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Case-Based Product Development of a High-Pressure Die Casting Injection Subset Using Design Science Research

High pressure die casting is widely used in metalworking industry. Many of the components and devices directly linked to the hot parts are subjected to severe wear. However, some design updates can enlarge the lifespan of these components and devices. This paper proposes to show how a sustainable maintenance can be obtained by focusing resources on the analysis of the critical problem and its consequent mitigation, whereas they are originated on the human, machine/process or supplier level.
Design science research (DSR) was the iterative research methodology chosen to integrate this work. The completion of the objective with the implementation of this new injection subset concept brought extremely beneficial results, such as reduction of its consumption, reduction of acquisition cost and waste generated, and reduction of the intervention time during maintenance operations, as well as increase in equipment availability time.

Keywords: *Product Development; DSR; Maintenance; Sustainability; Die Casting;Productivity; FMEA; Wear analysis.*

1. INTRODUCTION

Automotive industry had an increasingly significant role within the economic structure of modern society in addition of being perpetually positioned at the forefront of productive systems technologic development [1-3]. This phenomenon can be attributed to several indicators such as its placement within one of the market sectors which has undergone one of the biggest increases on global equities for the last ten years. In addition, considering the level of competitiveness all organizations must ensure, a constant increment on the application of resources towards research and development activities has been observed. These represent the efforts carried out towards innovation, introduction of new offers or the improvement and reinforcement of the organizations' existing products and systems. This reinforcement is the focus of this work as a pinpoint regarding the optimization and quality enhancement of a specific process.

Spare part consumption is a major contributor to the consumption of economic and human resources within organizations' productive system. As such, the prime focus was centered in the reduction of the consumption of their most requested spare parts, as well as the control and stabilization of the process.

Sustainable manufacturing is a paradigm and strategy that thrives to create a viable production in accordance with the economic, environmental, and social commitment to the sustainable cause [4]. Through the balance of its three dimensions (Environment, Economy and People), organizations can obtain a significant competitive advantage [5]. Activity management on a strategic, operational, and tactical level, as well as long-term results, are ensured by maintenance, even in the aircraft industry and maintenance services [6-7]. As Franciosi et al. [8] and Ferreira et al. [9] studies state, these tasks have a significant impact on production volume, cost, productive system availability and efficiency, optimal manufacturing, and human resource use. Silvestri et al. [10] focused on technologies applied to maintenance within the Industry 4.0 spectrum and concluded that an effective management of the relationship between human resources and manufacturing systems must also be established, in addition to health and safety improvements. The impact of these last additions on sustainability was further demonstrated by Morgado et al. [11] through a study about safety management systems.

The influence that maintenance holds upon the development of a sustainable production can be subdivided into ten factors: spare parts management; cooperation with the equipment supplier; cooperation with technical services, as well as research and development (R&D) department, health and safety and environment department; maintenance workers of the technical process; implementation of preventive strategy and collection and subsequent data processing; and lastly, the equipment modernization [12-13]. Franciosi et al. [14] created a model for optimal spare part management, including the principles of Circular Economy and identified two main barriers regarding the implementation of a sustainable maintenance, namely data collection and, albeit small, an increase of maintenance costs. As

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Santos et al. [15] demonstrated, data collection is a vital source of information regarding the selection of the critical spare parts within all the productive systems, as well as the characterization of all root problems and failure modes, whether it is for a specific component or system. All data within this work was processed, analysed, and guided using Pareto's, FMEA, and Ishi–kawa's tools, because their contribution to data analysis and process otimization is effective.

The complexity of the product increases the number of conflicting factors about the application of product development making decision based on data of imper<–ative use [16]. Schönberg et al. [17], seeing as distinct data arises from different stages of a product life cycle, defined product data management maintenance systems as adequate for being used in potentiating a better understanding of the conflicting factors related to a service or function. This type of innovation is a key success factor for a company and is of extreme impor–tance for its R&D process [18-19]. Product development should also ensure an optimal performance/cost ratio while maintaining an effective risk management and intolerance to system flaws [20- 21]. Additionally, the product should offer a vast amount of outstanding features and attributes in comparison to the previous model [22].

Die casting is a process widely used in the metal–working industry, which promotes severe wear of many of the components and devices involved, espe–cially those that are subjected to higher temperatures [23]. This is the commonly used process to produce the tip blockers of Bowden cables, parts handled on a daily basis, when we open the car door, the hood, the trunk door, the handbrake or when we go up and down a window in a car window [24]. The injection nozzle area and corresponding connection to the mold have under–gone some changes in recent years, but not enough to avoid constant replacements, process stoppages and productivity losses [25]. Thus, it became urgent to invest in research in a new concept of nozzle and con–necting zone, in order to increase the efficiency of the process, acting essentially in the previously mentioned areas.

The design science research (DSR) is a usually used methodology to develop new products from existing ones, among others [26-27]. Grenha et al. [28] refer DRS as a convenient methodology due to its "techno–logy background and its focus on developing models and methods that address complex and ill-defined problems". Baskerville et al. [29] used Vaishnavi and Kuechler's [30] iterative process for the DSR journey of their project, which is divided into five stages: problem awareness; suggestion; development; evaluation; and conclusion, with each phase having a specific output and offering knowledge contributions. Devitt et al. [31] compared design science with design thinking. The Stanford school philosophy for design thinking was followed according to its stages: understand; observe; point of view; ideate; prototype; and test. For the DSR iteration process, the model was based on the studies of Peffers et al. [32]: define objectives for a solution; design and development; demonstration; evaluation; and conclusions. The conclusion came out as DSR, being a more suitable solution for more knowledgeable areas of problems. The full model of this methodology was implemented by Azasoo & Boateng [33], introducing the problem identification. Vom Broke et al. [34] also developed the previous model adding evaluation activities (problem, solution design, solution instan–tiation, and solution in use), as well as design know–ledge production and consumption within the problem and solution space.

Siedhoff [35] developed a new nominal process sequence for DSR based on the work of Devitt et al. [31], to be implemented after general problem identi–fication, by combining design thinking with pre-existing DSR stages and including both activity and cycle research. The process was divided into exploratory (problem clarification/definition and solution establish–ment) and prescriptive research, which, as shown by Gregor et al. [36] and Lepenioti et al. [37], are solution recommendations that lead to optimal decision making ahead of time.

2. MATERIALS AND METHODS

2.1 Methodology

The DSR process used in this work is the one developed by Siedhoff [35]. Relich et al. [38] already approved the use of case-based reasoning approach in the modification of an existing product rather than comple–tely restarting a new design. As such, the starting point of the DSR cycle for the product development is the initial design of the product under study.

Starting the exploratory research, a classification table showing ten different spare parts by quantitative relevance of requests was created, as shown in Table 1.

Table 1. Spare part consumption by number of requests and respective acquisition cost, and overall expenses for the first nine months of 2019.

Spare Part	Consumption (Units)	Acquisition Cost (€)	Overall Expenses (€)
SP01	527	38,00	20 026,00
SP02	448	9,00	4 032,00
SP03	309	55,00	16 995,00
SP04	261	7,35	1 918,35
SP05	258	7,00	1 806,00
SP06	227	51,86	11 772,22
SP07	219	6,30	1 379,70
SP08	218	5,15	1 122,70
SP09	206	22,50	4 635,00
SP10	198	21,00	4 158,00

Subsequently, a Pareto's analysis was carried out to simplify the selection of the most urgent components to be studied, taking into account the expenses shown in Table 1. The information attained by the Pareto's ana–lysis regarding the parts' consumption was not conclu–sive, as no real discrepancy between the consumption of the main spare parts is shown. Thus, in order to create conditions to substantiate a decision, acquisition costs were considered. Thus, the analysis was repeated, culminating in the results presented in Figure 1.

A brief introduction to the *injection system* and characterization of the productive system under study is presented in subsection 2.2, allowing for realizing the technical problems and specific solutions. It presents a full characterization of all materials, equipments, and testing methods used in this work. Subsequently, it is focused on FMEA and the identification of which of those failures exhibit the highest breakdowns and intervention times. Aiming at this goal, the study followed seven distinct stages: data collection; preliminary data evaluation; categorization of tasks by system; categorization of tasks by set of parts; definition of failure groups for each set; data processing and subsequent conclusions.

Therefore, for the same time frame set used on the previous subsection, the corresponding data was processed by characterizing and consequently categor–izing all handled issues. This was followed by a qua–litative characterization of various technical problems of productive systems. Finally, and focusing on the product development phase, the findings will then be implemen–ted during section three, solely dedicated to the product, facilitating the testing and evolution processes [39].

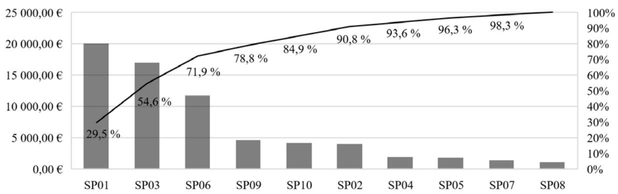

Figure 1. Pareto's analysis on spare part consumption by accumulated acquisition cost (Overall expenses).

No limitations on the nature of propositions on imp–rovement actions were established, allowing all systems characteristics to be subjected to modification, adaptation, or correction. Succinctly, the main ambitions for this work regarding the previously introduced ZHPIM consist of spare part request reduction; extend spare part lifespan; acquisition cost reduction; reduction on equip–ment corrective maintenance times; improvements on acces–sibility and general working conditions, and the optimi–zation and quality enhancement of the productive system.

2.2 Manufacturing Process Characterization

ZHPIM are characterized as high-pressure die casting injection machines having as main function the injection of Zamak 5 on a steel cable end. Many studies have been performed around Bowden cables [40-42], since the study of wire rope corrosion until the manufacturing process optimization. Depending on the figure dimen–sion and operator ability, these machines may produce up to 600 to 900 cables per hour. These machines are essentially composed of an *injection system*, *coupling system* and *workstation* (WS) (including all remaining devices). For a better characterization, each system was divided into different sets, subsets and main components displayed hierarchically, as shown in Figure 2.

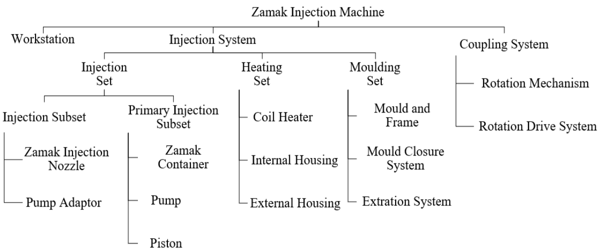

Figure 2. ZHPIM equipment structure by main systems, sets and working groups.

Throughout this section, all components that were deemed imperative to the comprehension of the productive system will have their function and location disclosed, as well as its importance revealed. In Figure 3 (please see it in annex), regarding the WS, all devices which are held by the support base (14), which works as a platform for supporting component, are presented: (1), (2), (3), (4), (5) and (6).

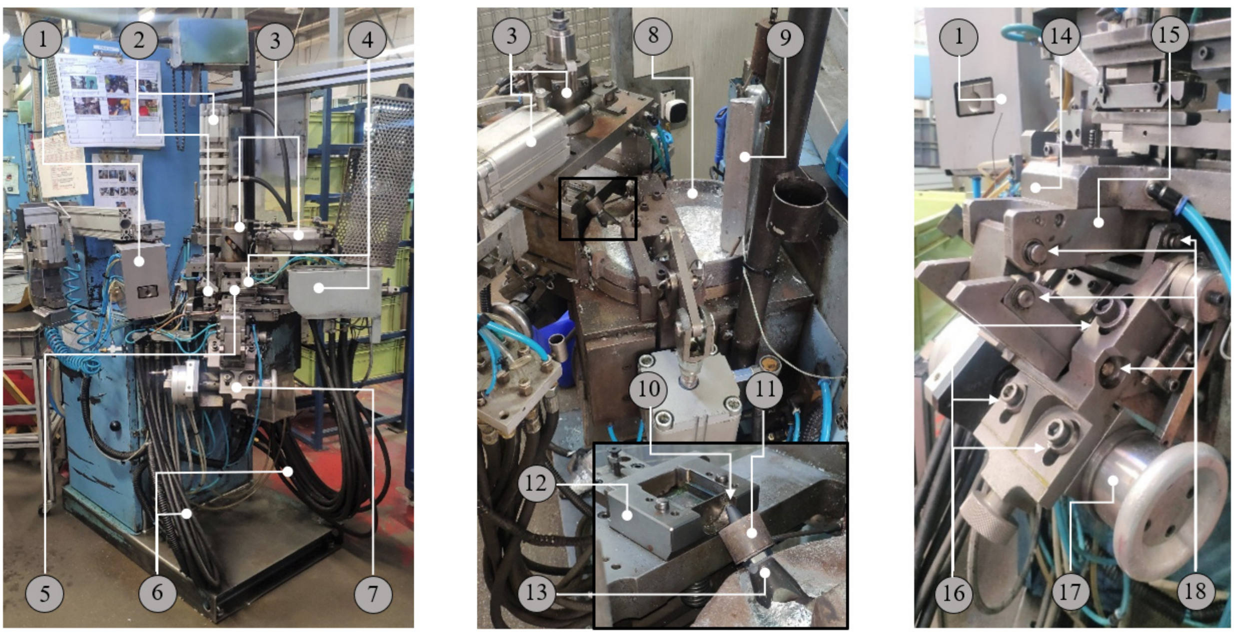

Figure 3. Workstation, Injection System and Coupling System and corresponding main components and location: (1) Cable trimming device; (2) Flower device and drive cylinder; (3) Mold closure system and drive cylinder; (4) Transfer and drive cylinder; (5) Mold and frame; (6) Air, water and oil hoses; (7) Coupling system; (8) Zamak container; (9) Zamak ingot; (10) Zamak injection nozzle; (11) Heating set; (12) Frame base; (13) Pump adaptor; (14) Support base; (15) Rotation mechanism; (16) Coupling tuning system; (17) Rotation drive system; (18) Dowel pins.

The first two are cable preparation devices, and the fourth is an automated transfer that removes the product from the mould. Compressed air, water, and oil hoses are used for operating pneumatically triggered devices and cooling system, and act as lubricant during moulding process, respectively. The remaining devices of the WS relate to the *moulding set* (MS) (3) are responsible for the compliance with injection times and parameters. As for (5), it holds the mould with the desired shaped cavity, as well as its frame, supported by (12), acting as the counterpart for the coupling process, more specifically the *bottom half of the frame plate* (BFP). The injection occurs by means of a simple pressure contact between this last component and the ZIN (Zamak Injection Nozzle) (10), more specifically the coupling of both their *injection contact zones* (ICZ). ZIN is mechanically adjusted to the *pump adaptor* (13), making up the *injection subset* and functioning as the connection to the *primary injection subset*, which supplies the whole system with the molten Zamak (9). This is possible because the pump is inserted within the *container* (8), keeping the Zamak at the desired temperature, around 440˚C, and injecting the metal at a pressure ranging from 4 to 5.5 bar. Improvements to the die casting mould and the otimization of the injection process were already attained in previous studies [43-44]. The main role of the *heating set*'s (11) is the preservation of the temperature along the path and the cold zones. As such, the *coil heater* oscillates from 585˚C to 600˚C. Lastly, there is the *coupling system,* which is responsible for the transmission of the rotational motion that couples the BFP to the static ZIN. The movement is initiated by the *rotation drive system* (17) and transmitted to the *rotation mechanism* (15) using *dowel pins* (18). Additionally, it can be subjected to a *machine tuning* defining the whole movement by means of four slots (16). These slots allow the displacement of the *rotation mechanism*, specifying both angle and height of the approach, as well as the contact pressure between the ICZs.

2.3 Materials

The material used for the ZIN manufacture is a ∅25 mm rod of MG50 - Uddeholm Orvar® Supreme, a Premium H13 steel. Defined as a hot work tool steel, it undergoes an electro-slag remelting (ESR) process, thus enabling the production of high-quality ingots. This is achieved by eradicating all traces of micro and macro segregations, ensuring a homogenous chemical compo–sition and the materials isotropy regarding its mechanical properties, as well as achieving a high level of purity through improved distribution of inclusions [45-46]. This H13 ESR hot work tool steel features an increase in wear resistance under elevated working temperature, thermal conductivity, hardness, toughness, and tensile strength [47]. The final product undergoes a quenching and nitriding process, obtaining a hardness ranging between 48-52 HRC. The *pump adaptor* is manufactured from the same material as the ZIN, but it solely undergoes a nitriding process until it reaches its maximum hardness. The *heating set* is comprised by the *heater*, an *internal housing* (AMPCO®18) with high thermal conductivity, and an *external housing* (AISI 316) with high anti-corrosion properties.

2.4 Equipment and Testing

Several equipment and testing devices were utilized throughout this product development. A Nabertherm N11/H oven was used to melt the Zamak alloy and leave the injection nozzle free of Zamak to be analysed by SEM (Scanning Electron Microscopy). ZIN wear analysis started with a SEM analysis, complemented with energy-dispersive X-ray (EDS) analysis, using a FE - CryoSEM/EDS - JEOL JSM 6301F/ Oxford INCA Energy 350 / Gatan Alto 2500 equipment. Following the spectroscopy, full wear characterization was accomplished, and metallographic and hardness testing were performed. For the sample preparation, the grinding and polishing operations were made on a Struers Rotopol-1. The sequence of grinding paper and speed was as follows: P80 (150 rpm); turn sample 90°; P500 (300 rpm); turn sample 90°; P1000 (300 rpm). Polishing was achieved by a slurry provided with diamond abravise particles of 3 μm diameter at 300 rpm, followed by another slurry with diamond abrasive particles of 1 μm at 300 rpm. Subsequently, the surface was etched for 10 seconds with a Nital 4 % solution (composed of 4 ml of nitric acid in ethyl alcohol). The results were observed with an Olympus BX51M Metallurgical Microscope using three different lenses: Olympus MPlan N 10x/0,25, 20x/0,40, and 50x/0,75. Regarding the hardness testing, the applicable standard for this kind of sample was adopted (ISO 6508-1:2016). As such, the Rockwell C test was performed using as main load 1471.50 N and dwell time of 10 seconds.

2.5 Software-Based Data Collection and Analysis

In general, companies have their functions supported by a task assistance software, which provides the full description of all the services performed throughout their installations. The gathered data includes a full depiction of the problem, the cause and the solution found, as well as the task intervention equipment and breakdown times. This section is focused on a better understanding of all the process failures. This will enable the avoidance of such situations, as well as the resolution of specific cases. Following the methodology. three categories were created, based on the main systems: *injection system* (85 %); *coupling system* (6 %) and *machine tuning* (9 %), enabling to define which present the highest number of interventions. Regarding the *coupling system* set, the data indicates that 35.4 % of the interventions regarding this system are related to the *rotation mechanism,* but the intervention time spent increases up to 55.2 %, indicating slow resolution times. The results for the *injection system* are as shown in Table 2 (please see in annex), where the main aspects to be concluded are the fact that *injection set* intervention and immobilization times are one of the major problems. Consequently, and initializing with the failure groups by set, the gathered data noted that 25 % of every intervention on the *moulding set* have been originated from a non-compliance regarding the frame.

Table 2. Intervention categorization by set for the Injection System, and by failure group for the Injection Set and Heating Set.

	Number of Interventions		Intervention Time [h]		Immobilization Time [h]	
Categorization by Set for the Injection System						
Injection Set	588	43,4%	1021,82	51,3%	1304,54	58,0%
Heating Set	118	8,7%	159,30	8,0%	187,39	8,3%
Molding Set	650	47,9%	810,17	40,7%	758,41	33,7%
Categorization by Failure Group for the Injection Set						
ZIN	262	44,6%	395,40	38,7%	528,78	40,5%
ZIN and Pump	117	19,9%	315,98	30,9%	382,75	29,3%
BIZ and Coil Heater	80	13,6%	130,87	12,8%	177,32	13,6%
Zamak Container	63	10,7%	77,78	7,6%	107,26	8,2%
Piston	55	9,4%	81,15	7,9%	88,65	6,8%
N/A	11	1,9%	20,63	2,0%	19,78	1,5%
Categorization by Failure Group for the Heating Set						
Coil Heater	66	55,9%	76,12	47,8%	88,74	47,4%
ZIN and Coil Heater	24	20,3%	50,23	31,5%	60,27	32,2%
N/A	22	18,6%	32,95	20,7%	38,38	20,5%

For the *injection set* and *heating set,* the results for the categorization are also displayed in Table 2 (please see annex). Concluding this study, all the ZIN inter–ventions were then studied to an extent to where it was possible, to fully characterize all failure modes regar–ding this component. The information was then analysed through a Pareto's diagram, as shown in Figure 4.

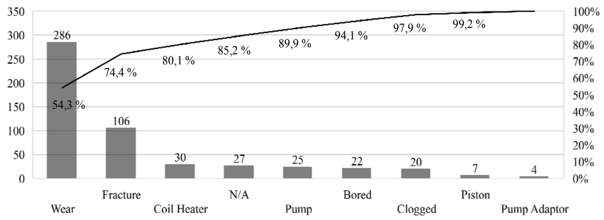

Figure 1. Pareto's analysis for ZIN failure mode count for the period under study.

This analysis proved to be of high value since it specified which failure modes presented the most urgent resolution when planning the product development. As it can be observed, most of the components are replaced due to wear failure on the ICZ or by fracture, always at the same location. With this research, it was also pos–sible to establish that 5.7 % of all ZIN failures are caused by a damaged *Heating Set* that could not be removed. In addiction, 79.9 % of the fractured ZIN led to pump replacement, and 72.3 % of the failures by wear only require its replacement.

2.6 Process Study Through Observation and Inter–vention Monitorization

Through the observation and monitorization of all the aspects of the manufacturing process, it was possible to complement and better define the software-based data by identifying some primary issues concerning the process. Some technical issues were found regarding the ZIM manufacturing process. Firstly, focusing on Figure 5, it is possible to identify injection failure, which oc–curs when wear on the ZIN or the BFP *injection contact zones*, fracture of ZIN or *pump adaptor* occurs*,* and every time there is a failure in the coupling pressure. This would ultimately lead to Zamak waste, which involves an increase in expenditures, and intervention and immobilization times.

Figure 5. Injection failure caused by technical problems on the coupling system elements.

In addition, the contact with the molten metal decreases the lifespan of both the ZIN and the *heating set*. The study of this issue was imperative, since 51% of any malfunctions of the system had this injection failure as consequence. Then, a failure is presented due to incorrect handling promoted by the operator and/or maintenance technician, who did not use the protection plates. The plate shown on the left side of Figure 6 aims to protect the *heating set* and the ZIN *injection contact zone* from the runners. On the right side, it is displayed the plate used to negate the access of Zamak to the internal elements that lack protection from external environment. It is also used to protect the ZIN and *heating set* from any failures that may have occurred internally.

Figure 6. Location of the protection plates of the heating set and the internal parts of the moulding set

On the next topic, a series of problems were found, as fit clearances were evident in both the coupling tun–ning systems slots (Figure 7) and the *dowel pins,* which connect the *rotation mechanism* to the rotation drive system, as can be observed on the left side of Figure 8.

Figure 7. Extreme wear on the coupling system tunning slots.

Figure 8. Clearances on the dowel pins that connect to the coupling system and group of washers found on the ZHPIM.

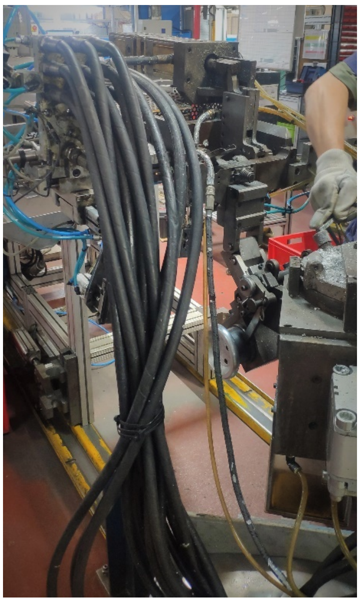

Figure 9. Intervention process impact on premature coup–ling and tunning system wear.

The movement defined by the *machine tuning* system does not correspond to the movement being effectively described. It can be stated that the movement described by the *coupling system* can be qualified as fully defined by the quality of the fittings. If, during the approach, the system suffers several deviations, then the contact will be made through extraordinary compressive stress, establishing conditions for wear and fracture ZIN failure modes. There is the lack of a normalized washer to base the tuning screws also contributing to the wear of the four slots, which damages the edges even further (Figure 8). Moreover, there is an excessive number of components on the support base (Figure 3 – 1, 2, 3, 4, 5 and 6).

This increases the wear on all *dowel pin* fittings, since all the components exert a considerable amount of weight, and do not have a uniform weight distribution in accordance with the centre of rotation as well. During the intervention process for the ZIMs, a single fitting will need to support the entirety of these components, as shown in Figure 9.

A methodology regarding the seal of the *heating set* from the external environment was never developed, as shown in Figure 10.

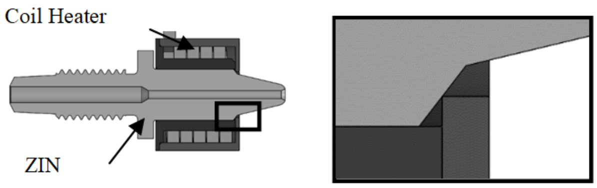

Figure 10. Technical problems with the seal of the contact between the heating set and the ZIN.

Intrinsically, the molten Zamak could easily get into contact with the coil heater, rendering it incapable of functioning (Figure 11), or in between the MG50 and the AMPCO®18 components, preventing its dissociation and leading to scrapping both the ZIN and *heating set.*

Figure 11. Failure mode by excessive corrosion of the heating set incapacitating the coil heater.

Moreover, the geometry of the ZINs *injection contact zone* and its interaction with the BFP was studied, more specifically, the regions in detail in Figure 12. The latter's ICZ cavity has a 3 mm radius, however, the ZIN contact zone is comprised of two 2 mm radius circles, as it can be observed in Figure 13-A. Further–more, the chamfer that is located at the end of the injection channel (Figure 13-B) creates conditions of high wear for the BFP.

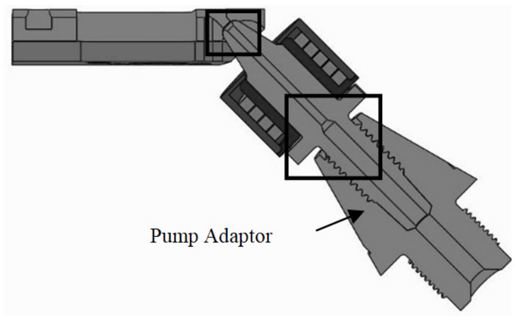

Figure 12. Bottom frame plate interaction with the ZIN.

As the molten Zamak engages the transition edges between the ICZ and the injection channel quickly degrading the area, high localized pressure is applied to the contact points, presenting wide underutilized contact area as well. These two issues were defined as one of the main factors for premature failure by wear of the component under study. All these technical problems are also aggravated by the discrepancy in hardness with the high-speed steel of the BFP. Another flaw in design was flagged has a major contributor for fracture component failure.

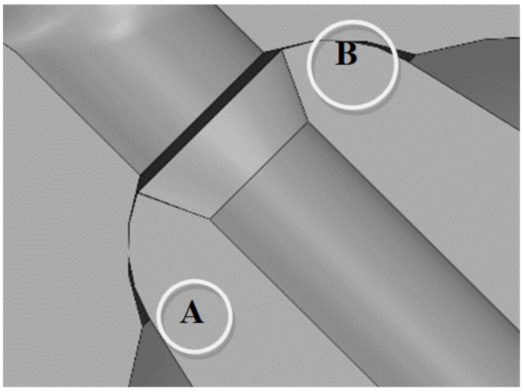

Figure 13. Contact points between BFP and the ZIN inject–tion contact zones.

As it can be observed in Figure 14, there is a gap between the transition of the thread and the beginning of the base. Additionally, this base, machined to present a hexagonal shape to provide a simple extraction, does not require such large dimensions, resulting in an overutilization of material.

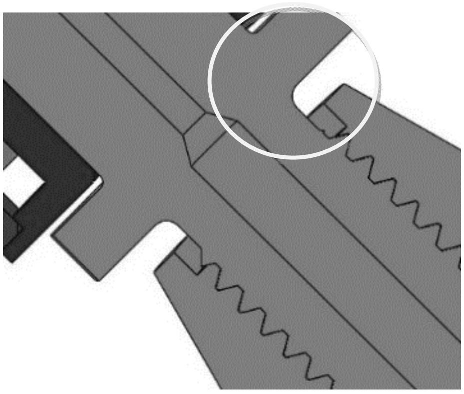

Figure 14. Geometric issues function as a major contributor to failure mode by fracture.

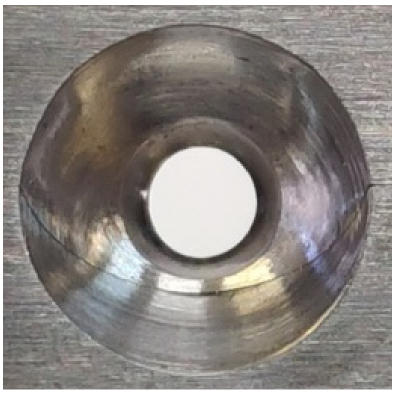

Figure 15. ICZ from BFP compliant with the required working state.

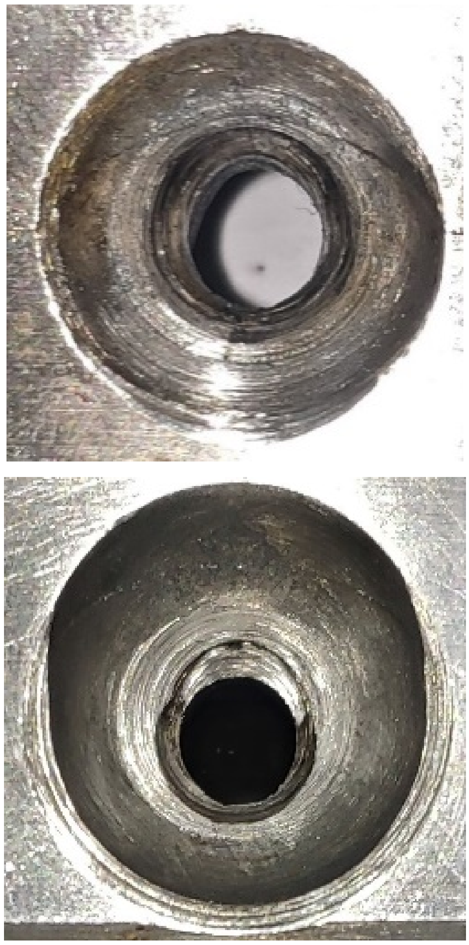

Figure 16. Non-compliance of ICZs for the BFP due to abrasion and impact.

Lastly, there is a general state of non-compliance of the BFPs *injection contact zone* with the minimum state required to carry out the contact efficiently and effec–tively. In order to accomplish this correctly, the BFP ICZ should remain in a similar condition to the one pre–sented on Figure 15.

Poor management of the component can be attri–buted to the abrasion marks revealed in Figure 16. In the latter, it is also possible to observe impact marks indu–ced by bad tuning. The impact contact point, on the right side of Figure 16, was set too high during the tuning process, which had severe consequences on the state of compliance of the BFP.

All the findings depicted on the present section were summarized to develop an Ishikawa diagram, which was a major tool utilized throughout all the development stages of this new part. The diagram is represented in Figure 17 (please see annex).

3. RESULTS

In this section, all development stages of the new *injection subset* concept are presented. Throughout the study, there were four major iteration processes, which, together with a detailed wear analysis, made possible the new concept to arise. As such, each developed model will be placed in accordance with groups of spe–cific improvement actions to both the ZIN and *pump adaptor* geometries, and general manufacturing process.

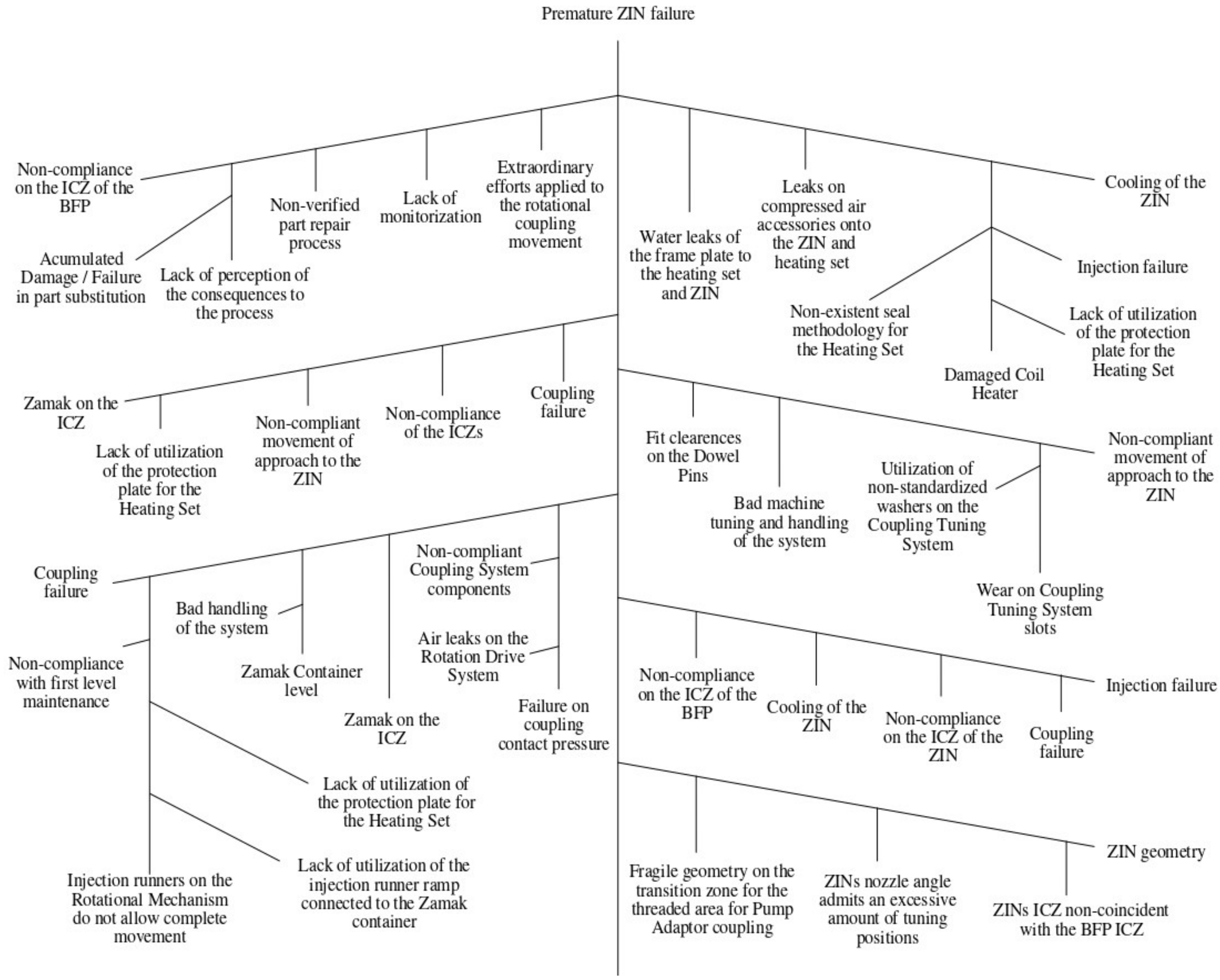

Figure 17. Ishikawa diagram for ZINs premature failure

3.1 First and Second Stage of Testing

The first stage was marked by the employment of inter–departmental modifications. Addressing the problems characterized in Figure 6 and Figure 15, it was initiated by the implementation of three improvement actions: protection plates were designed for each workstation; new wear limits for the BFPs contact zone were established; and all non-compliant frames with the new wear limits were removed from storage for external restoration purposes. Focusing on model development, the aim of this stage was the elimination of 74.4 % of failure modes by wear and fracture. As such, the ZIN models represented in Table 3 labeled as *Model 01*, *Model 02*, and *Model 03* suffered the following modi–fications: ZIN *injection contact zone* changed to single radius of 3 mm; chamfer removal from the ZINs injection channel end; elimination of the gap between the threads' end and the hexagonal shaped base; inc–rease in hardness to 56-58 HRC; and components drawing have been modified to indicate that the thread must not undergo the nitriding process and start or end at total depth. Additionally, the dimension of the rod used for its manufacture was reduced to ∅20 mm, which resulted in an 8 % percentile reduction of the acquisition cost. Consequently, the dimension of hexa–gonal shape was reduced, and the *external housing* suffered the corresponding alteration, which greatly reduced the exposed area where Zamak accumulation usually occurred. Moving to the second stage (*Model 04* and *Model 05*), a sealing methodology was developed through the creation of a step that not only supports the *external housing,* but also ensures an adequate fitting. Furthermore, in *Model 5*, geometrical modifications were implemented that reduced intervention time and waste, and ensured operator safety. This occurred as the level of Zamak in the container no longer needed to be reduced, to proceed with the removal and consequent replacement, as the transition between the ZIN and *pump adaptor* was elevated. Overall, none of the models fulfilled the main objective, the working time. The corresponding failure mode for each model from both stages are presented in Table 3.

The main design knowledge outputs conveyed by these iterations were as follows: the increase in hardness was not beneficial to the conservation of the ZIN *injection contact zone*; the fracture mode was eliminated through the modifications on the coupling method of the ZIN and *pump adaptor* (excluding *Model 05,* due to geometrical inaptitude); the advantages obtained on *Model 05* on the optimization of the intervention process should be further pursued; a more specific analysis on the premature wear of the ICZ should be performed; and the material behaviour does not match with the specific properties of the selected steel.

Table 3. ZIN models developed in the first and second stages of development.

Model 01	Model 02	Model 03	Model 04	Model 05
				
11 days	11 days	7 days	11 days	2 days
Premature failure by ICZ wear				Fracture
				

3.2 Wear Analysis

As the first and second stages delivered non-conclusive outputs regarding the source of the premature failure mode by wear of the ICZ, a more detailed research had to be performed. This was key in developing a more specific idea about the required design knowledge, to eliminate the primary failure mode.

Firstly, an attempt to disassociate the Zamak from the ZIN *injection contact zone* was made, by inserting a sample into the oven at 450°C, 500°C, and 550°C for twenty minutes each. The results were non compliant, as the Zamak did not turn into molten metal and did not expose the craters that would give the required insight regarding microstructural changes. As such, and in order to be able to take the sample into the SEM laboratory, an attempt was made with a steel wire brush to dissociate the Zamak from the MG50, but this procedure also rounded the transition edges between the surface and the craters. SEM analyses, as shown in Figure 18, allowed the establishment of three distinct zones on the failure impacted area: area of contact with the injected metal; area without contact with the ICZ; and area of contact between the ICZ of the BFP and the ZIN. Though, nothing could be concluded regarding the main objective, as the EDS only found elements originating from the zinc alloy on the surface.

Thus, another path was forged, and the mid section of a standard model was analysed for microstructural alterations and extremely evident changes of properties through metallographic and hardness testing. The results of the metallographic tests showed no microstructural changes on the sample in comparison with the control sample and the thermically or mechanically impacted areas. However, the Rockwell C hardness test showed a slight reduction in hardness on the impacted areas, nevertheless with minimal discrepancy levels and influence on the part failure mode.

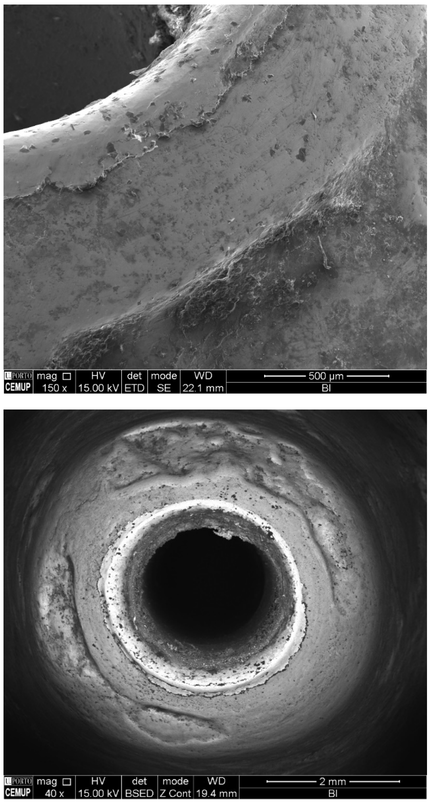

Figure 18. SEM analysis to the ZIN.

As the previous studies did not produce a full characterization of the failure mode, the surface was observed and the different phenomena were characterized. The main failure modes for the ZIN *injection contact zone* were pitting (Figure 19) and spalling (Figure 20). These premature failures are a consequence of several irregularities of the contact between the BFP and the ZIN, which were subsequently analysed.

Figure 19. Failure mode of the ZIN injection contact zone by pitting.

Figure 20. Failure mode of the ZIN injection contact zone by spalling.

The next issue originated from the machining process, as the feed marks (Figure 21) left by the tool induced crack nucleation and propagation, also aggravated by the fact that it presents a considerable difference in surface hardness with its counterpart.

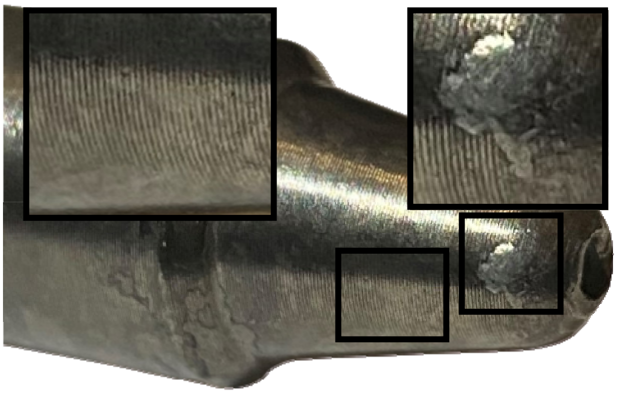

Figure 21. Feed marks impact on nucleation and propagation of premature failure.

Lastly, the material in use underwent a positive material identification (PMI), exposing a major flaw within the manufacturing process, as the analysis pointed to the use of a standard H13 steel. The main difference from this steel to the Premium H13 is the ESR process it undergoes, which is the main reason for the selection of this material as it was previously defined. In sum, the analysis showed that the solution to the premature wear failure can be solved by the redefinition of the machining process and material specification compliance.

3.3 Implementation and Validation of the New Model

Firstly, all of the fitting clearences were mitigated, and both material and dimension of the washers in use for tuning the latter were standardized. This ensured that the alignment and movement characterized by the tuning process was what was effectively being described by the *rotation mechanism*. Secondly, the models for this last phase of testing were divided into two, having as ultimate goal of culminating them into a single one, the new concept of *injection subset*. The approach taken on *Model 6* (Table 4 - Model 6) aimed at the mitigation of the third ZIN failure mode. Through the increase in the dimension that fits the *heating set* and the elimination of the *internal housing*, the direct contact of the ZINs material with the *coil heater* was tested.

The intervention processes were followed and the removal possibility continually monitored, as the efforts proved to be successful. This action greatly increased the efficiency and effectiveness of the *heating set* removal, having a direct impact on the reduction of part substitution due the adhesion of the *internal housing* and the MG50. *Model 7* is an extension of the development of efficient geometrical modifications aiming at the optimization of the intervention process initiated in *Model 5*. In addition to no longer requiring the reduction of the Zamak container level or the removal of the *heating set*, the planned actions grant an unconstrained access to the part. This was brought by the reduction of the parts length gaining accessibility to the ZIN from the outside and overcoming the need to fully open the machine to proceed with the part replacement.

Waste, intervention time, and effort inten–sity reduction were the main advantages implemented through this new geometry of the nozzle. Additionally, a systematic procedure of control for the purchased raw material was established. New specifications for the final roughness were settled, regarding the elimination of the feed marks left by the tool during machining. Thus, a final surface roughness of 0.8 μm was standardized.

The polishing process is followed by a general quenching and the nitriding of all ZIN and ICZ surfaces. All these restrictions, to material and machining process, were specified with a view to eliminate the premature failure by wear of the ICZ and mitigate the ZIN main failure mode, previously identified as brittle behaviour.

As shown in Table 4, this objective was fulfilled, as *Model 07* ICZ presented wear attributed to excessive plastic deformation, which is the intended behaviour. This made it possible to reach a working time of more than 140 days, only being removed for analysis purposes and maintenace tasks feasibility.

Table 4. ZIN models developed on the third stage of development.

Model 06	Model 07			
				
10 days	> 140 days			

Table 5. New concept of injection subset.

ZIN	Pump Adaptor	Sealing Methodology		Heating Set Fit	
					

As both models were validated, each action was implemented into the final concept of the *injection subset*. To make the ZIN able to support higher strain, its threaded connection was modified from M8 to M10 (Table 5 - ZIN). All aspects of machining and heat treatment processes were similar to those of *Model 7*, only differing on the sealing methodology and *heating set* fit, as presented in Table 5. The results followed the expectations as it surpassed the working time of its predecessor (*Model 07*) by 25 %, only being removed for analysis purposes.

4. CONCLUSIONS

Throughout the research cycles and activities, the observation and monitorization of both process and maintenance tasks defined all technical concerns and failure modes, which, together with the previous study, granted an optimized initial approach to the problem.

The product development led to improvements on the product's efficiency and effectiveness, and consequently increased the reliability of the equipment, through the reduction of part consumption by an increase of the working time. Additionally, a safer intervention process was established, as the technician no longer needed to handle molten metal or open the ZHPIM to remove the spare parts, also promoting waste reduction, and achieving a reduction in intervention time. Lastly, all these advantages were complemented by an acquisition cost reduction for the ZIN, keeping the previous cost values for the *pump adaptor*. All of the advantages to the ZHPIM process, regarding the new injection subset, can be summarized as follows:

- Improvements on product efficiency and effectiveness;
- Spare parts consumption reduction;
- Increase of spare part working time by 1100%;
- Reduction of part acquisition cost by 58%;
- Reduction of corrective maintenance time for the part by 55%;
- Safer intervention to the ZHPIM;
- Manufacturing process otimization;
- Increase in equipment time availability.

Concluding, the implementation of the DSR proved to be ideal to the development of this new concept of *injection subset*, as all defined objectives in the second section were fulfilled and, as such, the success of the work consequently settled. The iteractive methodology can be used for the optimization of the already established processes and products from a maintenance focal point, impacting the development of a sustainable manufacturing.

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РАЗВОЈ ПРОИЗВОДА НА ОСНОВУ СЛУЧАЈА ЗА ПОДСКЛОП ЗА УБРИЗГАВАЊЕ ПРИ ЛИВЕЊУ ПОД ПРИТИСКОМ ПРИМЕНОМ НАУЧНОГ ИСТРАЖИВАЊА ДИЗАЈНА

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Ливење под високим притиском се широко користи у индустрији обраде метала. Многе компоненте и уређаји који су директно повезани са врућим деловима су изложени озбиљном хабању. Међутим, нека ажурирања дизајна могу продужити животни век ових компоненти и уређаја. Овај рад предлаже да се покаже како се одрживо одржавање може постићи фокусирањем ресурса на анализу критичног

проблема и његовог последичног ублажавања, док они настају на нивоу људи, машина/процеса или добављача.

Научно истраживање дизајна (НДР) је итеративна истраживачка методологија, изабрана да интегрише овај рад. Остваривање циља имплементацијом овог новог концепта подскупа убризгавања донело је изузетно корисне резултате, као што су смањење његове потрошње, смањење трошкова набавке и насталог отпада, као и смањење времена интервенције током операција одржавања, као и повећање времена доступности опреме.

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