The tests on "mockup" prototype confirmed the validity of some the completely new design solutions introduced after DtV analyzes, drastically reducing the probability of having to make changes to them in the final prototype.

Once confirmations are obtained about the suitability of components validated first with mockup as they could constitute critical issues requiring changes to extruded or casted parts, it is possible to proceed with the creation of the final complete prototype, focused on the validation of remaining new components. Thanks to preliminary tests on mockup, possible issues that could emerge with final prototype are more limited, and relevant to intrinsic problems of remaining new components, thus, drastically reducing the probability of having to make changes to their stamps and moulds.

Furthermore, the results of the tests on the mockup are a first are confirmation that the approach used for performing the detailed design phase, also if initially could require more resources, it could then apport benefits, same time and resources in the following validation phase.

At the time of writing this text, the tests on the "mockup" have been successfully completed and the procurement of the final parts made by casting and extrusion processes is ongoing. Considering that the experimental results found thanks to mockup model are aligned with calculations and FEA predictions, it is expected that in final prototype also a certain alignment of the results will be found, avoiding major modifications of big impact.

4 barg

6 barg

8 barg

Figure 68. Increase of the cam denting with increase of supply pressure during high load cyclic test.

11.3 Validation of the complete final prototype

The second part of the validation will be based on a prototype identical to the final model intended to production. To create this prototype, small batches of components are usually supplied, using final drawings intended to production. All possible problems regarding the components not already checked with “mockup” could be discovered, and final changes could be carried out before the start of mass production. Tests of fundamental importance for the safety and reliability of the product will be performed, as briefly described in following sub paragraphs.

11.3.1 Quality, assembling and functional checks

The first step of the verifications on final prototype consists in performing quality checks on each one of the components intended to be the final version used for mass production, issuing "quality reports" where the characteristics of the components are fully examined, starting from respect of drawing indications, about dimensions and dimensional and geometric tolerances. For casting parts at this stage is checked the surface roughness and the good execution of the casting, using non-destructive examinations, such as penetrant liquid, x-rays or ultrasound examinations.

Figure 69. Check of the components of the cam - stud bolts connection after high pressure cyclic test.

Other components obtained by casting are plastic components made by injection moulding, like pinion guide bushings and piston support bearings. Also in this case it was necessary to proceed with an analysis of the optimal tolerances of both the components and of the machining of components housing them. For example, the proper fitting of the moulded bearing in the groove of center body must be verified, to check that it guarantees correct assembly, and at same time do not present excessive clearance not allowing the correct sliding of the piston. Another analyzed situation concerned the verification of correct coupling and assembly of the new designed piston guide bearing, where a tolerance study of this plastic component during the assembly phases has been fundamental. Both for pinion bushing and piston bearings, an approach that has been very useful was to introduce in the phase of test on mockup some prototypes made through mechanical machining, that is milling and turning on a lathe. In this way, it has been possible to avoid the problem already discussed for metal parts, that is directly proceeding with the creation of stamp for injection moulding. In fact in the event of need of design modifications it would be necessary to produce new stamps, requiring long time and high additional costs. The use of machined prototypes from solid is a very effective tool. In fact, it allows to produce components with good precision and tolerances exactly as the ones indicated in construction drawing. In addition, the production can be limited to the pieces necessary for the validation and several versions of the component can be produced, like in the case of piston pad, for choosing the best option and have confirmation about values at both ends of tolerance range. Finally, in case of modifications it is easy and very quick to obtain new modified components with necessary dimensions. This approach allowed to send to suppliers for mould production components with dimensions already tested and with probability of suitability.

As described for the tests on "mockup", the final prototype assembly constitutes an important validation activity, where all the couplings between the newly designed parts are checked.

Figure 70. Piston prototype obtained by machining to be used for the validation of the new sliding pads design.

Furthermore, all the O-ring grooves are checked, with verification of the correct size and consequent achievable O-ring compressions. In details, the main checks that is possible to perform are the following ones:

1) Coupling among new cast piston, new pinion and new extruded center body, considering new pinion bushing and new piston guide bearings;

2) Coupling among final version of the center body with the lateral closing flanges, with verification of the correct sizing of sealing system. In details, check of the correct positioning of the fixing screws holes inside flanges and check of correct assembling of the screws, and correct tolerance of threading;

3) Verification of springs mounting in the correct position, checking the suitability of the appropriate housings foreseen as spring guides in piston and closing flange surfaces. The model chosen to be built as prototype is in fact a "single-acting" actuator, so called as it contains springs and under their action one of the two maneuvers is carried out, leaving to pneumatic supply only to perform a single acting.

When all the special couplings have been checked, it is possible to proceed with the assembly of the complete prototype. Once the complete prototype is available, its correct functioning is verified by making the actuator perform some opening and closing maneuvers, to verify that there are no jamming and that the movements occur smoothly, without little jumping due to incorrect tolerances. The strokes are performed by manually operating the actuator, as the safety against of pressurized components and absence of leakages has not yet been tested. In fact, once the correct assembly and free load functioning has been verified, the immediate following step is to move on to other types of tests of fundamental importance for confirming the safety of the product, as described below.

11.3.2 Pressure tests

The first objective of good design is to place safe products on the market, so a fundamental part of the validation tests concerns safety verification, that must be analyzed from different points of view. First of all, the product must not cause possible damage to the operators and technicians responsible for installation and maintenance, therefore it is necessary to check that there are no sharp surfaces, nor pinch points of or moving parts that could cause clothing to be trapped during movement or crushing operator's hands. Another aspect is functional safety, already mentioned when presented the need of SIL certification obtainment. Finally, it is of primary importance to ensure the safety of the product when it is powered, in this case when it is pressurized, and then the safety of the parts under pressure. For this reason, the first tests to be carried out on the actuator before to power it in presence of operators are the following ones. These tests are performed, both during prototype validation and on each single actuator once mass production is started.

A) *Leakage test at low pressure, for checking the correct functioning of sealing system.*

As done for the "mockup" prototype, the first necessary step is to proceed with the verification of the pressure sealing systems at low pressure values by means of a foaming liquid, also called “bubble test”. all the seals are checked for detecting possible leakages. In fact, absence of leaks is necessary before proceeding with the main tests at high pressure values.

B) Structural pressure tests, at pressure equal to 1.5 times the design pressure.

During this test the actuator structure containing the supply pressure toward external environment is pressurized to a value higher than the nominal one, also called design pressure (Pd), that is the maximum for which on the field the safety of the actuator is guaranteed. The importance of this test is such that all reference standards for actuators require it to be carried out systematically on each single produced actuator. The assumption is that once this test has been passed the actuator will not have problems when in the field it is pressurized with pressure values up to the design pressure. These checks go beyond checking the correct functioning of the product, which will be carried out in the subsequent steps, but are first and foremost something essential to the health of the operators and are therefore put first both during the development of the project and once production has started. According to main reference standards for pressure vessels, the test pressure test value has been chosen equal to:

$$1{,}5 \times Pd = 1{,}5 \times 10.5 \ barg = 15{,}75 \ barg \quad (7)$$

By carrying out this test it is possible to confirm the structural strength of the pressure containing parts. With this test it is possible to intercept all the defects present in the castings, such as porosity, which have not already been identified in the quality controls and in any non-destructive controls previously carried out. The importance of this test is such that all reference standards for actuators require it to be carried out systematically on all individual produced actuators. The assumption is that once this test has been positively passed the actuator won't have problems when in the field it will be pressurized with pressure values up to design pressure.

These checks go beyond the verifications of the correct functioning of the product, that will be carried out in the subsequent steps, but are first and foremost something essential to the health of the operators and are therefore put first both during the development of the project and once production has started.

For safety reasons, the structural pressure tests on the first prototypes are carried out by feeding them with hydraulic oil, so that, in the event of a component collapse, the sudden leakage of oil is not linked to an explosion, which could instead occur when the actuator is powered by a compressible fluid such as air instead of oil. However, these tests still present great risks, especially in the case of components tested for the first time, either because they have new design or because they are supplied for the first time by new suppliers. For this reason, all the tests described in this section are carried out inside a special laboratory equipped with a special bunker, completely isolated from the surrounding environment. The actuator is installed inside the bunker, which is equipped with ducts, through which the hydraulic and pneumatic tubing can connect the actuator to supply lines.

C) *Burst pressure test.*

This test is performed only during validation, and it is aimed to ensure that pressurize parts are as much safe as possible even in case of improper use or failures of the pneumatic supply system. These tests are in fact aimed at having an internal evaluation of how far these components can resist before being subject to structural collapse. In addition, these checks allow to have very important data regarding the actual safety margins that exist when the actuator is powered at highest admissible pressures in the field.

To carry out this test, a special prototype is created, where all internal parts not directly involved in the test are removed. The components to be evaluated are in fact those constituting the "external casing" of the actuator, comprising the screws holding it together.

D) For performing the test, the actuator is powered by gradually increasing the supply pressures, up to a value that has been assessed as a possible value the actuator could accidentally being subjected in the field in case of errors of faults. Actuator will be then gradually powered up to a pressure equal to 2.5 times the design pressure:

$$2{,}5 \ x \ Pd = 2{,}5 \ x \ 10.5 \ barg = 26{,}25 \ barg \qquad (8)$$

Components are expected to plasticize and have permanent deformations. The screws connecting the central body and the lateral closing flanges will have big elongations, causing a possible detachment between the components. In this situation, O-rings placed between center body and flanges may be extruded out of their seats, causing the actuator to begin to leak. Such a behavior can be assessed as positive, as the pressure could decrease, thanks to leaks, before the collapse of components, excluding then the event of an explosion. This behavior would confirm then that even in the event of serious errors of faults the risk accidents with explosions can be reduced. The positive results of these test are an important confirmation necessary to the manufacturer to confirm that the new developed product has a good quality with regards to safety aspects.

Once all the tests for the verification of the integrity of pressure containing parts subjected to high loads have been completed, it is possible to start the tests for carefully validating the correct functioning and the reliability of the final actuator prototype.

E) Repetition of tests on the travel adjustment system

It was appropriate to repeat all the tests performed for validating the new design of this system on the "mockup" model also on the final prototype. In fact, in "mockup" model a central body obtained from an aluminum solid piece by machining was used, while in its final configuration is produced through an extrusion process. It is therefore necessary to repeat the tests to evaluate the actual deformation of the final central body in correspondence of pinion and of threaded holes for stop stroke screws. In addition, during this test is possible to verify the deformations of the final version of other components, firstly the cam and the piston with its plastic guide bearings, when the pneumatic load at design pressure is transmitted in static conditions from pistons to body by means of cam mechanism. In a second step, the effect of repeated impacts on the components when the actuator cycles at high speed and high pneumatic load is also assessed. Obtaining results aligned to the ones found by testing the "mockup" prototype confirms, on the one hand, the correctness of the design choices, and on the other the usefulness of upstream checks, both during the calculation and FEA phase, and during the tests on the "mockup", reducing the probability to make changes at level of final prototype.

Once this re-verification using the final components intended for production has been completed, it is possible to move on to the phase dedicated to the performance validation of the new actuator design.

11.3.3 Verification of actuator performances

This phase of the validation is focused on verifying the performances the actuator, verifying that the torques delivered during the experimental tests are aligned with the values theoretically predicted with calculations and with historical data of previous design. In fact, in DtV phase, during the discussions about the performances of the new version, it has been assessed as a best choice to not modify the actuator parameters influencing the generated torques, and the expected result is that the new model delivers torques aligned with those of the old design model.

To verify that the actuator delivers the expected torque, an indirect test is initially performed, consisting in checking the equilibrium pressures that allow the inner springs to be compressed until the angular positions of 0° and 90° are reached. With this method it is possible to trace back to the forces delivered by the springs in the two main working positions and check that they coincide with required nominal ones.

If one or both spring working forces do not fall within the acceptability limits it may mean that:

1) One or more connections among actuator components present an excess of friction, so that it will be necessary to identify the area not working in a smooth way and proceed by modifying the involved dimensional tolerances;

2) Springs have not been correctly tested and provide less force than expected;

3) Other causes of malfunctioning are present and need to be investigated and solved before proceeding with other tests.

If, on the other hand, equilibrium pressures fall within the expected ranges, it is possible to predict with a good amount of probability that the torques delivered by the actuator will be aligned with expected ones, barring further problems that could only be detected during the direct measurement of the torques, that is in fact the next step of the tests. The torque measurements are performed by means of a calibrated dynamometric brake, where the actuator is assembled on, by using a special coupling kit. The brake is equipped with a torque meter, measuring the torque delivered by the actuator shaft.

A chart is issued, containing a curve composed by actuator measured torques at different angular positions. Several curves are produced at gradually increasing pressures, to record the behavior of the actuator when subjected to low, medium, and high loads. The target is obtaining measured torques aligned with theoretically calculated one and comparable with old design ones. Torques aligned with the expected ones confirms that the new components involved in torque transmission do not present unwanted deformations, capable of increasing friction, and then causing a reduction in transmissible torque.

Once performance validation phase has been completed, it is possible to conclude the validation activities by finally performing a cyclic endurance test, finalized to an in depth verification of actuator reliability.

11.3.4 Cyclic endurance Test

This test finalized to verify the reliability and the good fatigue life of actuator components, by analyzing their behavior when subjected to a very high number of cycles [*54*].

Figure 71. Preparation of the prototypes of cam, stud bolts and pinion for the validation of the new angular stroke adjustment mechanism via actuator mockup prototype.

Analyzing the behavior of the actuator when it must face a very high number of cycles is extremely important, both because in some applications it will actually be engaged in hundreds of thousands of valve strokes but also for uses where it will be subjected to few intervention requests per year. In fact, the cyclic test also represents one of most important tests required for SIL certification obtainment. SIL certification evaluates the reliability of the actuator when it must intervene for an emergency function, and, among assessment results, associates product reliability to parameters, expressed as hourly failure rates, called lambda, and having for actuators values of the order of 10^{-8} or 10^{-9} h^{-1}. Lambda values are obtained by means of a dedicated branch of reliability calculations, and depending on the type of associated failures, they are divided in four categories: Detected Dangerous, Detected Safe, Undetected Dangerous, Undetected Safe. Positively passing a cyclic test with more than 100,000 cycles without significant damages is one of the first confirmations necessary to validate the correctness of the reliability parameters associated to the actuator.

One of the most important direct experimental checks that is possible to perform by means of the cyclic test concerns the confirmation of the design of the sliding components subjected to wear, in particular the pinion guide bushings installed in center body and the piston sliding inserts. With re- design activities these components have been updated to optimize their features. For example, pinion bushings have been modified for improving assembly operations, that for old pinion guide bushings were very long, and requiring special equipment.

The cyclic endurance test is performed until the maximum number of cycles that the actuator is expected to perform during its operational life is reached. This test simulates the most demanding conditions of use from the point of view of fatigue, occurring when the actuator is coupled to a regulation valve requiring to vary its open position in an almost continuous manner, so that the actuator must perform up to tens of cycles per minute [*54*].

In accordance with the new version of the reference standard for quarter turns actuators EN15714-3:2022, the minimum number of cycles to be performed without failures for actuators in the torque range of examined prototype is equal to 500,000 cycles.

This value is very high and for this reason the test is performed with a procedure where the cycles are carried out through successive steps. It is planned to carry out 3 subsequent phases of the test, divided as follows:

1st step : 0 - 150000 cycles

2nd step: 150000 - 350000 cycles

3rd step: 350000 - 500000 cycles

At the end of each one of the three steps, the actuator is disassembled and the components subject to wear are carefully inspected. Firstly, the surfaces of the pinion bushings and the piston guide ring are carefully examined. Furthermore, each actuator component subjected to mechanical loads is inspected, especially in the areas that according to FEA analyses present higher levels of stress, for verifying the absence of any cracks. If any problem is observed, the actuator can be reassembled and placed on the torque bench for the subsequent cycles interval. Once positively passed all the intermediate verifications, the actuator be considered as validated for applications in the field up to that number of cycles.

During test execution a report is drawn up, where all the performed checks are described and reported together with photographic documentation and measurements results. After the last positive control at the end of 500,000 cycles, the report constitutes important evidence for demonstrating that the actuator complies with EN15714-3 requirement about the reliability of the product. In addition, due to the importance of this test for the obtainment of SIL certification, the tests can be directly inspected by certification body SIL inspectors.

11.3.5 OK to launch of first production batch

In summary, during the validation tests, first on the "mockup" prototype, and finally on the final prototype identical to the models intended for production, the actuator is subjected to a long series of detailed quality checks, followed by many experimental tests, during which the new designed components are subjected to loads much greater than the typical ones present in normal operating conditions.

The main validation aim is to discover and highlight all the possible problems that the new design choices may present and that are escaped to upstream checks by calculations, FEA and drawings review. All assembling and functioning issues linked for example to incorrect tolerances must emerge. Furthermore, all structural problems not correctly evaluated in previous phases must emerge.

Validation allows to correct all unexpected problems before the project enters the following phase aimed to preparation of first production batch. A Good validation is a crucial step for the entire project, as it allows to obtain a confirmation that the product to be placed on the market is safe and reliable.

On the other hand, it is normal that during validation activities problems of small entity could emerge, like the needs of optimizing the tolerances of a coupling or to modify an O-ring size for improving sealing. With the end of these adjustments related activities, it is possible to consider the validation as positively completed and give technical OK to the production of first actuator batch intended to mass production.

As already anticipated during the discussion on mockup prototype, at the time of writing this text, the activity of procurement of the final version of the components for testing the completed prototype is ongoing.

Anyway, the results on components structural strength obtained up to now thanks to the tests on "mockup" show that there is a good alignment between experimental results and predictions obtained by means of FEA simulations. As acceptability criteria used during FEA evaluations are the same for both the parts already tested and those that could be tested once final prototype is ready, it is expected that a good degree of correspondence between the behavior of the components during FEA simulations and the real one observed during experimental tests. All the results so far obtained go in fact in the direction of confirming that the use of the design techniques described in the previous chapters are effective, as summarized in the conclusions.

12 Final Considerations

The results of the activities carried out in the context of this case study show that a multimethodology based on the Design-to-Value process, integrated with innovative design techniques based on FEA simulations, and valorization/maximization of teamwork [*55*], make it possible to obtain a significant improvement in the re-design of a product present on the market since decades, as shown in Figure 72, maintaining constant safety, reliability, quality and performances.

In details, the case study up to now demonstrated that by means of a re-design project using the studied methodology is possible to obtain significant product improvements, about the following aspects.

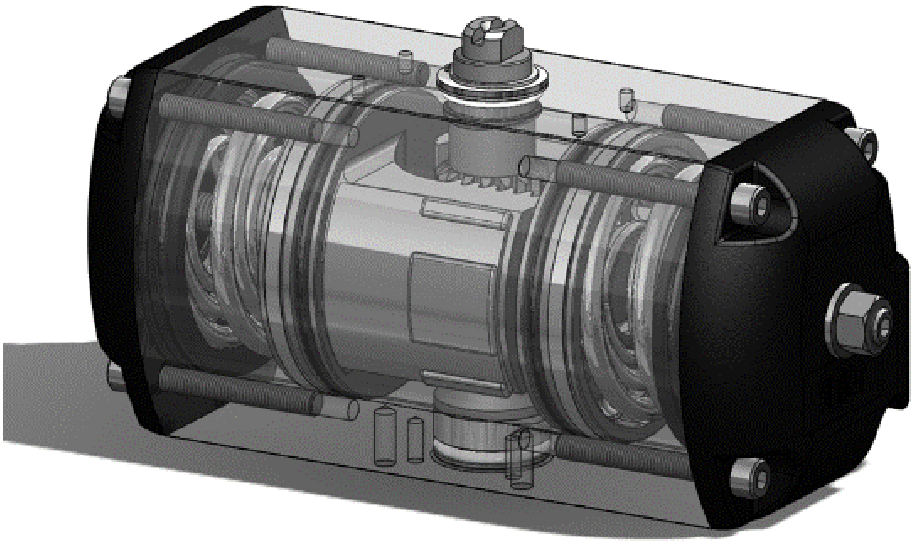
12.1 Design compliance with most up-to-date reference standards

The renewal of the design of a product is an opportunity to align it with quality, reliability and safety requirements indicated in most updated versions of applicable standards. In the case of the studied actuator, the opportunity was taken to verify the conformity of the new optimized version with the requirements present in main product standards for actuators (EN15714-3:2022, ISO12490:2011, API 6DX:2020), and with main reference customers specifications (for example, S-707 "*Supplementary Specification to ISO 12490 for Actuators for On-off Valves"* by IOGP *"International Association of Oil&Gas Producers*").

Furthermore, one of the requirements present in the reference actuator standards just reported, asks for a verification of the conformity of components withstanding the actuator inner pressure load with reference to a recognized pressure vessel code. There are different standards that can be taken as reference, and for the studied actuator the re-design has been opportunity to check compliance with design rules present in last version of EN13445-3 standard.

Finally, one of main objectives of re-design, was to improve the characteristics of the product while maintaining a good level of reliability. For this reason, the actuator has been designed and tested so as to be compliant with requirements of EN61508 standard and of a new standard related to functional safety of valve-actuator assemblies and entering into force in 2024: EN 19755 "*Industrial valves - Functional safety of safety-related valves and actuators*".

OLD DESIGN



NEW DESIGN

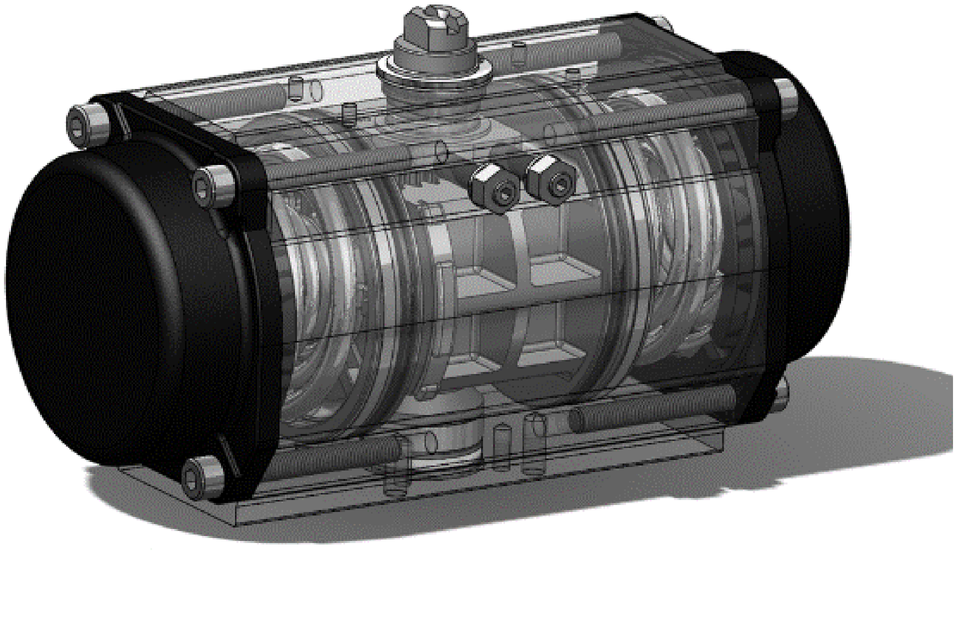


Figure 72. Comparison between the first version of the rack and pinion actuator, designed in 1984, and the new proposed version thanks to the value-oriented design enhancement activities.

Compliance with these standards allows for the obtainment of SIL certification, confirming that the actuator can be used in applications requiring high levels of functional safety, defined by the standard as SIL3 “Safety Instrumented systems” (SIS).

The confirmation of compliance with all the standards just reported is an extremely important source of value for the product, as the request for compliance with them is one of main instruments used by customers for expressing the need for safe and reliable products.

12.2 Actuator components and functions improvement

By integrating structural verifications based on formulas with FEA simulations, it is possible to obtain the following improvements at level of component and actuator functions, identified thanks to DtV as main sources of value:

A) Re-design of product functions, like new strokes adjustment system, featuring a simpler and user-friendly design, made of a light-weight components, so that operators can quickly and easily interface with them;

B) improvement and optimization of components shape, also called "topology". At the time of the first design, the only available tools for the design verifications were reliable structural calculations. Calculations are in some cases necessarily approximated, and the related solutions, are on one hand safe and reliable, allowing to successfully pass the experimental validation via prototype, but on the other hand can also be highly conservative. The procedure used for first design allowed then to obtain a high-quality product. However, a doubt remained that some choices were too conservative, and the material of the components were not fully exploited.

It is now possible to overcome this weak point thanks to simulation techniques not available at that time. In fact, using FEA, as demonstrated in the previous chapters, it is possible to perform a detailed analysis about how the reduction or the increase of a certain thickness can influence the deformations and then the average and peak stress levels within the components. In this way it is possible to identify the best shape for each component, reducing as much as possible the areas where unused material is present. Conversely, it is also possible to easily identify any possible weak areas and immediately improve them, arriving to validation phase with a fully examined and reviewed design.

Thanks to the simulations it is then possible to perform then a step forward in design activities, redistributing more easily and in detailed way the material where it is more necessary. This opportunity is very useful, especially in the case of a DtV project, where weight optimization is a very important source of value.

Having an efficient design is the key for improving other important sources of value for the customer, as specified in the next sub-paragraph. Thanks to the application of the approach described in this case study, the examined actuator underwent a profound transformation, where many components have been simplified and where possible lightened. The impact of most significant improvements is summarized in the graph of Figure 73.

Considering a balance between parts eliminated, new ones introduced from scratch, and redesigned ones by exploiting symmetries where non-symmetrical parts previously were present, it is possible to deduce the following complexity reduction index ***Ip***, based on the total number of part codes used for the assembly (note: the total number of components of the actuator is 49):

$$\boldsymbol{Ip} = (\text{new tot. code n°} - \text{old tot. code n°}) / \text{old tot. code n°} = (29 - 35) / 35 = -17\% \qquad (9)$$

A new fixing system for a bushing, representing a critical component, because requiring the need for a dedicated press installation, eliminated in the new version, made it possible to obtain a reduction in the total assembly time, estimated by the following index ***It***:

$$\boldsymbol{It} = (\text{new ass. time} - \text{old ass. time}) / \text{old ass. time} = (514\ s - 622\ s) / 622\ s = -17\% \qquad (10)$$

The total weight of the actuator has been reduced of the following mass improvement index ***Iw:***

$$\boldsymbol{Iw} = (\text{new mass} - \text{old mass}) / \text{old mass} = (6044\ \text{gr.} - 6582\ \text{gr}) / 6582\ \text{gr.} = -8\% \qquad (11)$$

Table 8 reports the weight reduction obtained for the main components of the actuator thanks to topology optimization activities and to function analysis. Also Grouping into a single component, represented by the center body, the main complex mechanical machining that were previously distributed among multiple components has tangibly contributed in reducing weight and complexity. As examples, in new design the threaded holes of the stopper bolts are located in the center body only whilst before were located in end caps and in a piston. The holes for the pneumatic supply of the external chambers have been also moved to center body from end caps.

The first column of Table 8 reports the total weight reduction of the actuator assembly. In this the simplification of the design, in addition to topology optimization, contributed to the reduction of the total weight. The total number of components used for construction has been reduced, from 52 to 49 parts. The complexity also of new introduced parts is lower with respect to old ones.

	Weight [kg]							
	Assembly	*Body raw*	*Body machined*	*End cap*	*Piston Left*	*Piston Right*	*Piston (average)*	*Total Other Components*
Old design	6.58	2.64	2.32	0.53	0.48	0.40	0.50	2.85
New Design	6.04	2.50	2.18	0.45	0.39	0.39	0.39	2.63
% Variation	-8%	-5%	-6%	-14%	-19%	-4%	-23%	-7%

Table 8. Summary of the weight reductions achieved for main actuator components.
In first column the total weight reduction of the actuator assembly is reported also.

Weight reduction, reduction of codes, simplification of components, with relative reduction in machining time, and simplification of assembly activities lead to the following estimated economic benefit, expressed by the index ***Ic***:

$$\boldsymbol{Ic} = (new\ cost - old\ cost) / old\ cost = -6\% \qquad (12)$$

The expected achievable performance increase, represented by actuator MOT (Max Operating Torque, in Nm) for the present case study can be estimated with the following Torque efficiency index ***Im***:

$$\boldsymbol{Im} = (new\ MOT - old\ MOT) / old\ MOT = (211 - 181) / 181 = +17\% \qquad (13)$$

The expected achievable cost/performance KPI, expressed in dollars expended for each Nm of achieved torque ($/Nm), for the present case study can be estimated with the following KPI index ***Ik***:

$$\boldsymbol{Ik} = (new\ KPI - old\ KPI) / old\ KPI = -22\% \qquad (14)$$

12.3 Improvement of environmental and economic efficiency

The reduction of the actuator weight and the simplification of the components, requiring less machining indirectly leads to the achievement of another important improvement of a source of value, as identified during the preliminary phases of the DtV project. In fact, on one hand the reduction in weight allows for a lower consumption of raw materials. On the other hand, the simplification of the characteristics of the parts allows for shorter and simpler machining, requiring a lower quantity of energy.

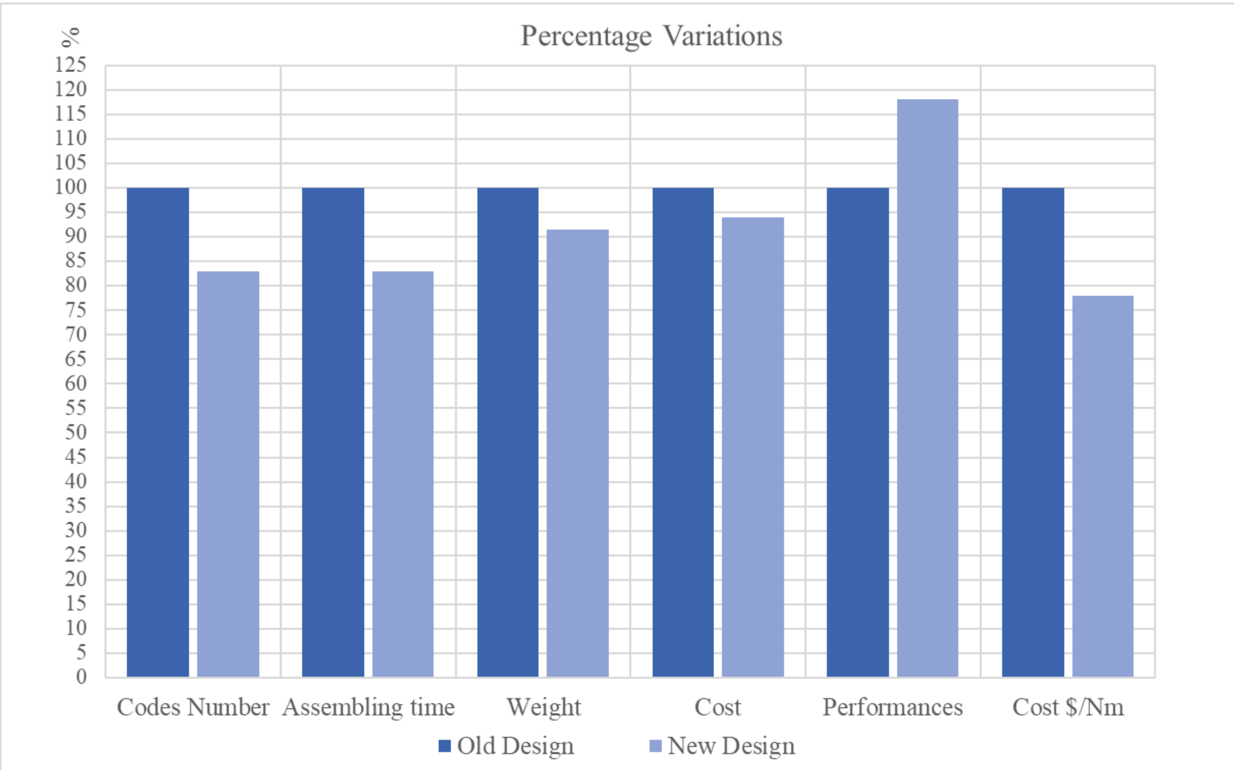


Figure 73. Increases in product efficiency.

A lower quantity of energy required to production as well as lower energy required for producing raw materials lead in their turn to lower carbon dioxide emissions into the environment. The design update allowed then to achieve a target that is becoming more and more important, that is to obtain a product version that is more sustainable than the previous one.

Finally, as a direct consequence of all the improvements just described, the design improvement project allowed to increase the economic efficiency of the actuator, while maintaining high standards of safety and reliability.

In fact, a great advantage that can be achieved thanks to weight reduction is an immediate benefit in terms of costs. Less use of material brings to a reduction in the cost of each component. Furthermore, components simplification with a reduction in machining time and required energy for production processes, led to a consequent further reduction of costs.

Finally, studies about simplification of assembling activities led to increase productivity. For example, the re-design of pinion guide bushings for increasing the ease of assembly brings to a reduction of the time required for the assembling procedure and therefore to a reduction of production costs of each actuator.

Reducing the cost of the product is a key element allowing a company to remain competitive, obtaining an acceptable profit margin from placing on the market products maintaining high standards of safety and reliability.

12.4 Conclusions

In conclusion, the Design to Value (DtV) process, applied for the design enhancement of a product present on the market for decades, represents an effective tool for identifying all the possible areas where to obtain product improvements. For example, thanks to the investigations carried out in the context of the new used approach, it has been possible to discover how to simplify construction choices, such as the system necessary for regulating actuator angular strokes, without compromising the functionality and the ease of intervention by operators.

In addition, the DtV process associated with new design techniques could guarantee still greater improvements, thanks to the possibility to improve some old design choices, based on design techniques available at time of first design. For this reason, the introduction of innovative design tools in the detailed re-design phase has been an extremely profitable element, allowing to improve some of the most important sources of value of the product, while maintaining high levels of safety and reliability.

The studied project demonstrates how the application of advanced simulation techniques, now available to medium and small-sized companies also, and not only to big companies active in the sectors of high complexity products, bring important advantages in terms of:

1) confirmation with good probability of the components safety, already at the stage of design stage, then in an upstream stage with respect to validation on prototypes;

2) compliance with international industry standards, such as the standards for pressure vessels, allowing for the use of FEA simulations as useful design integration;

3) Significant improvement of the shape, also called “topology”, of the components, through the technique called “topology optimization”. Thanks to a process based on iterative simulations, it is possible to obtain the most efficent use of the material in each studied component, finding the most suitable material distribution in stressed areas and a lightening in unloaded areas. This approach typically leads to weight reduction also, with all the benefits above described.

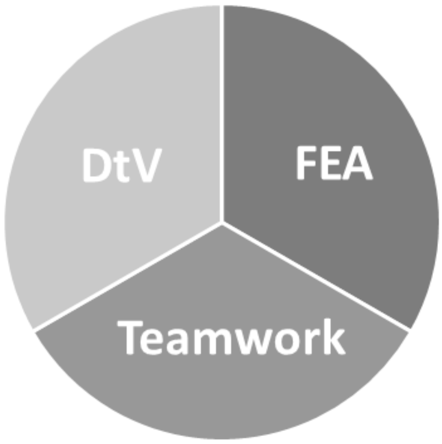
Resuming in few words the main results of all the activities, the results of the performed analyses allow to confirm that the DtV method, linked to advanced simulation-based design techniques, is an extremely useful approach, that when applied by companies whenever the need to redesign a product arises, can undoubtedly contribute to:

A. Introduce on the market safe products, with a good reliability;
B. Promote a sustainable industrial development;
C. Keep competitive and innovative the company applying the methodology.

Further extensions of the methodology here described may concern the application of FEA during detailed re-design for performing simulations in the fields of explicit dynamics and fatigue also, increasing in this way the detail of achievable predictions, and entering experimental validation phase with solutions more and more verified "upstream".

The current limitations to the integration in the design of components obtained by addictive manufacturing will also be investigated.

Fundamental "secret ingredient" for the success of all project activities has been the Collaboration. Teamwork and know-how exchange aimed at mutual enrichment are essential components for increasing the commitment of the team during all the project phases and for stimulating the team towards the most ambitious achievements.



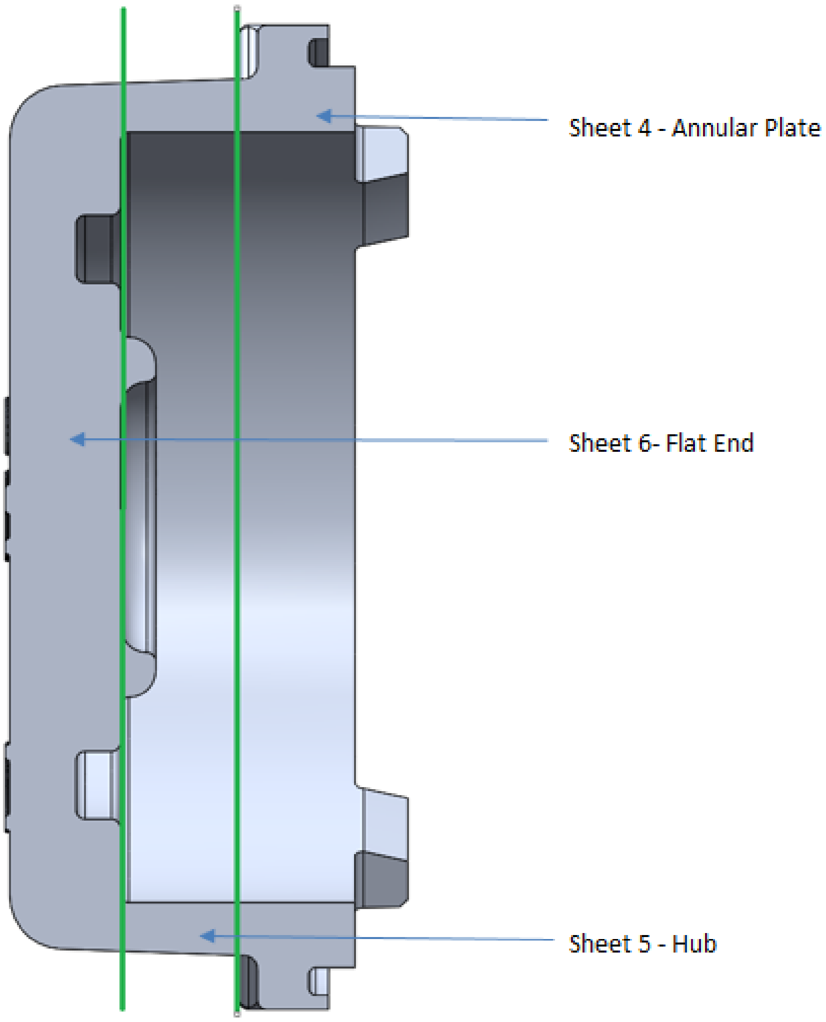
Appendix 1 – Verification of End Cap according to EN13445-3 Design by Formulas rules

Below is reported an extract of the spreadsheet for the verification of the structural strength of the lateral end caps of the actuator, when subject to a pressure load equal to Design Pressure (10,5 barg) and Test Pressure (10,5 x 1,5 = 15,75 barg).
The calculations are performed in accordance with the rules reported in the EN13445-3:2021 standard, according to the Design by Formulas Route.
As the component has a complex shape, to carry out the checks it has been divided into simple sections, as explained in paragraph 9.1.2 "Introduction to EN13445-3 "Annex B - Design by Analysis - Direct Route".

DESIGN CALCULATION EN13445-3
MODEL S085 2.0

4. Calculation of End Caps

For the verifications, the end cap has been considered as composed by the following three sections: Annular plate, Hub, Flat End.
In the following sheets, the calculations for the verification of each one of the three sections are reported. Verifications following the "design by rule" procedure concerns the pressure load. These verifications are integrated by the "design by analysis" procedure for considering the load given by springs, by performing a FEA analysis.



DESIGN CALCULATION EN13445-3
MODEL S085 2.0

4. Verification of End Cap - Annular Plate

End Cap Material		**EN AC-46500-D-F (EN 1706)**	
		EN AC-44500-D-F (EN 1706)	
Rm/25	tensile strength 25°C	240	MPa
Rp0,2/25	yield stress 25°C	140	MPa
Rp0,2/150	yield stress 150°C	111	MPa
v	Poisson ratio	0.33	
Data			
F p	Design Pneumatic load at full piston area	5958	N
P	Design pressure	1.05	MPa
F t	Test Pneumatic load at full piston area	8937	N
Pt	Test pressure	1.58	MPa
Dx	Inside diameter of the annular plate	71.2	mm
Dy	Outside diameter of the annular plate	121.3	mm
a'	smaller width dimension of equivalent non-circular flat end	25.05	mm
b'	greater width dimension of equivalent non-circular flat end	96.25	mm
te	Annular Plate extension thickness (below o-ring groove)	5.3	mm
t	Annular Plate thickness	7.3	mm
C	bolt pitch circle	105.3	mm
G	gasket reaction diameter	89.05	mm
c	flange bending arm (mean dist. betw. C and G)	8.1	mm
n	number of bolts	4	mm
tb	mean bolt pitch	83	mm
m	gasket factor	0	
k	end cap bolt pretensioning factor	1.10	
W	design bolt load in ass. Condition = Fp * k	6554.05	N

End cap Design Stresses

fd'		(Rp0,2/150) / 1,5	74.00	MPa
fd''		(Rm/25) / 2,4	100.00	MPa
fd	maximum value of the nominal design stress for normal operating load cases	min (fd' ; fd'') EN13445-8:2021 table 6.3-1 (Group 23)	74.00	MPa
ftest	maximum value of the nominal design stress for testing load cases	(Rp0,2/25) / 1,05 EN13445-8:2021 table 6.3-1 (Group 23)	133.33	MPa

4.1 Calc. of Annular Plate extension thickness *(EN13445-3:2021, 10.7.3, 10.7.2.2)*

ep1	= [(6 * W * c)/(n * tB * fd)]^ 0,5	3.61	mm
et1	= [(6 * W * c)/(n * tB * ftest)]^ 0,5	2.69	mm
e1	= max (ep1; et1)	**4.00**	mm

minimum allowable thickness annular plate extension: as **e1 <= te : Checked**

DESIGN CALCULATION EN13445-3
MODEL S085 2.0

4. Verification of End Cap - Annular Plate (...continuous)

4.2 Calc. of Annular Plate Overall Thickness *(EN13445-3:2014 10.7.2.1)*

a'	smaller width dimension of equivalent non-circular flat end	25.05	mm
b'	greater width dimension of equivalent non-circular flat end	96.25	mm
a' / b'		0.26	
C4	Shape fact. from fig. 10.7-4	0.74	
C3	Shape factor For bolted non-circular Flat ends		
	= [C4 + (6 * W * c)/(P * n * tB * a'^2)]^ 0,5	1.5	
ep	= C3 * a' * (P / fd)^ 0,5	4.43	mm
et	= C3 * a' * (Pt / ftest)^ 0,5	4.04	mm
e	= max (ep; et)	**4.00**	**mm**

minim. allowable thickness of overall annular plate: as **e <= t : Checked**

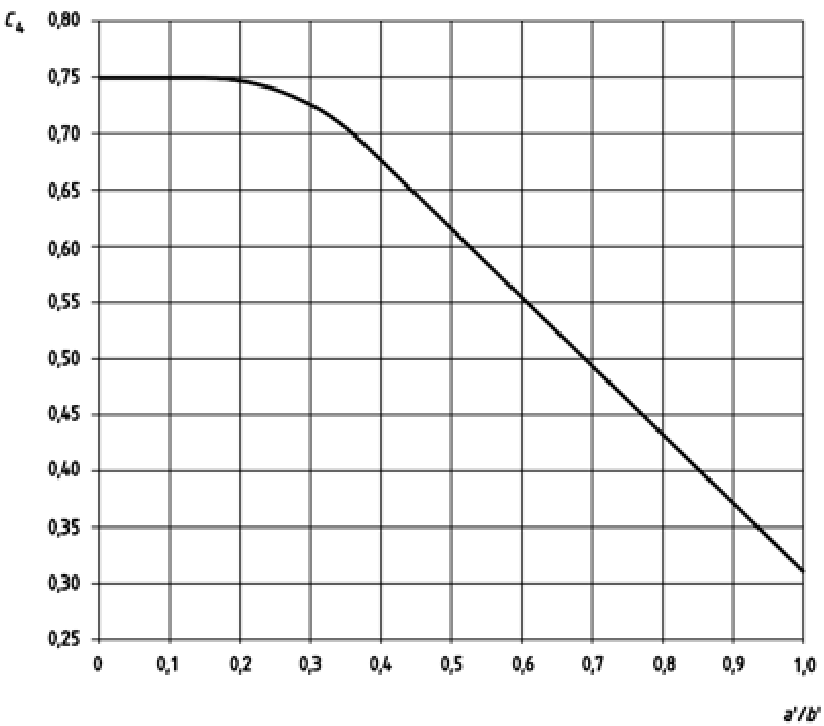


Figure 10.7-4 — Shape factor C_4 for bolted non-circular flat end with narrow-face gasket

DESIGN CALCULATION EN13445-3
MODEL S085 2.0

5. Verification of End Cap - Hub

Material			**EN AC-46500-D-F (EN 1706)** **EN AC-44500-D-F (EN 1706)**
Rm/25	tensile strength 25°C		240 MPa
Rp0,2/25	yield stress 25°C		140 MPa
Rp0,2/150	yield stress 150°C		111 MPa
Data			
Di	inside diameter		71.20 mm
De	external diameter		83.52 mm
c	corrosion allowance		0.00 mm
δn	negative tollerance on nominal thickness		0.42 mm
Pd	design pressure		1.05 MPa
Pt	test pressure		1.58 MPa
z	joint coefficient		0.85
Design stress			
fd'		(Rp0,2/150) / 1,5	74.00 MPa
fd''		(Rm/25) / 3	80.00 MPa
fd	maximum value of the nominal design stress for normal operating load cases	min (fd' ; fd'') EN13445-8:2021 table 6.3-1 (Group 23)	74.00 MPa
ftest	maximum value of the nominal design stress for testing load cases	(Rp0,2/25) / 1,05 EN13445-8:2021 table 6.3-1 (Group 23)	133.33 MPa
5.1 Calculation	*(EN13445-3:2021, 7.4.2)*		
en	nominal thickness	(De - Di) / 2	6.16 mm
e min	minimum liner thickness	en-δn	5.74 mm
Normal operating load case			
e	required thickness	(Pd * Di) / (2*fd*z-Pd)	0.60 mm
		as	**e < e min : checked**
		as	**e / De < 0,16 : checked**
Testing load case			
et	required thickness	(Pt * Di) / (2*ft*z-Pt)	0.50 mm
		as	**et < e min : checked**
		as	**et / De < 0,16 : checked**

DESIGN CALCULATION EN13445-3
MODEL S085 2.0

6. Calculation of End Cap - Flat End

			EN AC-46500-D-F (EN 1706)
End Cap Material			**EN AC-44500-D-F (EN 1706)**
Rm/25	tensile strength 25°C		240 MPa
Rp0,2/25	yield stress 25°C		140 MPa
Rp0,2/150	yield stress 150°C		111 MPa
v	Poisson ratio		0.33
Data			
P	Design pressure		1.05 MPa
Pt	Test pressure		1.58 MPa
Di	inside diameter of the cylindrical shell welded to a flat end		71.20 mm
es	thickness of cylindrical shell adjacent to a flat end		5.74 mm
t	End cap central minimum thickness		6 mm
End cap Design Stresses			
fd'		(Rp0,2/150) / 1,5	74.0 MPa
fd''		(Rm/25) / 2,4	100.0 MPa
fd	maximum value of the nominal design stress for normal operating load cases	min (fd' ; fd'') EN13445-8:2021 table 6.3-1 (Group 23)	74.0 MPa
ftest	maximum value of the nominal design stress for testing load cases	(Rp0,2/25) / 1,05 EN13445-8:2021 table 6.3-1 (Group 23)	133.3 MPa

6.1 Calculation flat end overall thickness for normal operating load cases
(EN13445-3:2021, 10.4.4.4, eq. 10.4-12)

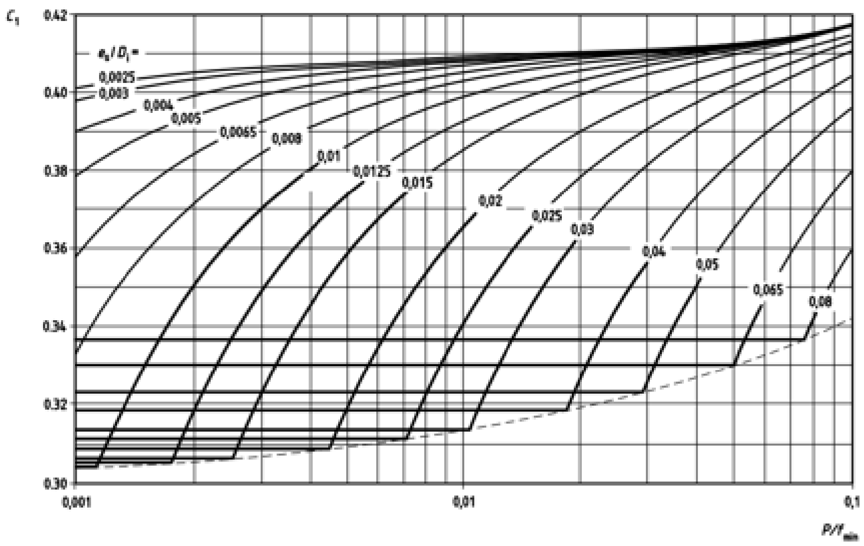


Figure 10.4-4 — Values of coefficient C_1

DESIGN CALCULATION EN13445-3
MODEL S085 2.0

The minimum required thickness of the end is calculated using Formula (10.4-12) instead of Formula (10.4-10). In fact a simplified assessment of the fatigue life of the flat end is performed according to Clause 17.

P / fd		0.01
es / Di		0.08
C1	shape factor for calculation of circular flat end	0.337
C1 is given by EN13445-3:2021, Figure 10.4-4		
e	= C1 * Di * (P / fd) ^0,5	**2.9 mm**
min. allowable thickness for operating loads: as		**e <= t : checked**

6.2 Calculation flat end overall thickness for testing load cases

(EN13445-3:2021, 10.4.4.2, eq. 10.4-12)

Pt / ftest		0.01
C1test	shape factor for calculation of circular flat end	0.337
C1 test is given by EN13445-3:2021, Figure 10.4-4		
et	= C1test * Di * (Pt / ftest) ^0,5	**2.6 mm**
min. allowable thickness for testing loads: as		**et <= t : checked**

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Acknowledgments

An initial infinitely big Thank You goes to Professor Gianni Nicoletto, the person without whose support my dream of attending a PhD would not have been possible.
When I proposed myself asking for a help to realize the dream I had been chasing for so long time, he decided to support me, despite his many commitments and despite I did not present myself as a canonical student, and with certainly many more shortcomings than the other very skilled students he accompanied. Nevertheless, with his intuition he glimpsed that something good could come from me too, and for this I am infinitely grateful.
His great example remains with me. In particular, his great goodness of hearth will remain in my mind, as well as his very big curiosity toward any technical subject, making me think "it must be this incredible curiosity towards the world pushing big souls to change the reality, aiming to a positive impact on people's life, since Leonardo da Vinci's inventions onwards".

A second huge Thank You goes to Professor Luca Collini, who since became my new tutor made the PhD journey even more extraordinary, providing me with invaluable teachings in very important fields that were unknown to me, and making me look at the world of machinery design with completely new eyes. With his huge competence and his great teaching skills (his many examples during the lessons helped me so much!) He guided me on a super interesting path full of stimulating challenges.

A third tremendous Thank You goes to my company tutor Lorenzo Vigliano. With his enormous experience in the field of actuators design always gave me precious advices in moments of need.

I thank all my colleagues, from the Mezzago's, Budapest's, Suzhou's, Haywards Heat's and Bangalore's offices (my global village team!), and in particular Giuseppe Carucci and Francesco Fornasari, the persons with whom we share so many battles during the daily life of an R&D/Engineering office.

I thank all my friends, especially Andrea, Lele, Gab e Gianluca, who have been so patient during my numerous absences always due to the usual reason: "sorry devo finire la tesi!". A special thanks goes to morning rosary group also, a bunch of special souls.

I thank all my family who never failed to cheer for me all along this path, and in particular my cousin Luigi, who always helped me teaching guitar in the moments of relax between a page and another of the thesis.

Finally, I infinitely thank my mother Annamaria, that in the spirit of my beloved father Battista, always supports me with infinite patience during all my adventures!