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Original Paper

A study of metallurgical simulations and mechanical analyses for casting valve products through OPEX approach

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ABSTRACT

In this study, information about the improvement of metallurgical simulations for the processes, and mechanical analyses for the designs of valves, which are generally preferred made of bronze in marine industry and thought to not be able to be improved much anymore, was shared with the operational excellence (OPEX) approach. The two-dimensional (2D) designs of the products to be analysed were made in AutoCAD, and the three-dimensional (3D) designs were made by using design and solid modelling program (Solidworks). Mechanical analyses for determining the mechanical strength of the specimens were performed with the help of finite element analysis (FEA) method by using the ANSYS software. The definition of the fluid resistance and flow coefficients were carried out by using computational fluid dynamics (CFD) with the help of ANSYS fluid option. The casting stages' simulations were carried out to define filling time, change in temperature, internal stresses, which causing micro and macro shrinkages, and solidification mechanism by using Anycasting. Simufact Forming simulation program was used for defining the parameters of disc material production by hot forging method. Minitab data analysis program was selected to provide a correlation in the torque value between the disc and the body. The total consumed energy and carbon footprint was determined by using Solidworks sustainability report. Cast body weight and production time was improved 19.46% and 26.67% respectively, and hot forged valve core disc were produced with zero defect by OPEX approach. 31.87% energy savings with a total energy consumption, and 26.05% carbon footprint improvement was achieved in existing products. Finally, 81.50% improvement in the flow coefficient and 204.89% improvement in fluid resistance coefficient has been obtained as an excellence part of this study.

I. INTRODUCTION

Companies need to perform at the highest level to maintain their presence in the market and increase their competitiveness under the influence of increasing competition in the globalizing world [1]. Nowadays, companies have realized that good performance alone is not enough to survive in the market. For this reason, they have made the necessity of making more sustainable progress their priority [2]. So, what kind of path should companies follow to both improve performance and be sustainable?

Companies should adopt competitive strategies to become exemplary companies in the industry as well as being leaders in their own sectors by keeping their current markets constant. Operational excellence (OPEX) is one of these strategies. Therefore, OPEX becomes no longer an option for companies to survive, but it has become almost a necessity for success [3-7].

Many definitions of OPEX are existing in the literature. Examining some sources shows that OPEX is the correct and coherent application of some basic methodologies such as TPM, Lean, TQM, Six Sigma, and tools like SMED, Kanban, Visual Management, Kaizen, DMAIC for the companies [8-12].

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OPEX is the last point of the sustainable development journey of companies. Achieving success in the OPEX journey can only be possible if the scientific, academic, technical, and commercial 4E phases (Essentials, Effectiveness, Efficiency, and Excellence) are handled and evaluated well [13-16].

The operation must be master on the four main phases such as essentials, effectiveness, efficiency and excellence respectively to become a true Center of Excellence.

1.1. Essentials

The main stage of research and development activities is basic research. During the basic research phase, information about the theoretical and experimental parts of the subject is collected and the process is continued by referring to the literature, patents and standards.

Design is the creation of engineering drawings in the production process of a product. Designing describes the process of creating and developing a plan for a new product or object [17]. The initiation and maintenance of an engineering design can only be achieved by the effective use of these communication methods by different disciplines and their coordinated work [18]. The main studies carried out; research, design-analysis, development, prototype production and quality tests. Clearly, design is the basic requirement of all engineering and OPEX processes and is the most fundamental element of the essential phase [19].

1.2. Effectiveness

Effectiveness is the amount of work an individual or group performs in each period. More productivity means getting more done with less time or effort [20]. It can be measured success by the quality of work, the number of jobs completed, or the number of products created. Effectiveness principles: is to produce the right product/service at the right time, in the right amount, at the least cost, in a way that will create higher added value in accordance with customer expectations, while also considering human resources, without harming the environment. Ensuring standardized processes with simulation supported designs is important for the effectiveness phase [21-23].

1.3. Efficiency

Efficiency is usually a measurable ability to avoid energy, wasting materials, money, time while performing a task, and effort. More generally, it is the ability to do things successfully, without wastage, and well. Validation and verification terms, which are often confused to each other, are important at this phase [24-28].

Validation: It is the objective testing and confirmation of the suitability of a system for specific purposes.

Verification: It is the correction of the conformity of a system with the specified criteria with objective evidence.

Validation is the work performed to ensure that a process or a system performs its function in accordance with predetermined requirements. However, verification is the process of fulfilling by providing objective evidence that the objectives set through the review have been met. Virtual simulations, real tests and evaluation of these results are indispensable elements of the efficiency phase.

1.4. Excellence

Advanced systems can only be formed by handling and realizing of standardized product, standardized process, verified and validated definitions. These systems are the fundamentals of the excellence phase. It is possible to reach excellence with modern production methods such as additive manufacturing, academic elements such as microstructure research, computer-aided design, and simulation programs. The highest point that all this will reach is where sustainability is achieved [29-33].

The motivation that started this study was the desire to deal with metallurgical simulations and mechanical analyses in detail and to create a useful resource with the OPEX approach. For this purpose, two-dimensional (2D) and three-dimensional (3D) analyses of a valve were performed. The Finite Element Analysis (FEA) method was used for the mechanical strength of the 3D designs. Valve body and disc verifications were made with casting simulations. Hot forging simulation was performed for the disc material, which was inconvenient to be produced by casting. Computational Fluid Dynamics (CFD) analyses were carried out to define fluid resistance, and flow coefficients for the valve body and core disc system. CFD analyses were verified by comparing the Kv test setup. Data analysis was carried out to provide a correlation in the torque value between the disc and the body. Finally, the OPEX approach was discussed with the sustainability report, in which energy savings and carbon footprints were compared.

II. EXPERIMENTAL PART

Experimental studies were discussed under the 4 phases of OPEX, Essentials, Effectiveness, Efficiency and Excellence. The outcomes to be obtained from these titles and the necessary tools are shown in Table 1.

Table 1. Focus, outcome, and tools interaction regarding the four phases of OPEX

Phase	Essentials	Effectiveness	Efficiency	Excellence
Focus	Design	Production Types & Parameters	Verification Validation	High Energy Saving Low Carbon Footprint
Outcome	Standardized Product	Standardized Process	Higher Flow Coefficient Kv Lower Fluid Resistance Coefficient (ζ)	Advanced System
Tools	AutoCAD Solidworks	Ansys Anycasting Simufact	CFD Flow Test Setup	3D Printer Optical Microscope Sustainability Report

2.1 Essential Phase Experiments

The specimen's beginning drawings to be simulated were carried out by using CAD (computer aided design) with the help of AutoCAD program. This stage was the basis for 2D designs and 3D drawings. Figure 1 illustrates the 2D technical drawings, which would be transferred into the 3D design.

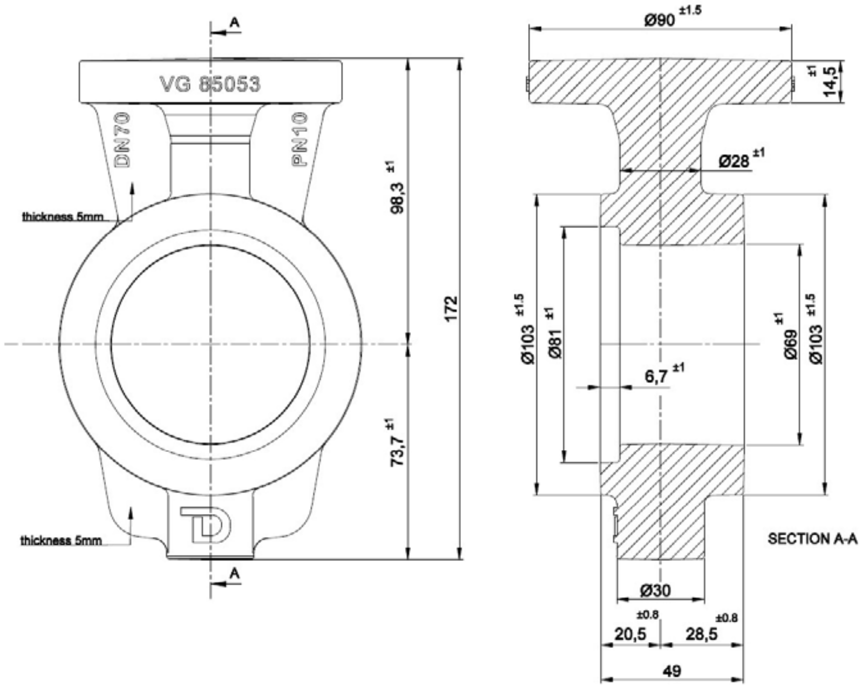


Figure 1. 2D Technical drawings to be transferred to 3D design.

2D drawings provided the fundamentals for the design, as well as giving the designer an idea for 3D drawings. The 3D drawings were made via solid modelling and design software (Solidworks 3D). Figure 2 shows the isometric 3D view of the design.

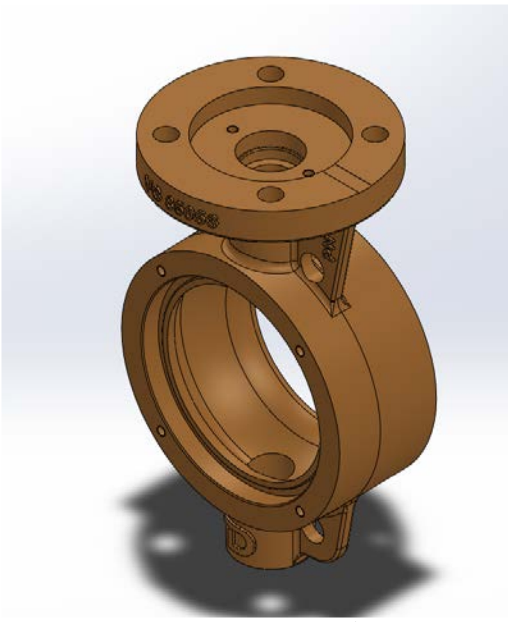


Figure 2. Isometric 3D view of design.

2.2 Effectiveness Phase Experiments

FEA method was preferred to define the material's mechanical strength values and optimum design limits. ANSYS simulation program was used for this purpose. The geometric analysis in ANSYS was carried out by taking over Solidworks 3D solid model designs. Figure 3 shows the geometric analysis of design. The strength limit values of the designs were pointed according to the boundary conditions as defined in EN 1704 standard. Semi and single assembled parts have been handled by using Rayleigh-Ritz method and their interpolation solution for the numerical methods was realized in FEA stage.

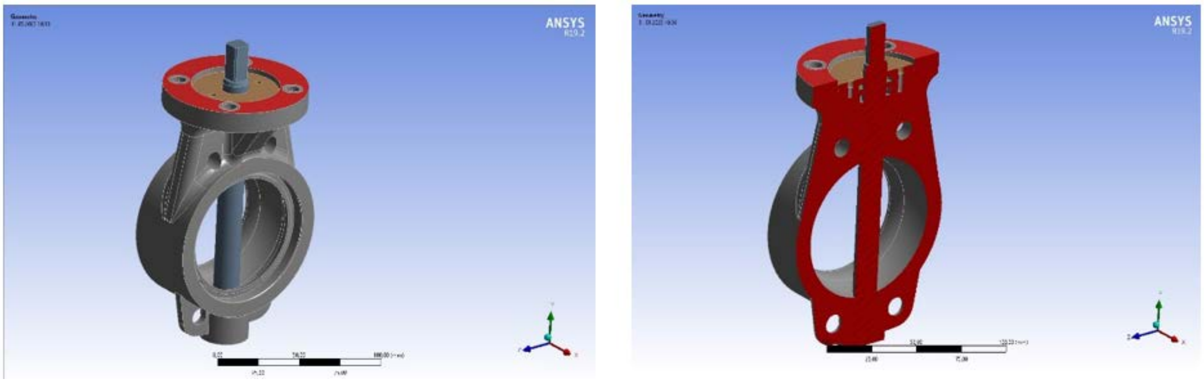


Figure 3. Ansys geometry analysis of the specimen

Numerical simulation applications were an important step in revealing material deformations, load-strain distributions on the material, dimensional changes between operations and similar mechanical and metallurgical properties depending on different parameters before going into production. For the test samples, valves made of bronze were selected due to their wide usage area and high corrosion resistance. Therefore, CuSn10 material was chosen as the basic material. The mechanical properties, chemical analysis, and physical conditions were given in Table 2 as defined according to ASTM B 505 C90700 standard.

Table 2. Mechanical properties, chemical analysis, and physical conditions of the samples

Chemical Analyses (%)	Cu: 89.0 (Average) Sn: 10.0 (Average) Zn: < 0.5 Pn: <1.0 Ni: <2.0 P: <0.2
Tensile Test	R_m: 260-280 (N/mm^2) $Rp_{0,2}$: 120-140 (N/mm^2) A5: 17-19 (%)
Hardness (HB)	70-75
Density (g/cm^3)	8.7

The determination of the parameters during the manufacture and ensuring the mechanical limits for the final product are essential. Because of this reason casting simulation programs help the designer to define optimum parameters. Anycasting simulation program was used to produce the product with suitable mechanical design under the right conditions and to determine the production parameters. Further details on boundary conditions and material properties can be seen in Table 3.

Table 3. Simulation properties on boundary conditions

Meshing	
Sub-Division Number	3
Total Number of Cell	4.572.216
Size of Unit Cell	2.5 mm
Number of Cell Along Axis	X:251, Y:184, Z:99
Simulation Time	100s
Material	C90700 / SAE 62, DIN 1075 - 2.1050, CC480K
Starting Temperature	1150 °C
Cooling	5.10^5 Wm^{-2} constant on all sides

First, the double runner feeding system was designed in Anycasting simulation. The data for the simulations was selected from the library and CuSn10 material was defined in designs with 1150 °C as casting temperature. The simulation data showed that this process took 19 seconds as seen in Figure 4 with inner stress, solidification and heating simulation images. Since the results of any numerical model are just as good as the boundary conditions (BC) used, a reliable solidification model will involve obtaining ascertained and verified thermal BC for the casting machine. Moreover, the actual thermal conditions in the caster can seldom be transferred from one caster to another due to the multiple specifics of each casting machine. Furthermore, from a metallurgical viewpoint, the thermal BC will often differ depending on the cast grade – due to the changing behaviour of different materials, casting and cooling conditions are often changed.

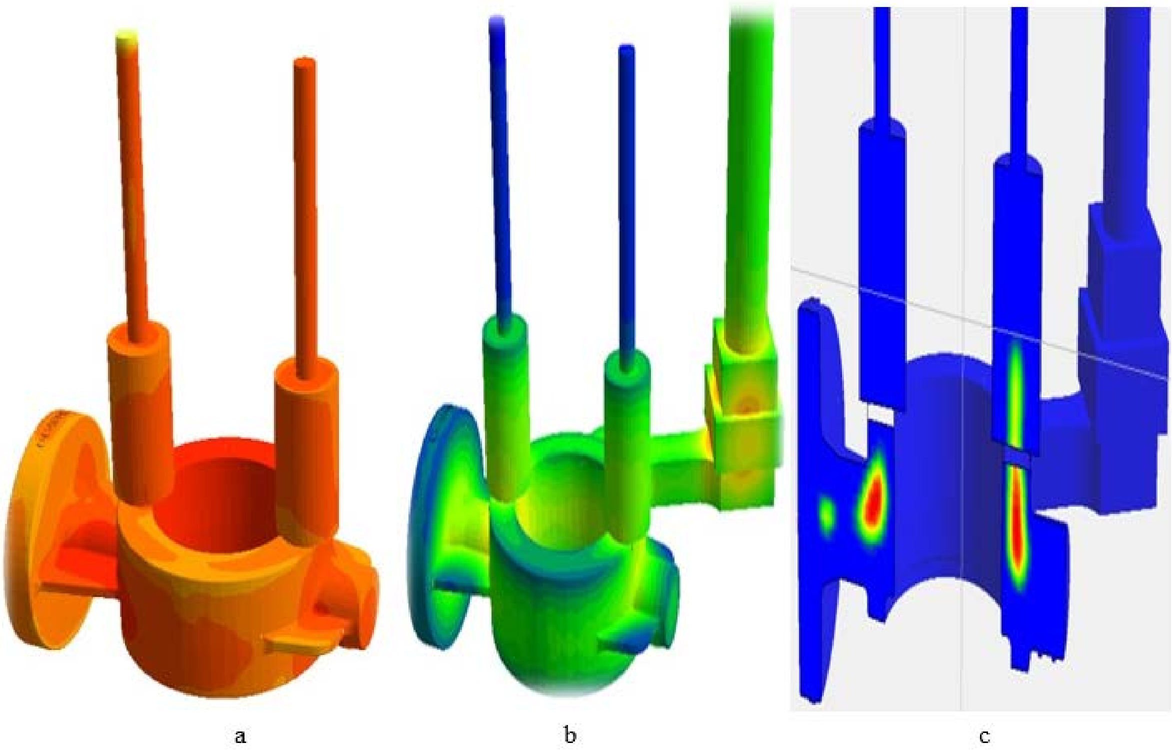


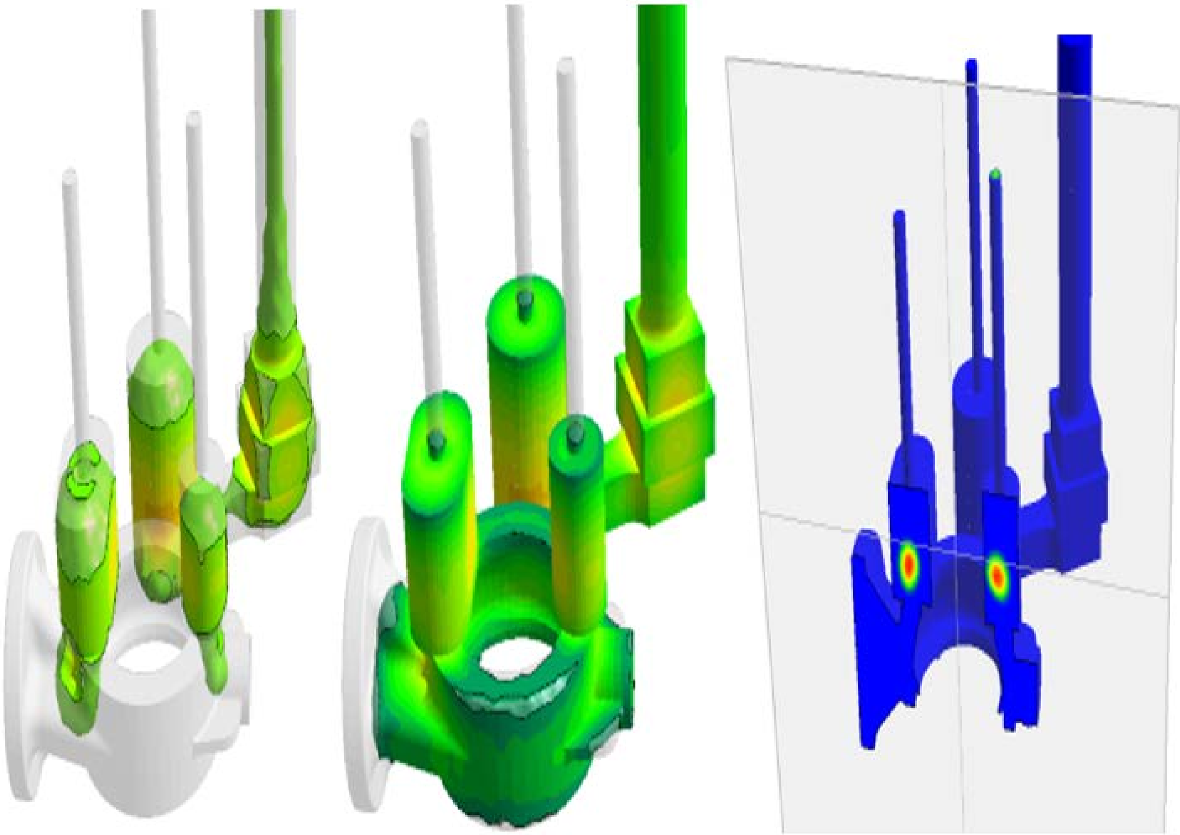
Figure 4. Casting simulation results; (a) heating, (b) solidification, and (c) final product inner stress areas

In the simulations of the first trial, a prototype casting of the product in which shrinkage and gap problems were observed was performed. The visual of this is given in Figure 5. The errors detected after machining will be more clearly revealed.

Figure 5. Trial production where casting simulations were verified

In the simulations of the first trial, a prototype casting of the product in which shrinkage and gap problems were observed was performed. The visual of this is given in Figure 5. The errors detected after machining will be more clearly revealed.

The results obtained in the casting simulation with heating and solidification; the feeding system has been revised. With the 3-way feeding, the difference in net weight from 16% has been reduced to 12%, on the gross weight while the production time has been improved by 27%. Moreover, the red areas that pose a risk in the simulation turned into a green colour that did not pose a risk, proving that the design has come to the safe side. Finally, the tension zones in the valve were removed from the system by transferring to the runner section (Figure 6).



a b c

Figure 6. Casting simulation results; (a) heating, (b) solidification, and (c) final product inner stress areas

Figure 7. Casting of the revised product design

A visual representation of the verification breakdown of the revised simulations is given in Figure 7. After determining that the errors detected in the two-runner system were eliminated in the simulations with the three-runner design, the prototype casting phase was started to ensure the validation of the simulations. The first critical process in casting was the determination of chemical analysis. Therefore, 89% copper including %1 nickel, %0.5 zinc, and 10% pure tin ingots by weight were melted in an induction furnace. A trace amount of phosphorus was also added to ensure deoxidation. The process temperature was set to 1150 °C and it was carried out in a sand mould. During the melting process and after the crucible was removed from the furnace, the gas degassing tablets, and slag-forming perlite were added to the crucible to prevent contamination.

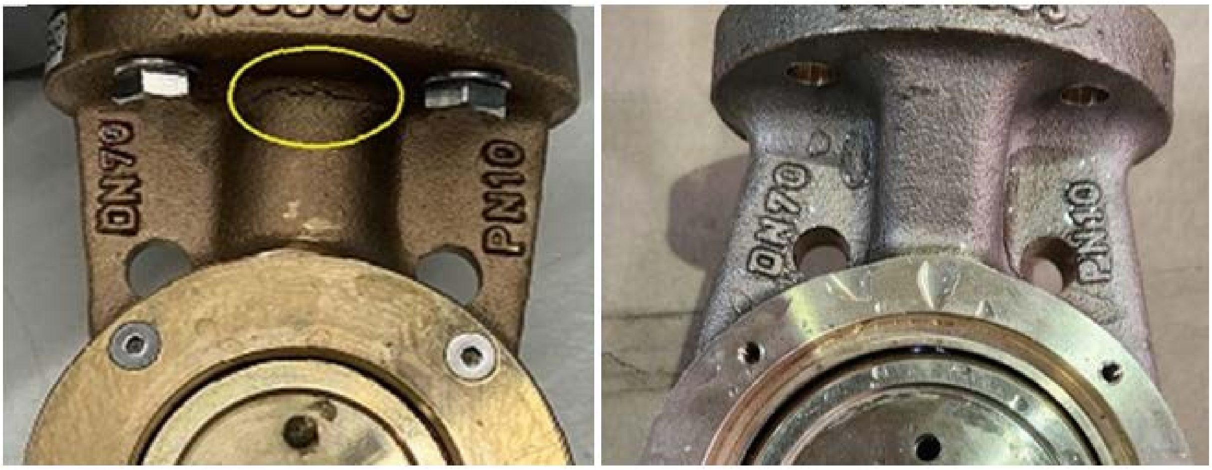


Figure 8. Casting of the revised product design

Figure 8 shows the final images of two products designed as two-runner and three-runner, in comparison. The part circled in yellow represents the region where there was shrinkage in the simulation of the two-runner design, and while crack damage was observed here, no defect was observed in the image of the three-runner design on the right.

Although positive results were obtained in the casting simulations for the valve body as given in the Figure 6, same positive results were not obtained in the casting simulations of the disc that would control the flow rate in its body. According to the data of the Anycasting simulation program in Figure 9, the disc material could not reach the ideal casting temperature of 1150 °C, allowing casting to be made around 975 °C. This might cause damage such as micro-macro porosities and cracks. This temperature difference was not only an indication that it does not pose a risk in terms of production, but also a sign that damage to the materials due to deformation was prevented.

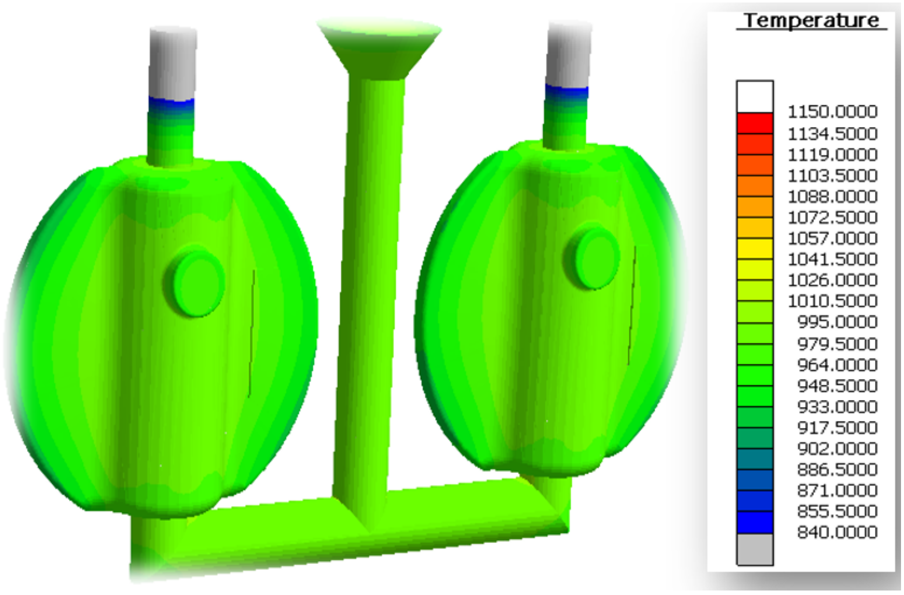


Figure 9. Disc material casting simulation analysis

Figure 10 shows the pattern, mold and casting of the validation of the products verified with simulation.

Figure 10. Disc material casting

In order to prevent problems in the production of disc material by casting, Simufact Forming simulation program was used to get an idea about the production of disc material by hot forging method. While designing the product and mold in the hot forging process, the raw material diameter, product operation transitions, extrusion-reduction ratio, length of the part, lubricant structure, and usage etc. features were critical. These parameters might affect mold life and cause mold damage and breakage. For this reason, Simufact Forming numerical simulation supported software was used to provide maximum benefit. Figure 11 indicates the hot forging simulation image. The "Medium Interaction with Steel Dies" condition was selected to define the heat transfer between the dies and the workpiece during the process. The heat transfer coefficient value of this condition is 10.000 W/m^{2}K and this value is consistent with the values mentioned in the process section. The "Heat Transfer with Air" condition was used for the heat transfer of the workpiece with the environment. In this condition, the heat transfer coefficient of the workpiece with the environment is 10 W/m^{2}K. The ambient temperature during the process is defined as 50 °C with mesh size 2. Prototype design performed to check product simulation data is shown in Figure 12.

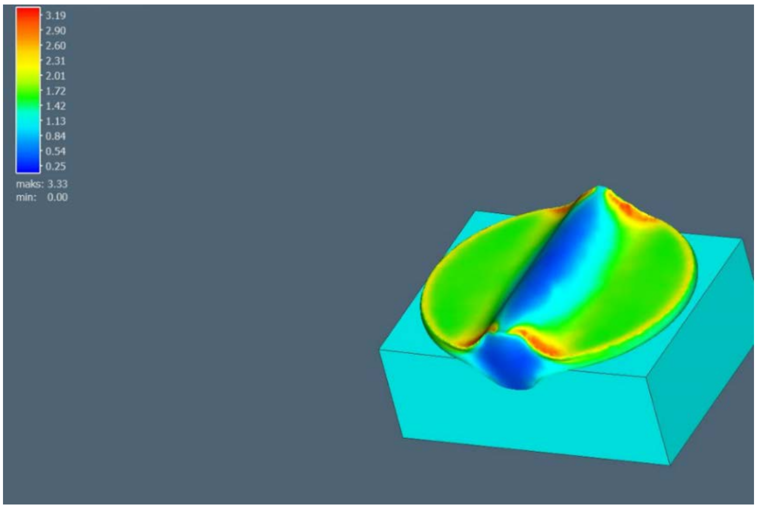


Figure 11. Core disc analysis with simufact forging simulation program

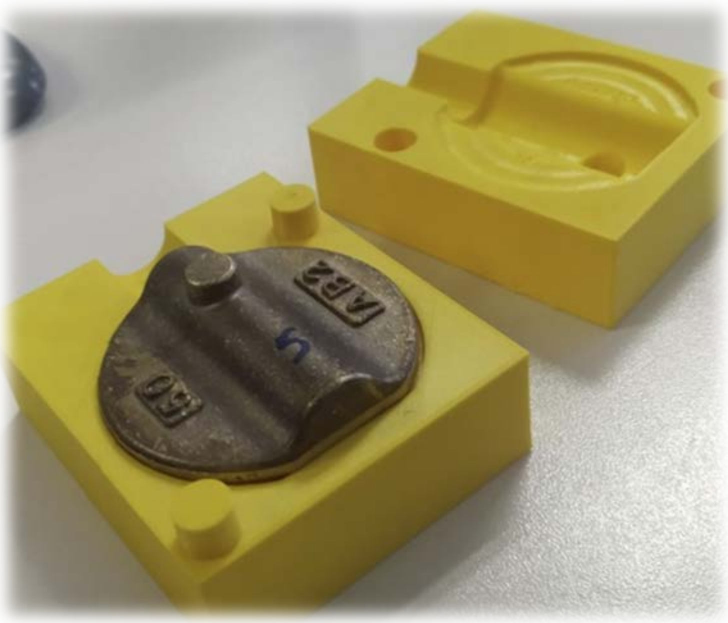


Figure 12. Core disc prototype production

2.3 Efficiency Phase Experiments

After the decision was made to produce the valve body by casting and the disc by hot forging, it was started to analyse the performance of the products in practice. Therefore, the flow coefficient (Kv) and fluid resistance coefficient (zeta-ζ) must be defined. For this purpose, ANSYS CFD module was used. 16 bar pressure was simulated by choosing 160% of the maximum application pressure of 10 bar, to have better results for flow coefficient and fluid resistance. While CFD analysis carried out, K-epsilon turbulence model was solved by keeping the y+ value at 3 and below. The limit in the layers (boundary layers) and the mesh improvements have been made during the process. Flow coefficient and pressure loss coefficient formulas were defined according to EN 1267:2012 (E) standard. Accordingly, the flow coefficient (Kv) is calculated with Equation 1.

$$Kv = Q\sqrt{\rho \div (\Delta p \times \rho_0)} \quad (1)$$

In the equation, Kv (m^3/hour) is the flow coefficient, Q is the flow rate in m^3/hour, ρ is the density of water in kg/m^3, ρ_0 is the density of water in kg/m^3 at 15 °C, Δp expresses the pressure loss in the valve (difference between inlet and outlet pressure). The pressure distribution analysis to which the disc material was exposed is given in Figure 13.

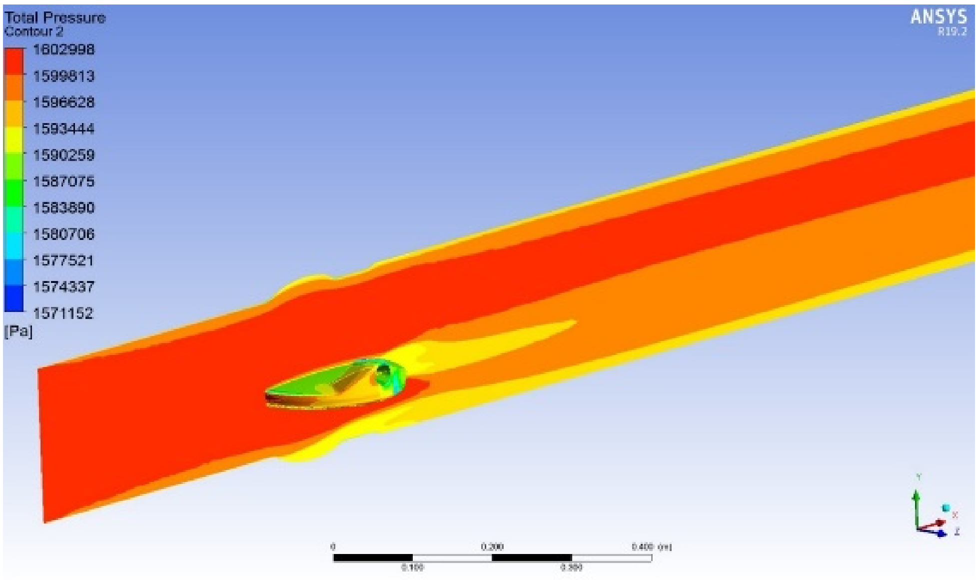


Figure 13. CFD analysis of the system

When the flow occurred at a certain speed and pressure, the total strength was analysed by performing the distribution analysis of the flow filaments for the system. The flow filament distribution analysis of the system under 16 bar pressure is shown in Figure 9. As 4m/s was defined in the standard as a vector speed, this value was chosen in the CFD analysis. In order to better interpret the characteristics of this behaviour, velocity vector analysis was performed. Accordingly, when the valve is in the fully open position, the resistance of the valve and its body against flow can be characterized more clearly. Velocity vector analysis of the system in Figure 14 is given for a better understanding of the subject.

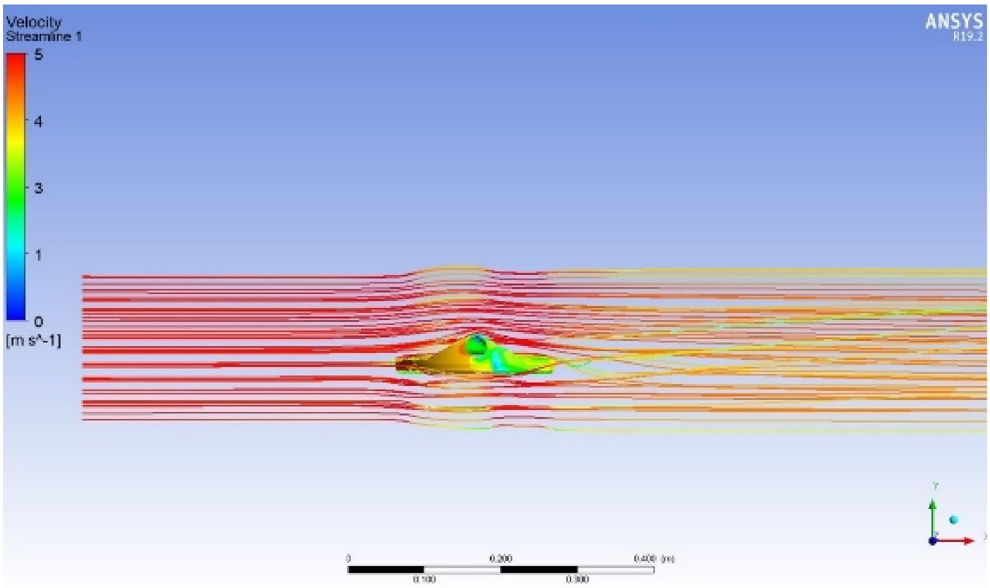


Figure 14. Flow strands distribution analysis

Following the flow and pressure analyses, the hydrodynamic forces on the core disc were performed. Since the defined pressure of the system was 16 bar, CFD analysis is critical when the disc material is exposed to a flow of 16 bar. There should be no red regions in the system, while green and yellow regions indicate that the design is in the safe area. Figure 15 illustrates the CFD analysis image of the hydrodynamic forces on the disc.

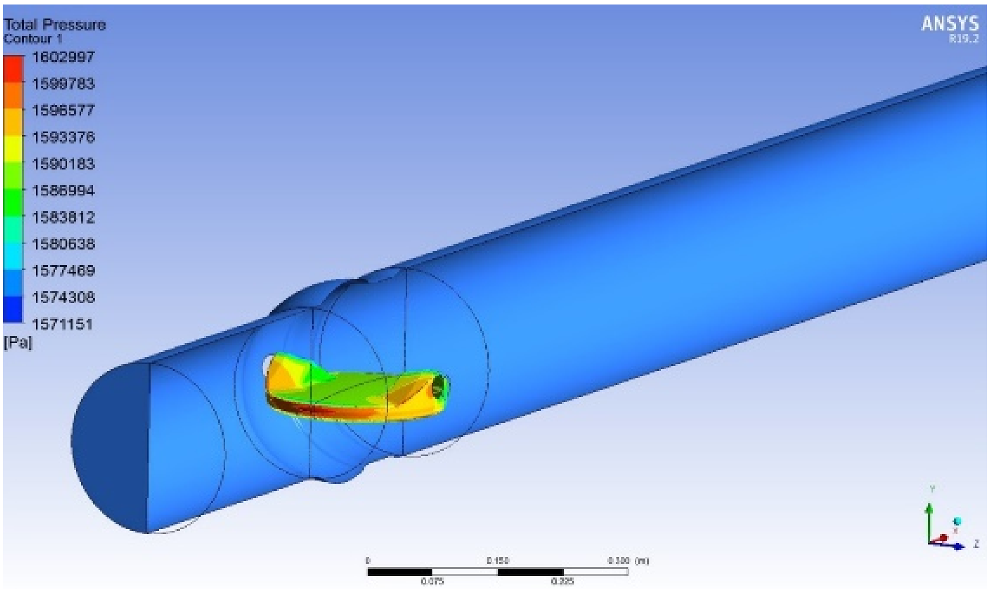


Figure 15. CFD analysis of hydrodynamic forces on the core disc

A mesh independence test was performed to prove that the results of the mesh analysis performed were reliable. Figure 16 shows the corresponding graphic. Accordingly, the volume flow rate was determined as 116.14569 at element number 8,000,000 and the value was 116.15249 at element number 9,234,500.

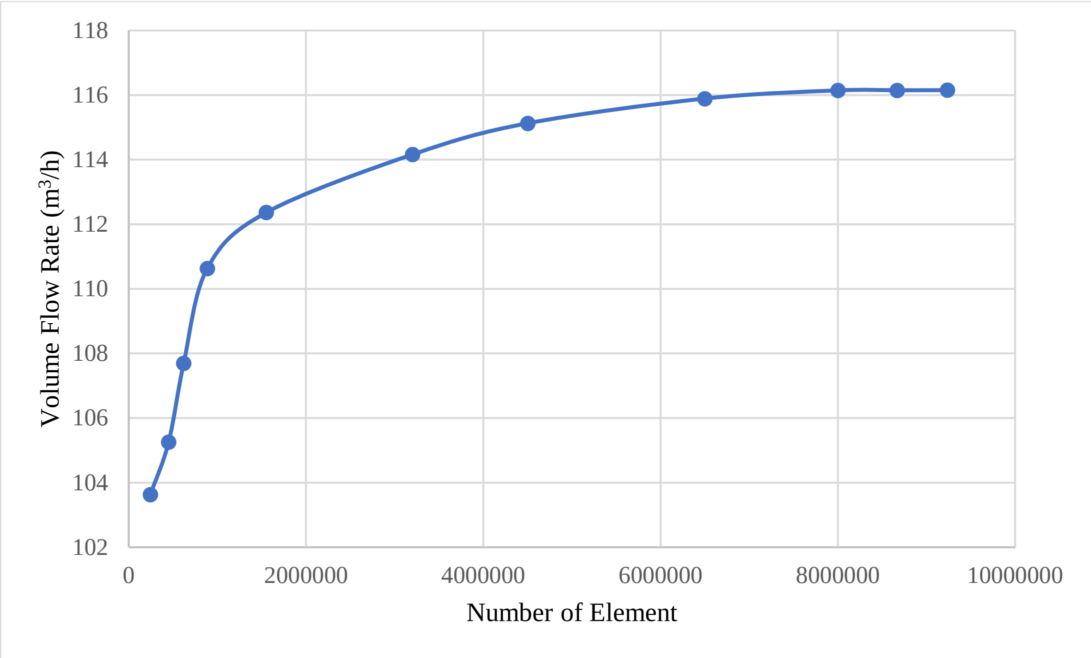


Figure 16. Mesh independence study curve

2.4 Excellence Phase Experiments

In order to provide an innovative product in the disc and to approach OPEX, the additive manufacturing method for the disc moulding was preferred. Zortrax M200 Plus model additive equipment was used for the additive manufacturing phase as shown in the Figure 17.

Figure 17. 3D additive manufacturing equipment

Support angle, nozzle diameter, and maximum wall thickness were selected as 30°, 0.4 mm, 3.13 mm, respectively during the manufacturing process. As the samples must show high mechanical resistance on the high temperature applications, ABS material was selected as filament. The process took three hours and half with 35 gram corresponding to 15-meter ABS raw material. The pre and post designs details are given in Figure 18.

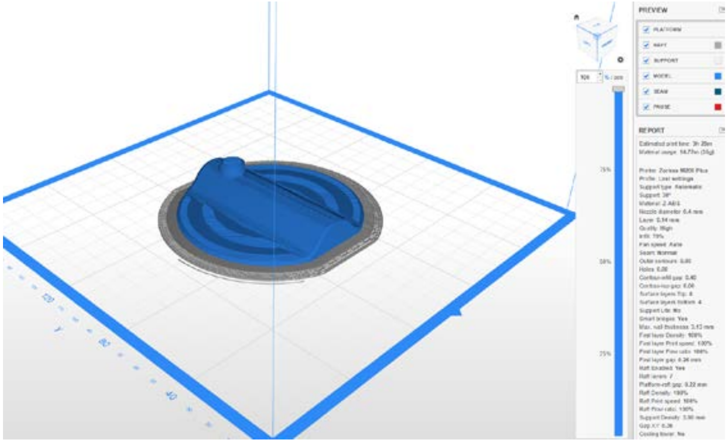


Figure18. Additive manufacturing zone and layer parameters (left side image), final product produced by additive manufacturing (right side image)

While the mould of the disc material was produced with a 3D printer, the body material was also produced by casting. The microstructure of the valve body material is given in Figure 19. The surface was etched 15 g $FeCl_3$, 75 ml HCl, 25 ml HNO_3, 25 ml H_2O for 10 seconds. The image of microstructures presented in Figure 19 shows clearly developed dendrites of solid solution α. In the inter-dendritic spaces, there are precipitates of α + ε eutectoid mixture. The grain boundaries show themselves distinctly by changing the direction of the main dendrite axes in individual areas.

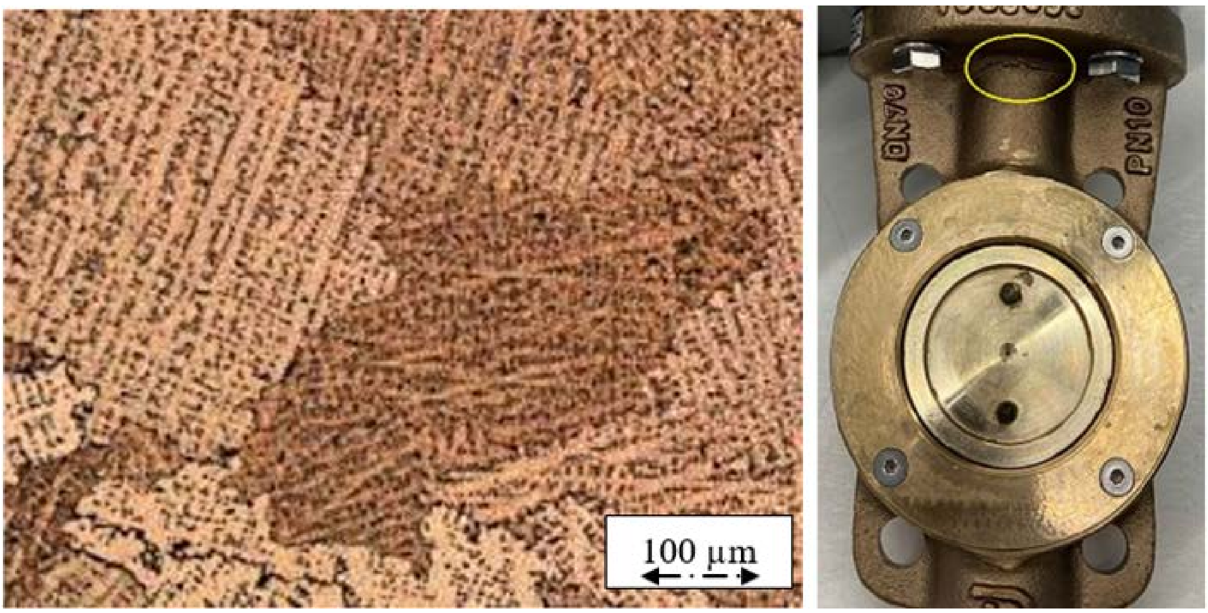


Figure 19. Microstructure of the casted valve body

After the body and disc were produced without any problems, the flow resistance of the system consisting of these components was tested. This test was defined in EN 1267 standard, and according to this standard, the valve and disc must be tested in the fully open position. Therefore, the system was modelled in the Solidworks drawing program with the valve in the fully open position. The virtual modelling and the real test setup are shown in Figure 20. The flow and capacity measurements of the product were made in the given Kv test setup.

Figure 20. Test model (a) and field application (b)

Torque measurements, which gave the rotational force of the disc in the body, were made after real flow tests. At this stage nine different torque values were measured by changing disc diameter, disc core length, body diameter, and body core length. Minitab Data Analysis program was used to determine the correlation of the torque value by changing of these data. The changing values are given in the Table 4.

Table 4. Data covered in minitab

Data	Disc Diameter (mm) A	Disc Core Length (mm) B	Body Diameter (mm) C	Body Core Length (mm) D	Torque (Nm)
1.	150.54	145.33	152.42	147.04	102
2.	150.60	145.28	152.45	147.05	80
3.	150.56	145.32	152.43	147.02	94
4.	150.54	145.33	152.45	147.05	108
5.	150.54	145.33	152.43	147.02	106
6.	150.60	145.28	152.42	147.04	109
7.	150.60	145.28	152.43	147.02	87
8.	150.56	145.32	152.42	147.04	81
9.	150.56	145.32	152.45	147.05	106

The pareto chart image obtained from the Minitab Data Analysis program is given in the Figure 21. The corelation of the disc diameter, disc core length, body diameter and body core length by considering the integration of the rubber coated body and hot forged disc for the optimization of wet torque values showing experimental design was carried out and verified. In this chart A represents the disc diameter, B represents disc core length, C represents the body diameter, and D represents the body core length effecting directly torque values.

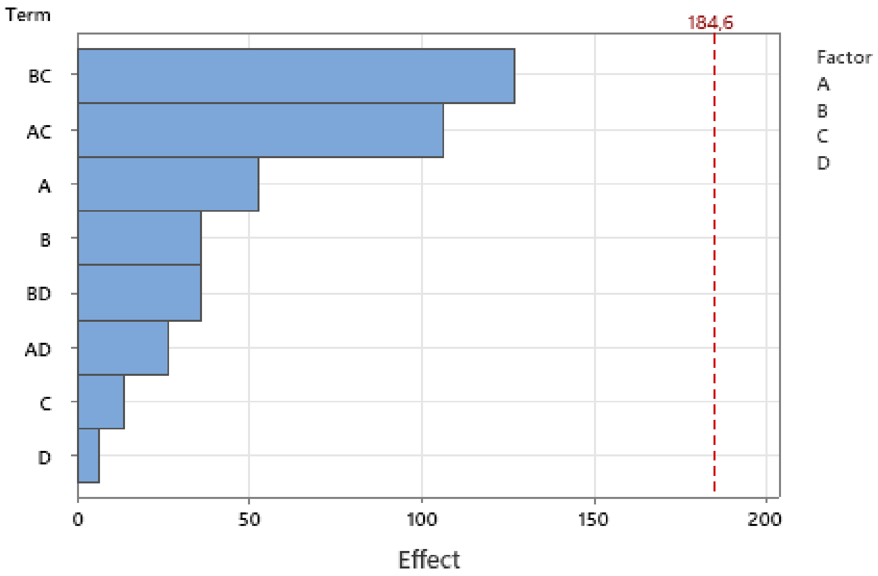


Figure 21. Pareto charts of the effects for torque values

After all the productions were done, the tests were completed and the torque limits were defined properly, it was time to prepare the sustainability report for the product. The sustainability report of the design was taken from the Solidworks sustainability option. In this report, total consumed energy for the material, production, transportation and end of product life values were evaluated. Figure 22 illustrates the total consumed energy data for the developed and previous version of the product. Previous version values were identified in red.

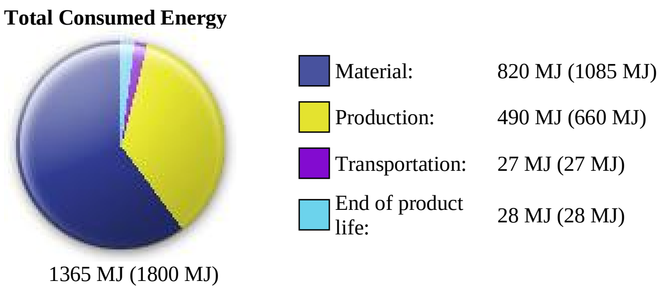


Figure 22. Total consumed energy values of the developed product

While preparing the sustainability report, the institution's average data for the last ten years for materials, production, use, transportation and end of product life were taken into consideration. These data exactly match the Canias ERP system data and were stated to have been calculated using the Solidworks RACI impact assessment method. By considering the total energy data, the data related to the carbon footprint were also evaluated. Figure 23 shows the carbon footprint measurements of the developed product vs previous version. Previous version's values were defined in red again like in total consumed energy comparison.

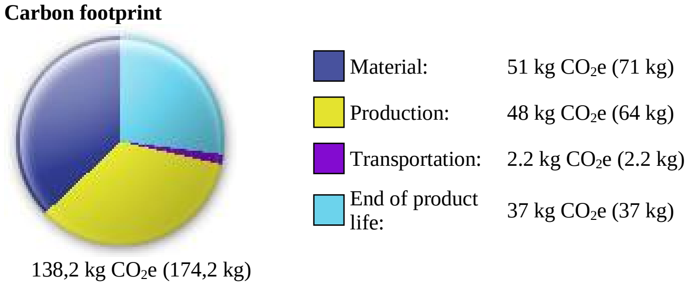


Figure 23. Carbon footprint of the developed product

III. RESULTS AND DISCUSSIONS

Metallurgical simulations and mechanical analyses of an existing product were carried out with the OPEX approach, and improvements in an existing valve product were observed by obtaining real test results with different production techniques, process optimization and virtual data. Material was selected as CuSn10, which widely used in marine valve industry due to its high corrosion resistance. Weight of the current product was 2.64 kg, and after the OPEX approach the weight of the new design was decreased to 2.21 kg. Moreover, 4 seconds of saving in casting filling time was achieved, and casting was carried out in 15 seconds. Preventing the valve core disc material's problems, hot forging method was selected under 300 MPa pressure at 500 °C for 0.1 hour. The mould of the disc for the hot forging was prepared via additive manufacturing method. Total system was tested at the K_v test setup and flow coefficient value was increased to 99624 from 54890 m^3/h. However, flow resistance coefficient was decreased from 0.5305 to 0.1740. Total consumed energy obtained from the sustainability report was measured as 1365 MJ, and the previous value was 1800 MJ. Moreover, carbon footprint was decreased from 174.2 to 138.2 kg CO_2 values. The product designed and produced with the OPEX approached and the current product comparison was given with details in Table 5. While two-runner production was handled in the traditional casting method, the designs handled with the OPEX approach had three runners, and it has been clearly observed that the same material becomes more efficient with the system efficiency by considering the duration time, gross weight, and net weight.

Table 5. The comparison of the OPEX approached design and current product

Parameters	Current Product	OPEX Approached Design
Kv (m^3/h)	54890	99624
Zeta (Unitless)	0.5305	0.1740
Total Consumed Energy (MJ)	1800	1365
Carbon Footprint (kg CO_2e)	174.20	138.20
Material Type (C90700 / SAE 62, DIN 1075 - 2.1050, CC480K)	CuSn10	CuSn10
Production Process Temperature (°C)	1150	1150
Duration Time (Sec.)	19	15
Gross Weight (kg)	3.27	2.87
Net Weight (kg)	2.64	2.21

The simulation results reveal that the runner design in the casting process has a direct effect on the product quality. It was observed that macro and micro shrinkage, filling time-flow rate values decreased concerning on the runner design. With the simulation results, it will be possible to prevent the production of defective parts and wrong mould design that may occur during the casting process, and to reduce the production costs per part. The metallurgical simulations, mechanical analyses, and real condition field practice tests for cast bronze valve product through OPEX approach were investigated in detail, and obtained results are summarized as follows.

1. 2D drawings provided the fundamentals for the design, as well as giving the designer an idea for 3D drawings.
2. Mechanical analyzes were carried out by using FEA method in the ANSYS simulation program with the Rayleigh-Ritz method, and no inconsistencies were encountered.
3. Bronze material, which is widely used due to its high corrosion resistance, was preferred and its chemical, mechanical and physical properties were defined in the system to meet the standard requirements.
4. While no problems were encountered in the production of the bronze body material by casting, it was decided to produce the disc material by hot forging method because the simulation results of the casting were negative.
5. Weight and production times of the cast body were minimized by OPEX approach. With the improvement of the design parameters, the gross weight was reduced by 13.94%, net weight was reduced by 19.46% and the casting time was reduced by 26.67% with the improvement of the production parameters.
6. By changing the production method from casting to hot forging in disc material, zero wastage production was achieved.
7. Numerous measurements were made to determine the factors affecting the torque on the friction surfaces of the body and disc materials; thus, the experimental design was used to optimize these measurements. According to the results the order of the factors was defined as, body diameter, body core length, disc diameter and disc core length. In other words, increasing body diameter results in a decrease in torque, and an increase in disc core length causes a decrease in torque.
8. With the help of Solidworks sustainability report 31.87% energy savings with a total energy consumption of 1365 MJ/product with material, production, and product life, was detected.
9. With the achievements in total energy saving, a carbon footprint of 138.2 kg CO_2e per product was obtained and a 26.05% improvement was achieved in existing products.
10. The excellence part of the improvements made was observed in the changes in the flow coefficient and fluid resistance coefficient. The 81.50% improvement in the flow coefficient and 204.89% improvement in fluid resistance coefficient has been obtained.

In order to increase the importance of the study for industrial decision makers who want to balance sustainability goals with economic performance, it is necessary to provide a summary detail about the cost-effectiveness analysis and financial viability of the improvements. In the part of the study that was not improved with OPEX, the total energy consumption cost was $117 per ton, but with the improvements this price decreased to $87 per ton. On the other hand, carbon emission tax is of critical importance for companies trading with European Union countries. As a result of the successful completion of this study, a 21% saving will be achieved in carbon emission tax depending on the currencies of the countries. In addition to the economic revenues obtained from carbon emissions, gains from new designs, processes, materials and savings from labour have also been identified. Accordingly, with the decrease in product weight, a profit of $25 per kilogram was achieved, and with the decrease in production time, a profit of $6 per kilogram was achieved on a labour basis. Finally, thanks to the commissioning of the improved materials detailed in the article, an economic gain of $20 per ton was achieved through the revenues obtained from their final processing.

The primary goal of this research was to bring an original study into the literature, in which the overall productivity increase in the processes from design to final use was discussed in detail. Computer aided design, simulation, numerical analysis, and digital transformation software were used to increase product efficiency with design, process optimization and energy efficiency, and operational efficiency with OPEX approach. Within the scope of integration of the system in mould casting of a bronze valve, the validation of the products can be carried out in a short time period without needing to a lot of prototypes.

IV. CONCLUSIONS

In this study, metallurgical simulations, mechanical analyses, and real test applications were handled with the OPEX approach. For this purpose, computer aided design, simulation processes, FEA and CFD analyses, prototype manufacturing, data evaluation, parameter optimization and final product characterization processes of bronze butterfly valves, which are widely used in marine valve industry, were carried out. All cases in this article from design to excellence were handled in detail of OPEX 4E phases. There are many articles in the literature regarding the OPEX approach. These approaches are often referred to as CAPEX integration, which includes investment processes [34-41]. As a result of the study, savings in material, labour and time were achieved and detailed information about the academic and commercial studies of high-efficiency, low-cost products was shared with the readers. The unique aspect of this article compared to others is that it deals with the data of a traditional method used in industry in an academic language and includes practices that do not require investment. The details of design development and process improvement studies, which are the two important points of reducing costs today, were given together and a privileged study was presented with a different approach. As a result, it has been clearly demonstrated that excellence in all operations can only be possible with the optimization of the data to be obtained by different disciplines both in the computer and in the real field environment with a good teamwork.

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