Universidade do Minho
Escola de Engenharia

Gabriel Fernandes dos Reis

Optimization of Cooling Channels in Plastic Injection Molding Process – Conventional Straight-Drilled Cooling System Vs Conformal Cooling System

Thesis Dissertation

Integrated Masters in Polymer Engineering

Work under supervision of:

Professor Doutor Júlio Cesar Viana

Engenheiro Serafim Oliveira

July 2020

Universidade do Minho, _____/_____/_________

Assinatura:

ACKNOWLEDGEMENTS

First, I would like to express my gratitude towards my supervisors, Professor Júlio Viana from University of Minho and Engineer Serafim Oliveira from COPEFI, for their support, guidance and availability. Without their expertise this work would not have been possible.

COPEFI, where I had the possibility to carry out my work, to all the people who contributed with knowledge and patience towards me. A special thanks to Miguel Gonçalves for the constant help with the project and Adelino Braz for helping me with practical knowledge of molds.

To my family, who supported me during this journey, who stood up with me In the good and bad moments and for the education that have given to me.

A special thank to my brother for being an example of success to me, and for being by my side all the time during this project.

To my girlfriend for standing up with me during all the bad moments, for supporting me, for giving me hope and strength to accomplish my goals.

Finally, to my friends Pedro and João for giving me their true friendship throughout all my life and specially during this hard journey.

ABSTRACT

The optimization of the cooling system of a mold from the company COPEFI was carried out to improve the warpage of the parts. First, an optimization of the process parameters was performed using the mold in production. A comparison between simulated and experimental work was made with the intend to validate the simulation method. Afterwards, a new design, using conventional straight-drilled channels, was performed, and studied utilizing simulation software (Moldex3D). Finally, a new design, using conformal cooling channels, was performed, and evaluated resorting to simulation software.

To improve warpage, the process parameters chosen were: A – Mold Temperature, B – Injection Temperature, C – Injection Speed, D- Holding Pressure Time and E – Cooling Time. Regarding to the design optimization, the parameters chosen were: A – Diameter, B – Distance between cooling channels, C – Distance between cooling channels and the part, D – Mold material and E – Number of circuits. In both cases, Taguchi's orthogonal array was used as the Design of experiments (DOE) tool. An orthogonal array of L_{16} (2^{15}) was performed for all the simulated models and an orthogonal array of L_8 (2^7) was used for the experimental work.

Analysis of Variance was performed to find the contribution of the processing parameters on the improvement of warpage. Globally it was found a strong contribution of cooling time and injection temperature on process parameters optimization. An increase of cooling time seemed to decrease warpage and with a decrease of injection temperature should decrease warpage as well. In the case of conventional optimization, mold material was the factor with more contribution to warpage.

Comparing the three designs, conventional straight-drilled channels design had the best results to improve warpage with an improvement up to 14%.

Keywords: Cooling optimization, Process optimization, Conventional cooling, Conformal cooling, Injection molding process.

Resumo

A otimização do sistema de arrefecimento de um molde da empresa COPEFI foi realizada de forma a melhorar o empeno das peças. Em primeiro lugar foi realizada uma otimização dos parâmetros de processo, utilizando o molde em produção. Procedeu-se à comparação entre o trabalho de simulação e o experimental, com o intuito de validar o método de simulação. Posteriormente, um novo projeto, utilizando canais de arrefecimento convencionais, foi realizado e estudado com recurso ao software de simulação (Moldex3D). Finalmente, um novo projeto, utilizando canais de arrefecimento conformais, foi realizado e estudado, recorrendo ao software de simulação.

Para estudar uma possível melhoria do empeno, os parâmetros de processo escolhidos foram: A – Temperatura do Molde, B – Temperatura de Injeção, C – Velocidade de Injeção, D – Tempo de pós-pressão e E – Tempo de arrefecimento. Em relação Á otimização do design, os parâmetros escolhidos foram: A – Diâmetro, B – Distância entre os canais de arrefecimento, C – Distância entre os canais de arrefecimento e a peça, D – Material do molde e E – Número de circuitos. Em ambos os casos, a matriz ortogonal de Taguchi foi utilizada como ferramenta de design de experiências (DOE). Uma matriz ortogonal de L_{16} (2^{15}) foi realizada para todos os modelos simulados e uma matriz ortogonal de L_8 (2^7) foi utilizada para o trabalho experimental.

A análise de variância foi realizada para encontrar a contribuição dos parâmetros de processo na melhoria do empeno. Globalmente, foi encontrada uma forte contribuição do tempo de arrefecimento e da temperatura de injeção na otimização dos parâmetros de processo. Um aumento no tempo de arrefecimento diminuiu o empeno e com uma diminuição da temperatura de injeção também diminuiu o empeno. No caso da otimização convencional, o material do molde foi o fator que mais contribuiu para o empeno.

Comparando os três designs, o design com canais de arrefecimento convencionais teve os melhores resultados na melhoria do empeno com uma otimização de até 14%.

Palavras – Chave: Otimização do arrefecimento, Otimização do processo, Arrefecimento convencional, Arrefecimento conformal, Processo de moldação por injeção.

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1. INTRODUCTION

1.1 Motivation

Nowadays, Injection Molding (IM) is one of the most used processing technologies for plastics [1]. Like every processing technology, there are defects on the part due to the viscoelastic behavior of the polymer material. In the automotive industry, one of the most common defects is warpage [2]. This happens due to the complex geometries that are required to assure technical tasks during its usage. For this reason, there are many ways to overcome this problem such as optimization of the process parameters and optimization of cooling channels [2][3].

COPEFI, a company specialized in injection molding for automotive industry, faced some problems with the production of parts for Renault. The main problem within the part used in this study was the warpage in some points, which are critical in the assembly phase. The complex geometry of the part did not allow its efficient cooling inside the mold, due to the complexity of the extraction system.

Here, a DOE method was applied along with analysis of variance (ANOVA), to predict which parameters or technologies are more suitable to minimize warpage. Finally, an optimization of both the process parameters and the cooling system of the mold propose was proposed to avoid the parts' warpage.

1.2 Objectives

The main objectives of this dissertation were the following:

i. To study a mold from COPEFI, in order to improve the parts' warpage;
ii. To optimize process parameter and compare the results of computer-Aided Engineering (CAE) simulations with experimental results;
iii. To design a new configuration of conventional cooling system to apply in the mold using DOE method applied with ANOVA model;

iv. To design a new configuration of conformal cooling system in the mold performing DOE method applied with ANOVA model;

v. To analyze both design in Moldex3D;

vi. To compare the optimization of conventional cooling system and conformal cooling system;

1.3 Introduction to the Company

COPEFI is a company which produces components for the automotive industry. It has factories in Portugal, Mexico, Romania and France, and it is divided into COPEFI Automotive Components and COPEFI Engineering & Services. COPEFI has over 250 employees and its main factory is situated in Gualtar, Braga (Figure 1.1). Its main customers are TIER1 companies, classifying COPEFI as a TIER2 company in the market of the automotive industry. COPEFI's growth has been constant and systematic throughout the years. Due to its strategic location, this company serves the automotive industry quickly and with quality, and these attributes are highly valued by the clients.

COPEFI has quality standards in all factories according to the standards of automotive industry, such as, environmental Management system in accordance to the ISO 14001:2004 Standard, production and assembly of plastic injection components for passenger cars, commercial vehicles, heavy trucks and buses according to ISO/TS 16949:2009 Standard. These quality certificates allow COPEFI to deliver confidence and stability to their customers, searching the best results and sustainable economic models to improve the company's quality [4].

Figure 1.1 - Front view of COPEFI's plant in Braga, Portugal [4].

1.4 Organization of this dissertation

This document was divided into seven chapters to ease the reading and searching of contents.

In Chapter 1, a brief explanation on the motivation and goals for the dissertation was done.

In Chapter 2, the state of art was presented. In this section it all the theoretical content behind the completion of this dissertation was scrutinized.

In Chapter 3, the case study performed in this dissertation was presented.

In Chapter 4, the experimental work for this dissertation was demonstrated. It was subdivided in Process Parameters Optimization – Simulation, Process Parameters Optimization – Experimental, Conventional Straight – Drilled Optimization and Conformal Design Optimization.

In Chapter 5, all the results from previous methods were presented. It was made some discussion over the analyzes performed.

In Chapter 6, the comparison between Optimizations to assess which one was the best to improve warpage was discussed.

In chapter 7, the main objectives of this dissertation were concluded. Some correlations were made to summarize all the conclusion of this dissertation. It was also discussed the future work to do after the results obtained from this study.

2. State of the Art

2.1 Introduction

In 1868 a billiard company launched a challenge to replace ivory balls by another material. John Wesley Hyatt won the contest with injected billiard balls made of celluloid which allowed him to patent the first injection molding machine in 1872 (Figure 2.1). This machine was totally manual and had the assistance of levers. In the following years, many materials were introduced in the market and the interest in injection molding increased. However, only in the 1930s, hydraulically operated machines were introduced. The biggest development in injection molding occurred during the World War II. The German demanding for cheap, mass-produced products resulted in the discovery of new materials and in an exponential growth of injection molding industry. In the 1950s the machines were developed based on the properties of polymer melts leading to a substantial industrial improvement. The basic function of injection machines stood almost intact since then and significant advances were accomplished at the level of the control systems [5].

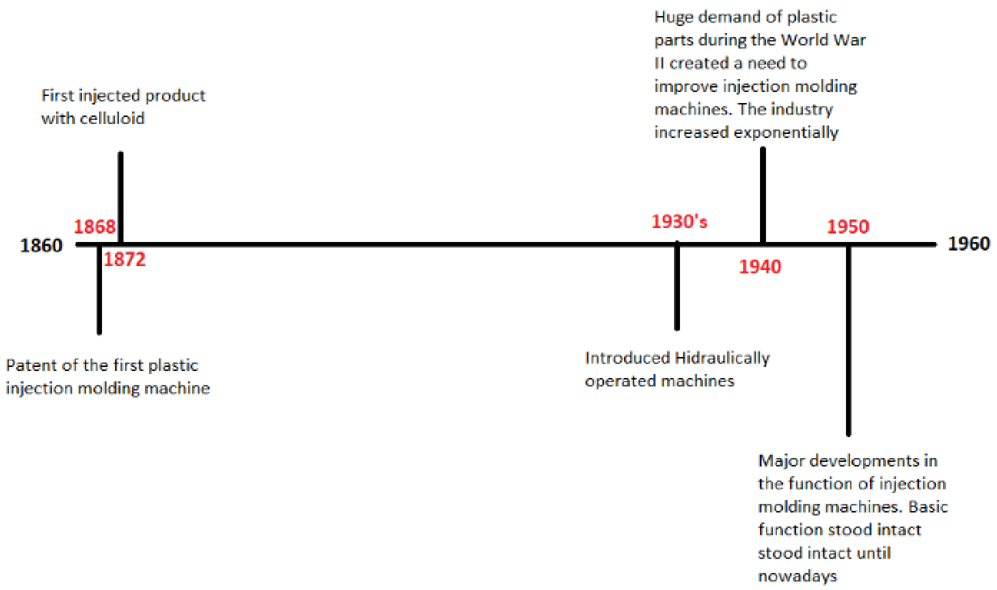


Figure 2.1 - Timeline of the Injection molding industry.

2.2 Injection Molding

In the plastic industry, there are many processing techniques (e.g. Extrusion, injection molding, rotational, thermoforming, microinjection) [6][7]. Injection molding is one of the most used in the industry and consists of melting granules or powder of a thermoplastic by heating. The molten material is then forced with a screw into a mold, which will give form to the part. When the part is cooled, the mold opens and begins its extraction. After this process, the cycle repeats. The main advantages of this process include: (i) versatility in molding a wide range of parts, (ii) ease to produce complex geometries, (iii) capability of doing large productions, and (iv) ability to automatize the complete process. The wide range of materials that can be used in injection molding allows the process to produce parts for many applications [7].

An injection molding machine is composed by four main units (Figure 2.2):

i. Power unit: Responsible for providing power to the machine;
ii. Command unit: Interface between the machine and the operator. All the commands to work with the machine are available in this unit;
iii. Clamping unit: Allows the fixation and movement of the mold. Is responsible for withstand ding the pressure, keep the mold closed during injection phase and the extraction of the part;
iv. Injection unit: Responsible for the transportation, heating and homogenization of the polymer from the base of the feeder to the injection nozzle;

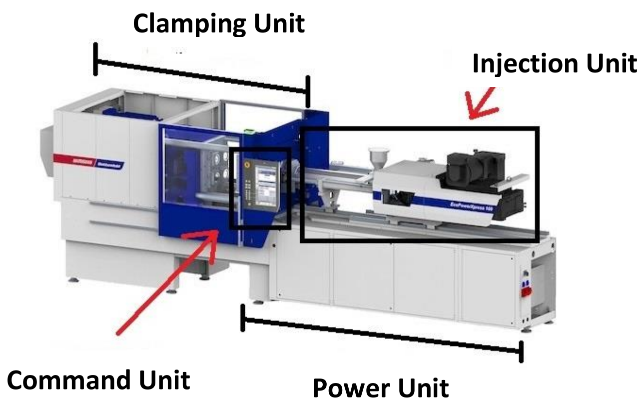


Figure 2.2 - Units incorporated in an injection molding machine. (Battenfeld EcoPower Xpress 160)

2.2.1 Injection Molding Process

The injection molding process is an extremely complex way of processing plastic involving several steps (Figure 2.3) [8]:

i. Closing - The mold closes to begin the cycle.
ii. Injection - The screw moves forward to transport the material inside the cavity through the nozzle;
iii. Pressurization - The screw maintains its position to apply pressure against the material, which is inside the mold, to prevent possible defects of the part (e.g. warpage or shrinkage);
iv. Plasticizing – The screw moves back, rotating, to pull material from the chamber behind. This phase is important because the distance that the screw will travel, and the speed of rotation, will define the volume which will be injected inside the mold;
v. Cooling – As the melt touches the walls of the mold, it begins to cool through conduction of heat. When the part is at a relatively low temperature (varies from the material), this phase ends;
vi. Opening and ejection – When the part is at enough temperature to be extracted, the mold opens and begins the extraction of the part;
vii. Pause – It's the time between the extraction and the beginning of the next cycle;

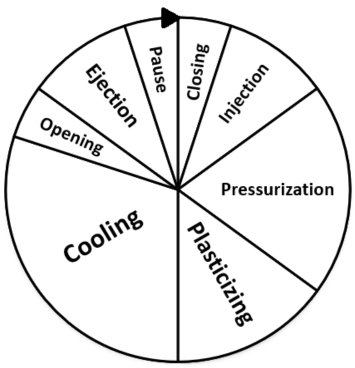


Figure 2.3 - Representation of the cyclic process starting in the closing phase.

2.2.2 Injection Molding defects

The major concern in injection molding is to produce parts without defects. The quality of the parts can be described by their mechanical characteristics, dimensional conformity, and appearance. Common defects are, for instance, flash, flow lines, sink marks, vacuum voids, weld lines, short shot, warpage, shrinkage, burn marks or jetting [9][10]. The quality is affected by many factors like processing parameters, mold dimensioning, the right choice of the machine, among others. Regarding warpage and shrinkage, one important factor is the cooling phase. Optimizing the dimensioning of cooling channels from the mold must prevent defects in the parts [10].

2.2.3 Cooling System Dimensioning

During the injection molding process, the temperature in the different components of the mold oscillate due to the cyclic behavior of the process. Thus, the modeling of the cooling system must be simplified due to the complexity of the process. So, it is accepted to make some simplifications in the calculations that doesn't affect the results of cooling system dimensioning: (i) Process almost static; (ii) Fluctuations in temperatures and thermal flows during cycles are despicable; (iii) It's considered the average values of the properties during the mentioned periods;

For the mold thermal balance, it is considered as positive the heat received by the system and negative the heat given by the system. In Figure 2.4 is shown the heat transfer processes that occur in the mold [11].

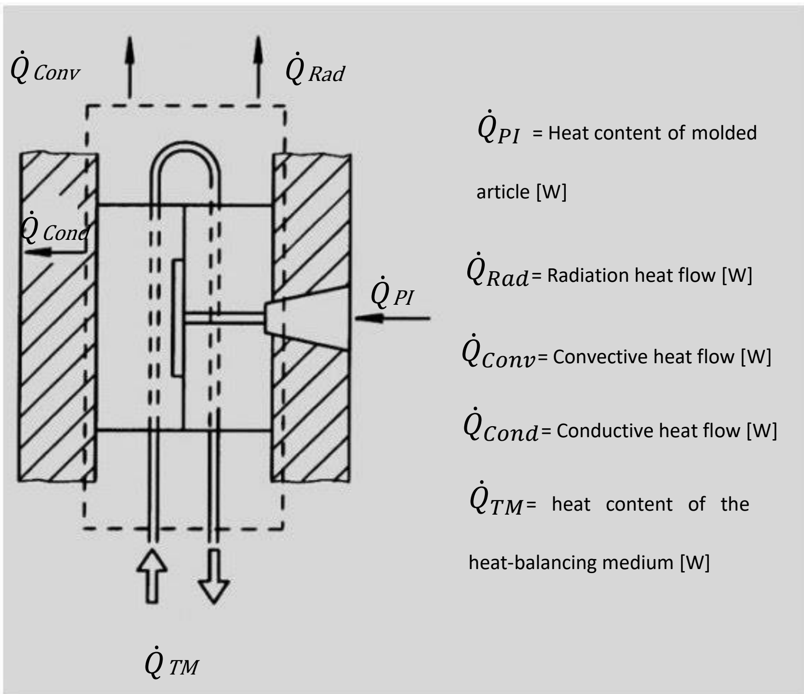


Figure 2.4 - Heat transfer processes in the mold during the injection molding process. Adapted from [12].

The cycle time can be obtained through equation (1):

$$tc = \frac{S^2 \ln(k.Y)}{\pi^2 \alpha_{ef}} \tag{1}$$

S – Wall thickness

α_{ef} – Thermal diffusivity

k – part thickness coefficient

Y – Adimensional temperature

The thermal balance of the mold can be expressed by the equation *(2)*:

$$\sum_i \dot{Q}_i = \dot{Q}_{TM} + \dot{Q}_{PI} + \dot{Q}_{Env} = 0 \tag{2}$$

Q_{TM} – Heat content of the heat-balancing medium

Q_{PI} – Heat content of molded article

Q_{Env} – Heat transferred to to the environment

Where:

$$\dot{Q}_{Env} = \dot{Q}_{Cond} + \dot{Q}_{Conv} + \dot{Q}_{Rad} \tag{3}$$

Q_{Cond} – Conductive heat flow

Q_{Conv} – Convective heat flow

Q_{Rad} – Radiation heat flow

The heat flow given by the molten plastic, when the cavity is filled with material, is given by the equation *(4)*:

$$\dot{Q}_{PI} = \frac{m * (h_{inj} - h_{ext})}{t_c} \tag{4}$$

m – injected material weight

h_{inj}(h_{ext}) – specific enthalpy of the injected material at injection temperature and extraction temperature.

Tc – Cooling time

The transmission of heat to the environment occurs through three natural processes: conduction, convection and radiation.

- Conduction – the heat flow by conduction occurs through the fixation plates of the mold and given by the equation *(5)*:

$$\dot{Q}_{Cond} = A_{fix} * \beta * (T_{Env} - T_{mold}) \tag{5}$$

A_{fix} – Mold area

β – proportionality factor

- Convection – The heat flow by convection occurs through the lateral area of the mold and is given by the equation *(6)*:

$$\dot{Q}_{Conv} = A_{lat} * \alpha * (T_{Env} - T_{mold}) \tag{6}$$

A_{lat} – Exposed area of the mold

T_{Env} and T_{mold} – Environment and mold temperature.

- Radiation – The heat flow by radiation is given by the equation *(7)*:

$$\dot{Q}_{Rad} = A_{lat} * \varepsilon * C_{Rad} * \left(\left(\frac{\theta_{Env}}{100}\right)^4 - \left(\frac{\theta_{Mold}}{100}\right)^4\right) \tag{7}$$

Assuming that the heat flow given by the molten plastic and the heat exchanges with environment are calculated by equations *(4)* and *(3)* respectively then the quantity of heat that must be removed with the cooling fluid is given by the equation *(8)*.

$$\dot{Q}_{TM} = -\dot{Q}_{PI} - \dot{Q}_{Env} \qquad (8)$$

With this value it is possible to estimate the minimum flow of cooling fluid. It is given by the equation *(9)*.

$$\dot{m} = \frac{|\dot{Q}_{TM}|}{C * \Delta T} \qquad (9)$$

Calculating the flow of cooling fluid, it is possible to determine the recommended cooling channels diameter (Table 2-1).

Table 2-1 - General rules for dimensioning the diameter of the cooling channels.

Flow (l/min)	Diameter (mm)
3,8	8
9,5	11
38	19
85	23,8

To make the heat transfer even more efficient and ensure the quality of the parts, the flow must be turbulent, and this regime happens when the Reynolds number is equal, or higher, than 3500. On the other hand, the cooling channels length is another, extremely important, parameter in cooling system dimensioning. Thus, through the equation *(10)* it is possible to calculate the minimum value of cooling channels length to assure the transmission of the pretended heat. [10]

$$L = \frac{2 * |\dot{Q}_{TM}| * e}{k * \pi * d * \Delta T} \tag{10}$$

e – distance between channels and the part

k – mold thermal conductivity

d – Channels diameter

ΔT – Temperature difference between cavity wall and water channels

In order to dimension the position of the cooling channels inside the mold, there are some relations between the design parameter of the cooling channels (Figure 2.5).

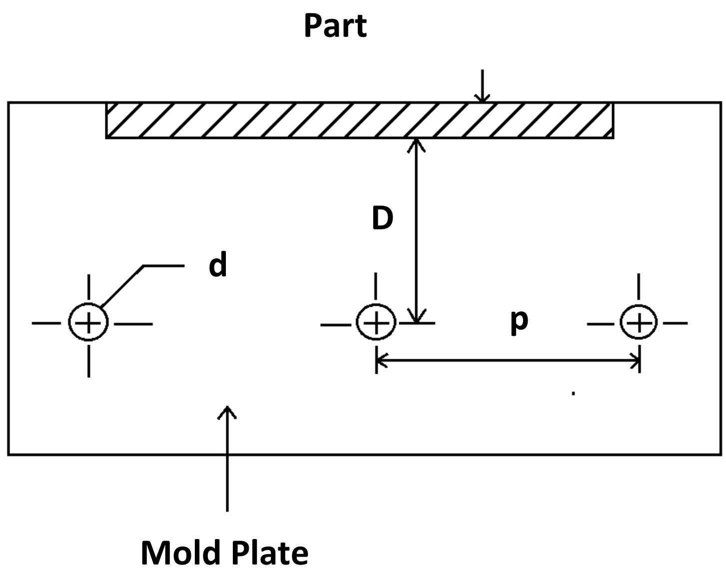


Figure 2.5 - Positioning variables of the cooling channels inside the mold. d = Cooling channels diameter; D = Distance between channels and the part – 2,5 to 3,5 d; P = Distance between channels – 0,8 to 1,5 p; Adapted from [11]

2.2.4 Conventional Straight-Drilled Cooling Channels

There are some general rules to design cooling channels using conventional Straight-Drilled technique such as [11]:

i. Consider symmetrical independent circuits regarding to the filling zone of the mold and try to follow, the best possible, the form of the part;
ii. The path of the fluid inside the mold cannot be too long, causing the fluid to increase its temperature more than 5ºC. It's better to have various independent circuits rather than one long circuit;
iii. OUT and IN of the circuit must be at the opposite side of the operator or, in some occasions, in the bottom of the mold;
iv. All the parts involved in the cooling channels like O-rings, quick couplings, blades, and more must be normalized;

2.2.5 Conformal Cooling Channels

The distance from the core surface to the cooling channel is an important factor affecting the cooling characteristics of the molding tool. Conformal cooling channels can guarantee a uniform distance from the surface of the core to the cooling channel (Figure 2.6).

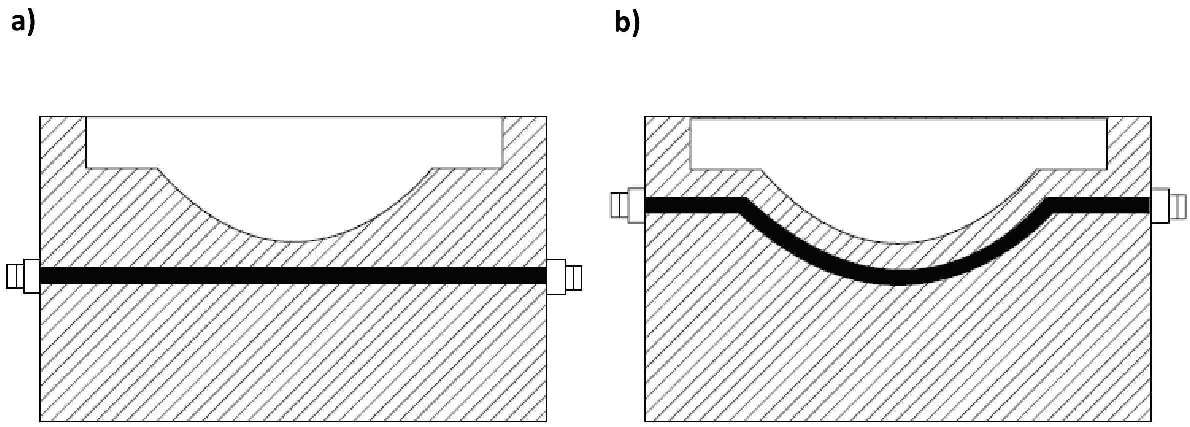


Figure 2.6 - Representation of two different cooling systems used in injection molding process. a) Conventional straight-drilled cooling channels. b) Conformal Cooling Channels.

Conformal cooling channels are manufactured by additive manufacturing (AM) method while the conventional straight-drilled cooling channels manufacturing is subtractive. There are seven different types of processes to manufacture products using AM. Products can be created by vat photopolymerization, material extrusion, material jetting, binder jetting, powder bed fusion, direct energy deposition and sheet lamination [13].

2.3 CAD/CAE Software

For the Computer Aided Design (CAD) modeling was used the software Solidworks. This software was used to design all the different configurations for further analyses.

For Computer Aided Engineering (CAE) analysis was used the software Moldex3D. This software is used as a platform for simulating the process of injection molding, including the simulation of filling and cooling processes, warpage and shrinkage predictions, so that engineers can change the unreasonable design of the part or mold. Based on the given data the process and design can be optimized (Figure 2.7)[14].

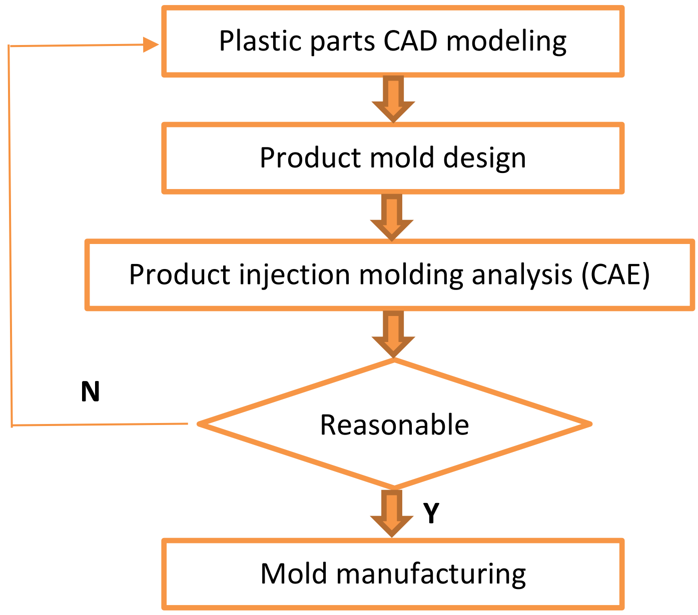


Figure 2.7 - Flow chat of mold manufacturing in injection molding industry. Adapted from [14].

2.4 Design of Experiments Taguchi's Method and Analysis of Variance

2.4.1 Design of Experiments Taguchi's Method

The Taguchi method of experimental design is a statistical tool based on several experiments using orthogonal arrays. In DOE we need to set the level for each input regarding the experiment. There are four distinct categories in a process (Figure 2.8):

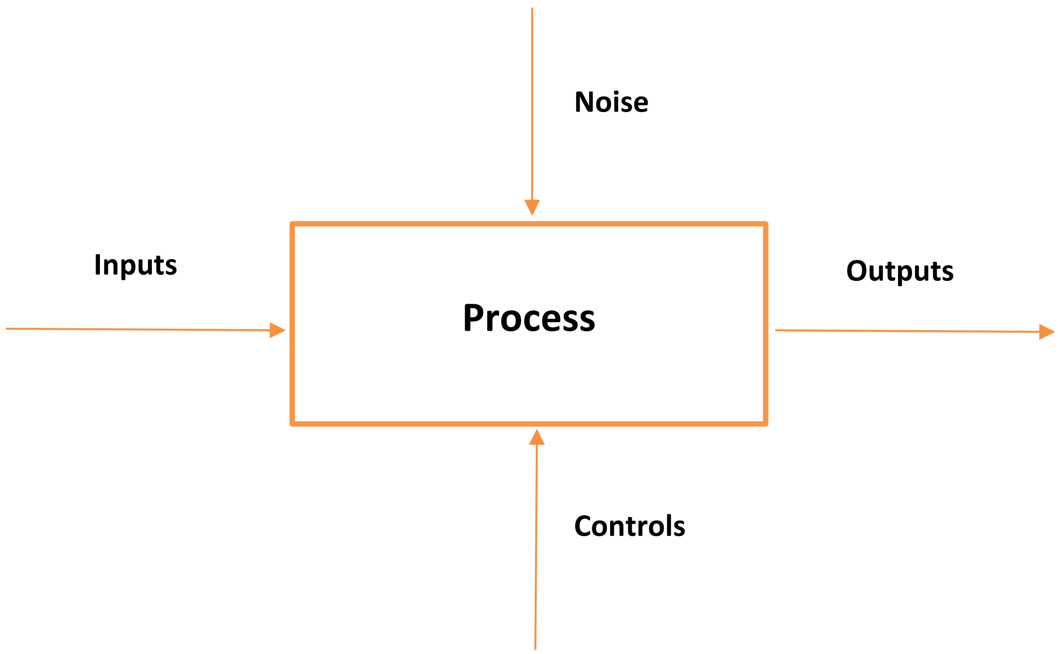


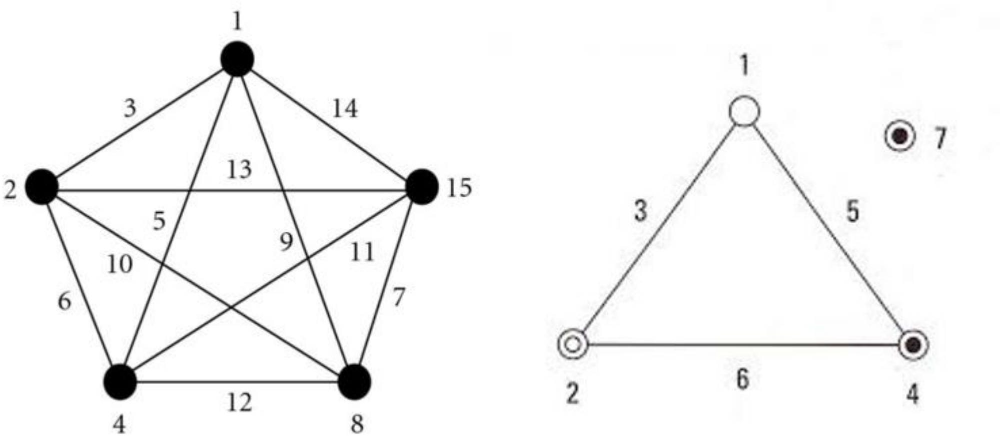
Figure 2.8 - Categories of a Design of Experiments. Inputs – Variables that will be varied during the experiment; Outputs – Response/result of the parameters from the experiment; Controls – Devices that will control the variables/parameters from the process; Noise – Parameters that cannot be controlled;

The injection molding process is affected by a wide range of variables being almost impossible to investigate them all. So, design of experiments (DOE) is a good tool to reduce the number of experiments. Regarding the experiment, the variables (factors), and its levels, that must be studied have to be defined. Using orthogonal arrays to plan the experiments is an efficient method to study the effect of several factors simultaneously (Table 2-2) [15].

Table 2-2 - Diferences between conventional Design of experiments and Taguchi's Orthogonal Array.

Orthogonal Arrays (OA)	Number of factors	Levels of factors	Number of experiments for OA	Number of experiments for full factorial design
L4 (2^3)	3	2	4	8
L8(2^7)	7	2	8	128
L9(3^4)	4	3	9	81
L12(2^{11})	11	2	12	2048
L16(2^{15})	15	2	16	32768
L16(4^5)	5	4	16	1024
L18(2^1 x 3^7)	1	2	18	4374
	7	3		

In the orthogonal Array method, there are some interactions between factors to fill the array (Figure 2.9).



a) **b)**

Figure 2.9 - Linear graphs for othogonal arrays. a) L16 b) L8. [16]

2.4.2 Analysis of Variance (ANOVA)

ANOVA is a statistical method that analyses an extensive variety of experimental designs. It is based in F – Snedecor distribution which subdivides the total variation of a specific data set into components associated to specific sources of variation, with the intend to test a hypothesis (null hypothesis testing) in the model factors. The hypothesis used are:

- The result of mean values using different levels of variation is equal;
- The result of mean values using different levels of variation is different;

If the null hypothesis could not be rejected, then the factors being studied had no influence in the response. If the null hypothesis could be rejected, then the factors being studied had an influence in the response [17].

2.5 Polypropylene

Polypropylene (PP) is one of the most used thermoplastic polymers worldwide due to a good combination of factors, such as, low cost, high stiffness, high thermal resistance, low density, easy to produce and moderate recycling cost. PP compounds are mixtures of PP Homopolymer with a copolymer (e.g. ethylene) adding up additives and fibers to improve the compound as the function of the part demand. PP (Homopolymer and compound) has been widely used in automotive industry (Figure 2.10). Considering the perks of PP, this material has a huge demand in technical and functional parts in automotive industry (e.g. instrumental panels and door trims) [18].

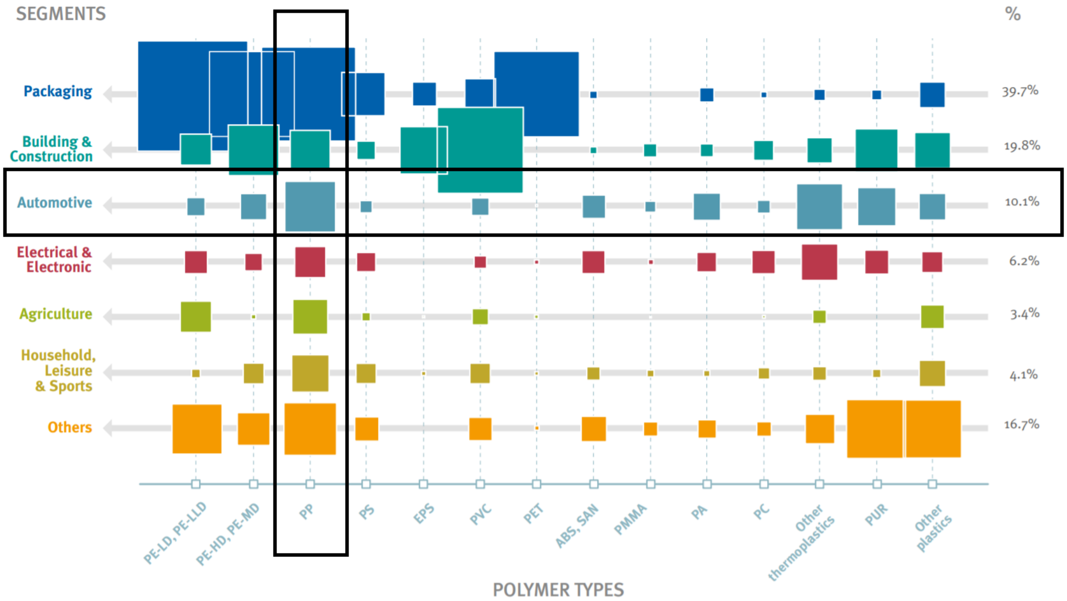


Figure 2.10 - Consumption of PP material in automotive industry worldwide. Adapted from [29].

Hostacom TRC 411N is a 15% talc filled PP copolymer compound with high flowability, good impact/stiffness balance and excellent scratch resistance. It is commercialized by LyondellBasell.

It is a good material for visible and functional parts, being used quiet often in automotive industry. It can be bought in different colors or natural [19].

3. Case Study

In this project we proposed to optimize the cooling channels of a mold from COPEFI, to prevent further complications in other projects within the company. We chose the mold that produces a part called *"Cache Retro",* for Renault in a combination of 2+2, left- and right-hand reference (Figure 3.1). It belongs to the interior of the car, more specifically the mirror trim (Figure 3.2)

Cache retro is produced out of Hostacom TRC 411N because, being a visible component in the car, it must be scratch and impact resistant.

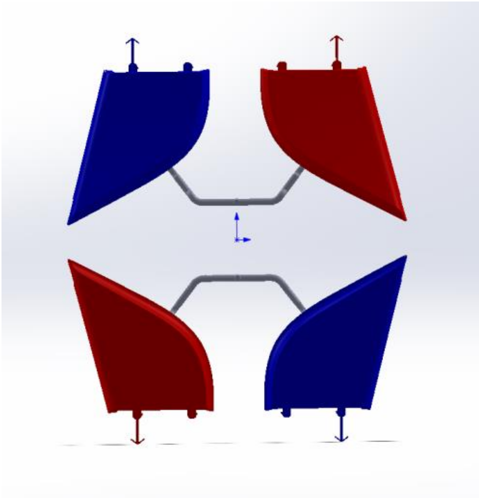


Figure 3.1 - Parts configurations in the mold. Red - Left part; Blue - Right part.

Figure 3.2 - Mirror Trim in a Renault Mégane.

The mold that was chosen for this case study was produced by Automoldes being a mold of two plates. The machine that operates the mold is a Tederic 1300 with 450t of closing force. The dimensions of the cavity plate and the core plate are shown in Figure 3.3 and Figure 3.4 respectively. In Figure 3.5 is shown the 3D of the mold.

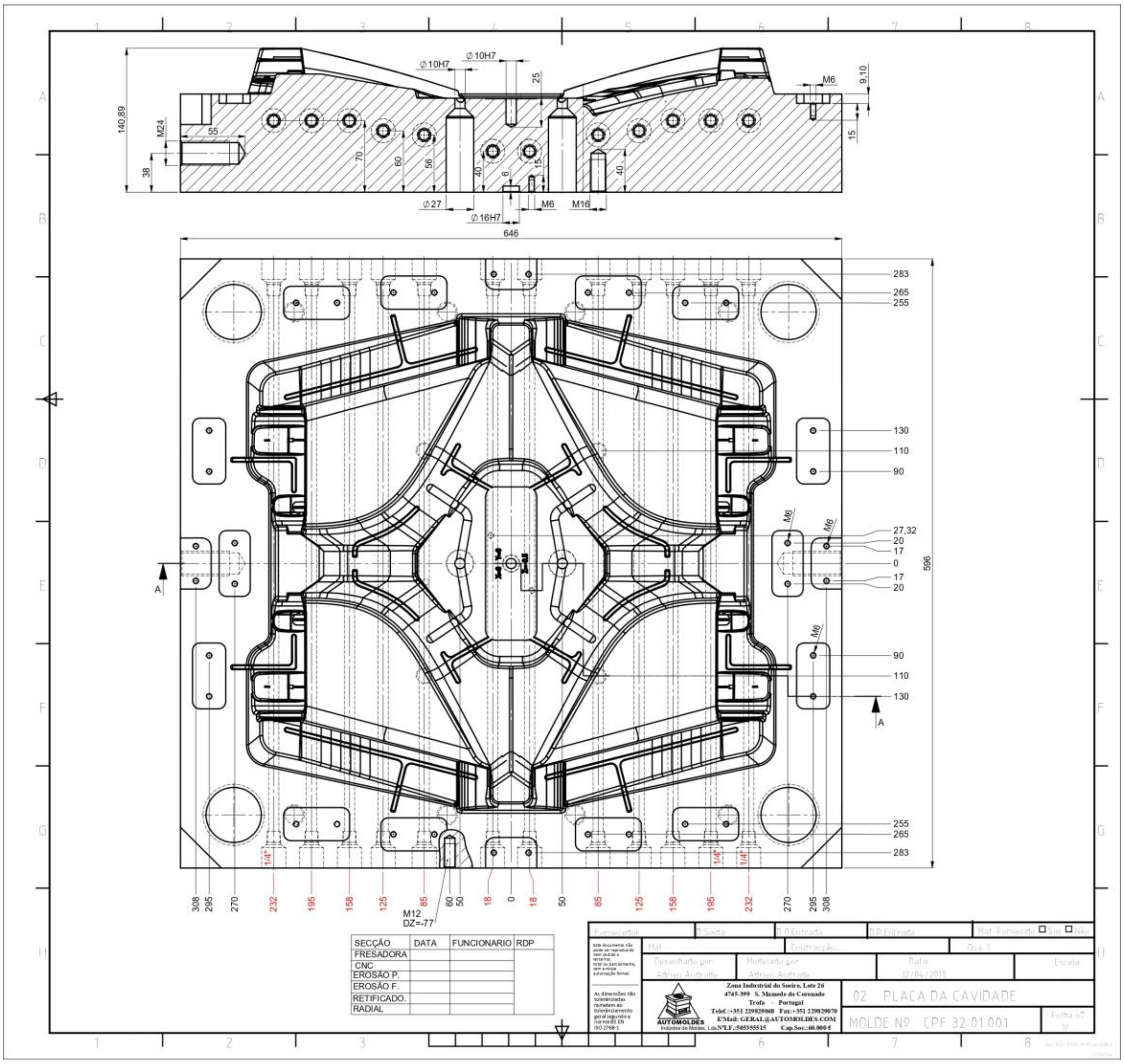


Figure 3.3 - Mold 2D

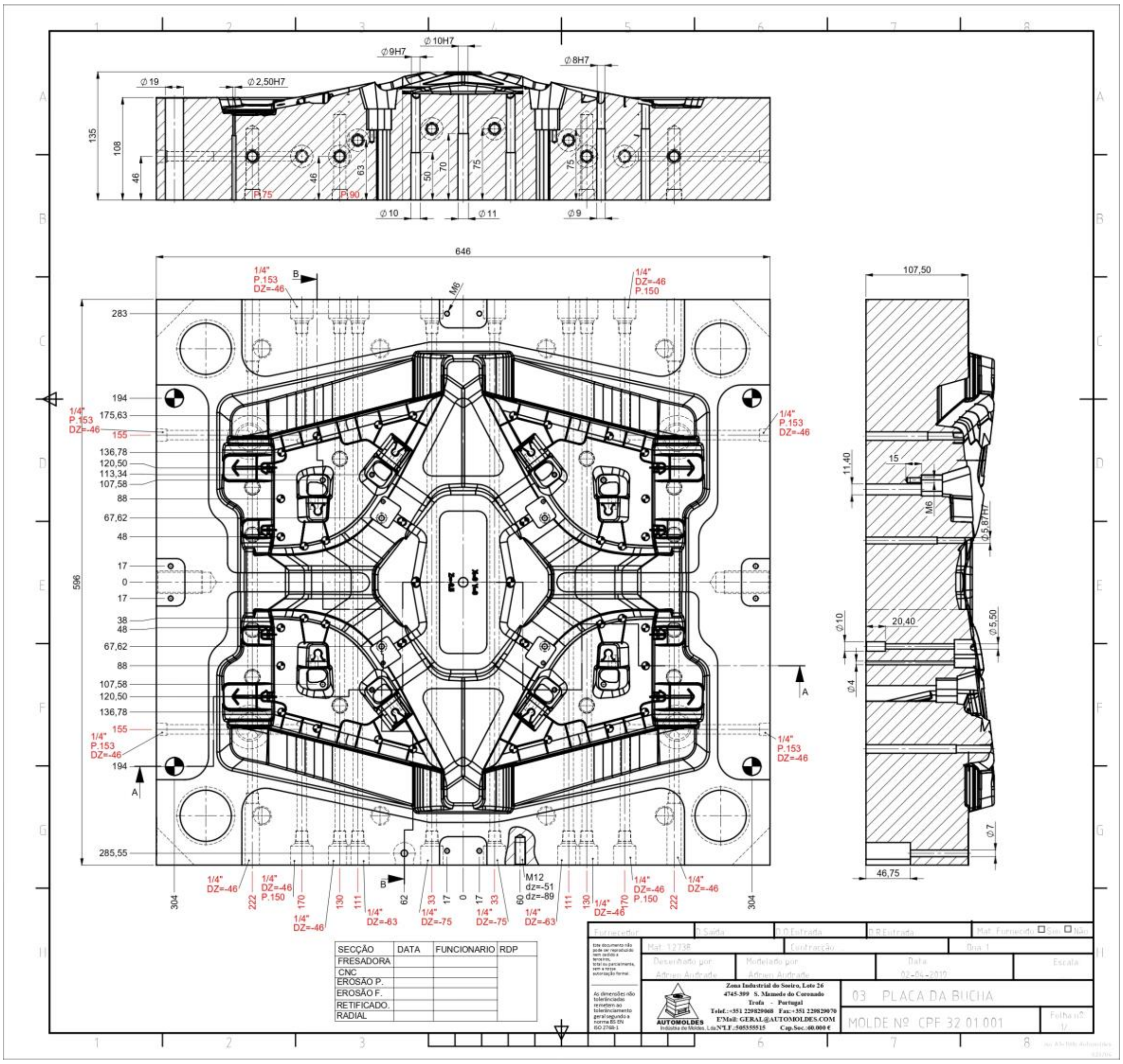


Figure 3.4 - Mold 2D

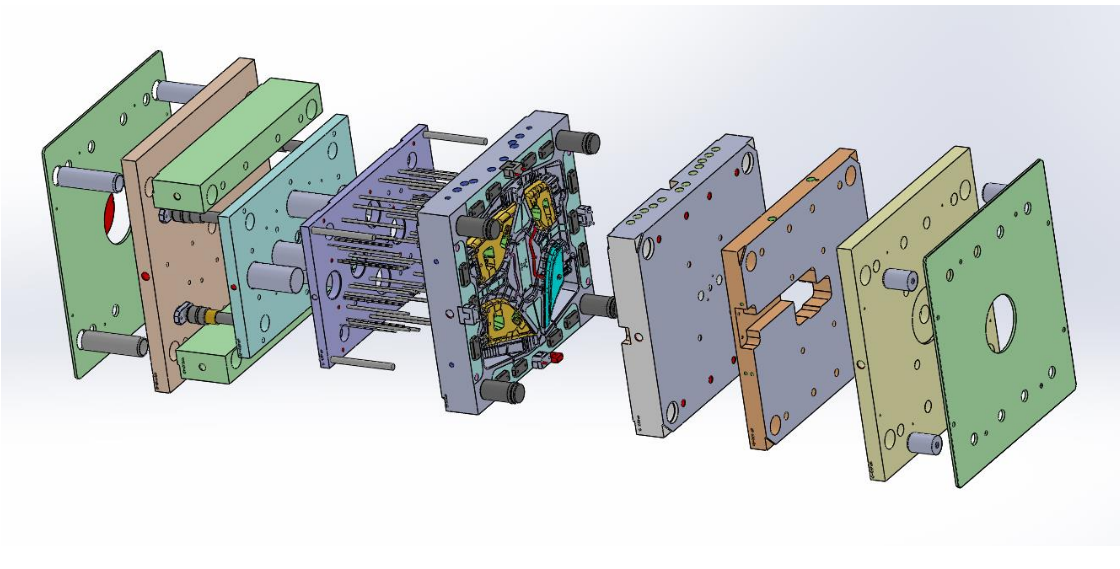


Figure 3.5 – Exploded view of the mold.

The mold had a hybrid feeding system using both cold runners and hot runners. It had two nozzles connecting two sprues that feeds two parts each one through a submarine gate (Figure 3.6).

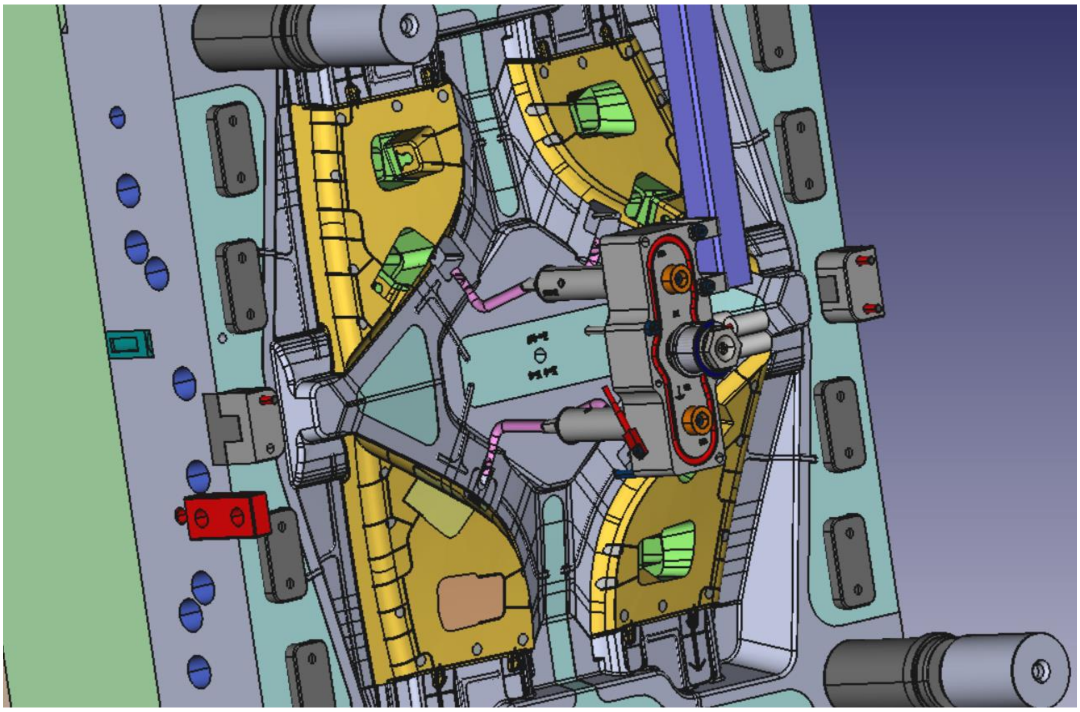


Figure 3.6 - Mold opened in the moving side.

The cooling system of this mold was composed by the core and cavity side of the mold. In both, the diameter of the cooling channels was 10 mm and the fluid was water at 40ºC. There is only one circuit for all the system, using hoses to connect all the cooling channels.

In the core side, due to the ejection system, there are few cooling channels and with non-uniform distances between them. To minimize this problem, some blades were added to improve the cooling of the parts (Figure 3.7) and (Figure 3.8).

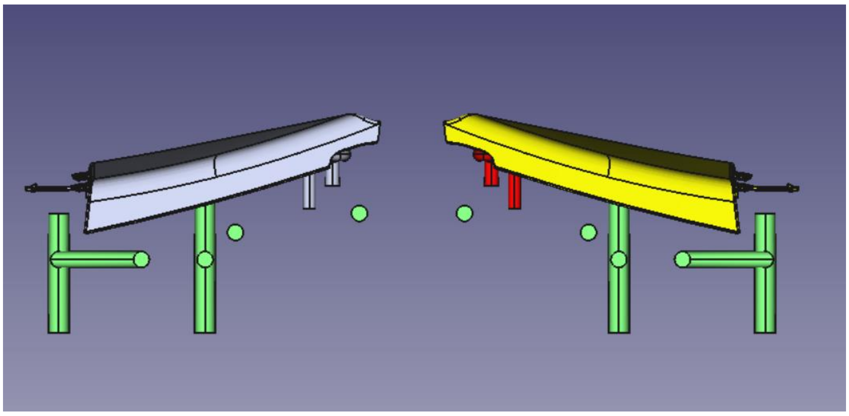


Figure 3.7 - Cooling channels in the core side of the mold. Green color represents the cooling channels, grey and yellow represents the part and red represents the feeding system.

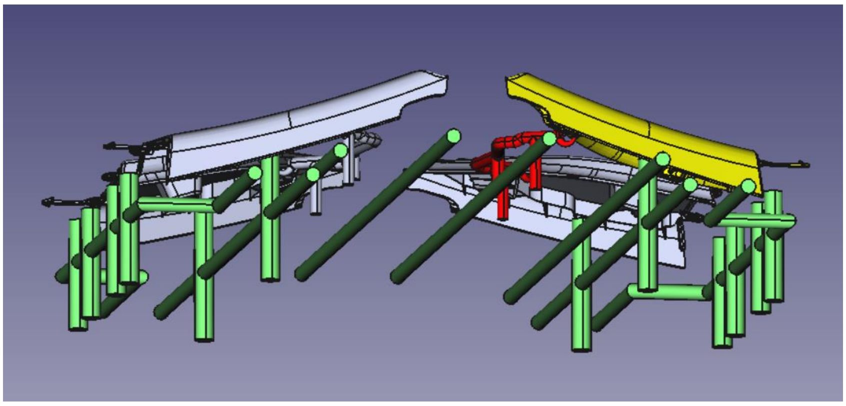


Figure 3.8 - Perspective view of the core side of the mold.

In the cavity side, there was no extraction system. Thus, there was free space to make the cooling channels at uniform distance. As mentioned above, there was only one circuit in the mold, thus the cavity side cooling system was connected with the core side cooling system. This connection was guaranteed with hoses (Figure 3.9) and (Figure 3.10).

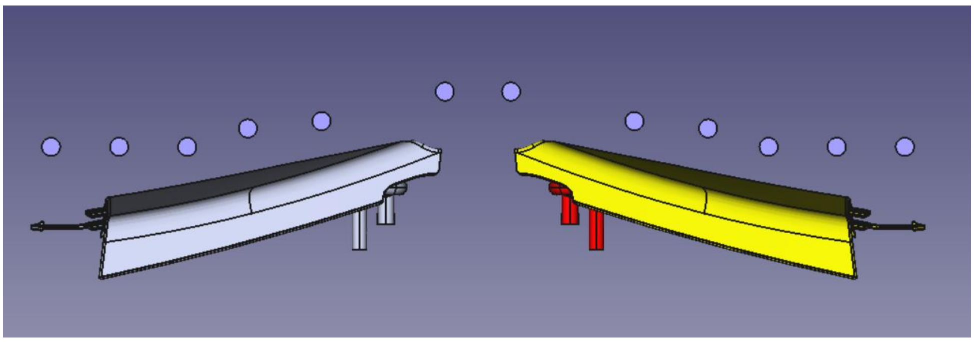


Figure 3.9 - Cavity side of the mold. Blue circles represent the cooling channels, yellow and grey represents the parts and red represents the feeding system.

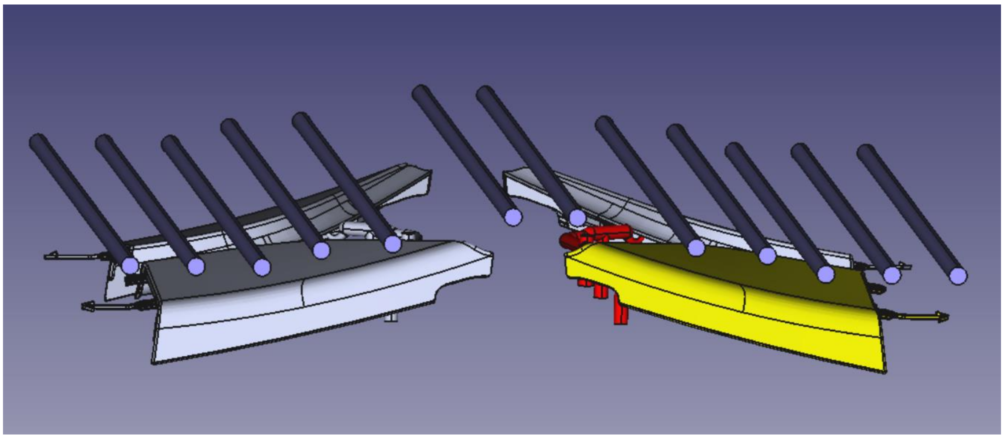


Figure 3.10 - Perspective view of the cavity side.

The mold has one extraction system in the moving side counting 15 extractor pins and two lifter systems for each part (Figure 3.11).

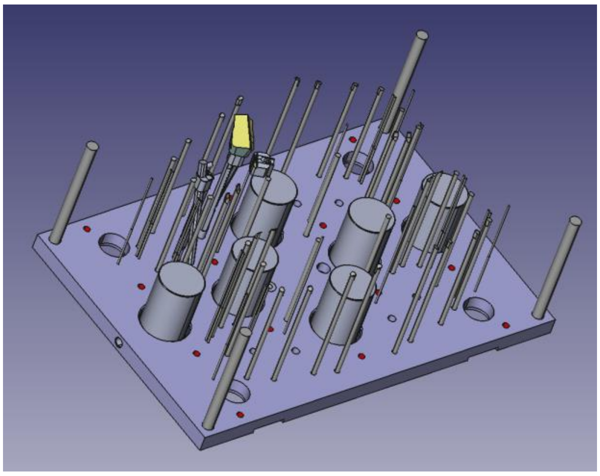


Figure 3.11 - 3D of the extraction system.

4. EXPERIMENTAL WORK

As the mold was already in production, it would be extremely difficult to optimize the cooling phase through dimensional parameters without spending huge amounts of money. Therefore, in this first phase, the optimization was made through process parameters using simulation. To choose the right process parameters, regarding the cooling phase, an Ishikawa Diagram was made being the output warpage as the main defect to be studied (Figure 4.1).

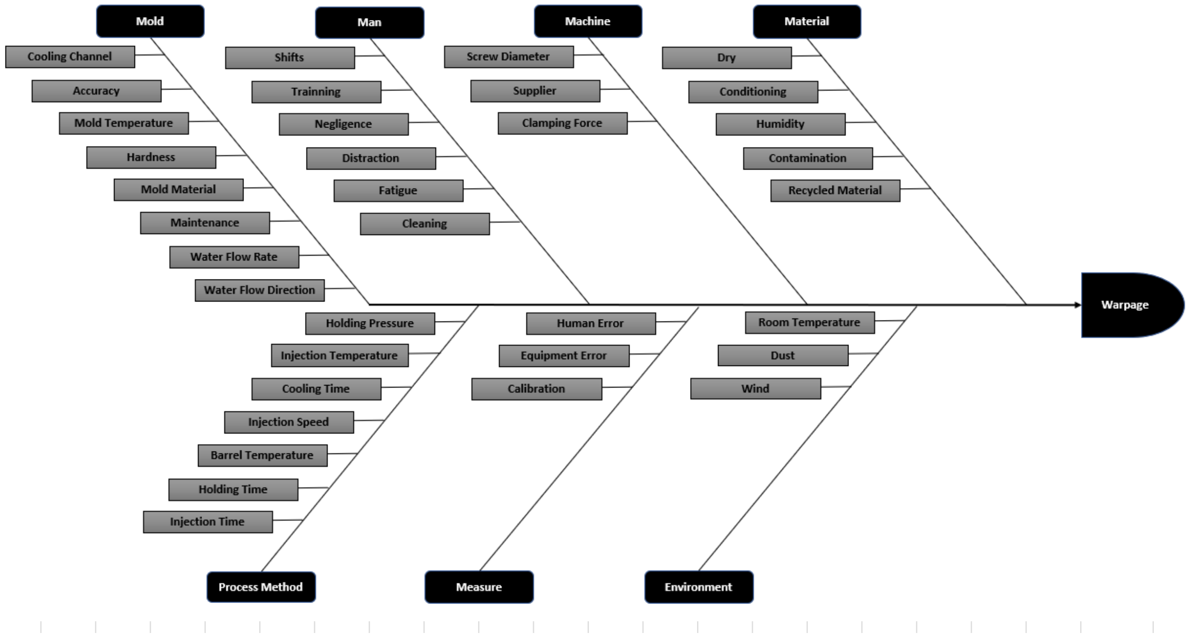


Figure 4.1 - Ishikawa diagram with Warpage as the output.

According to the Ishikawa diagram, the process parameters that have a connection with the cooling phase and have influence in warpage are Holding Time, Injection Speed, Cooling Time, Injection Time, Holding Pressure and Barrel Temperature. In this phase, the following parameters were studied: Mold Temperature, Injection Temperature, cooling time, Holding Pressure Time and Injection Speed. Note that Mold Temperature is added to the study due to its importance for the cooling phase.

4.1 Process Parameters Optimization - Simulation

To choose the values of the parameters to study, the datasheet of the material was used, and some calculations were made. Cooling Time was calculated using equation *(2)* and the value was equal to 2,05s. According to the Holding Pressure Time value, cooling time must be equal or higher. For this reason, and due to the influence of cooling time towards warpage, Cooling time was changed for a range between 6 – 12 s (Table 4-1).

Table 4-1 - Parameters from the Hostacom TRC 411N material Datasheet.

Parameters	**Values**
Mold Temperature	20 – 50 ºC
Injection Temperature	230 – 270 ºC
Injection Time	0,5 – 1 s
Holding Pressure Time	5 – 6 s
Cooling Time	6 – 12 s

4.1.1 Design of Experiments – Orthogonal Array Taguchi Method

Taguchi method uses an Orthogonal Array to create the experiment. For this experiment, a 2^{15} orthogonal array was chosen using five parameters as inputs and 10 relations between them (Figure 4.2).

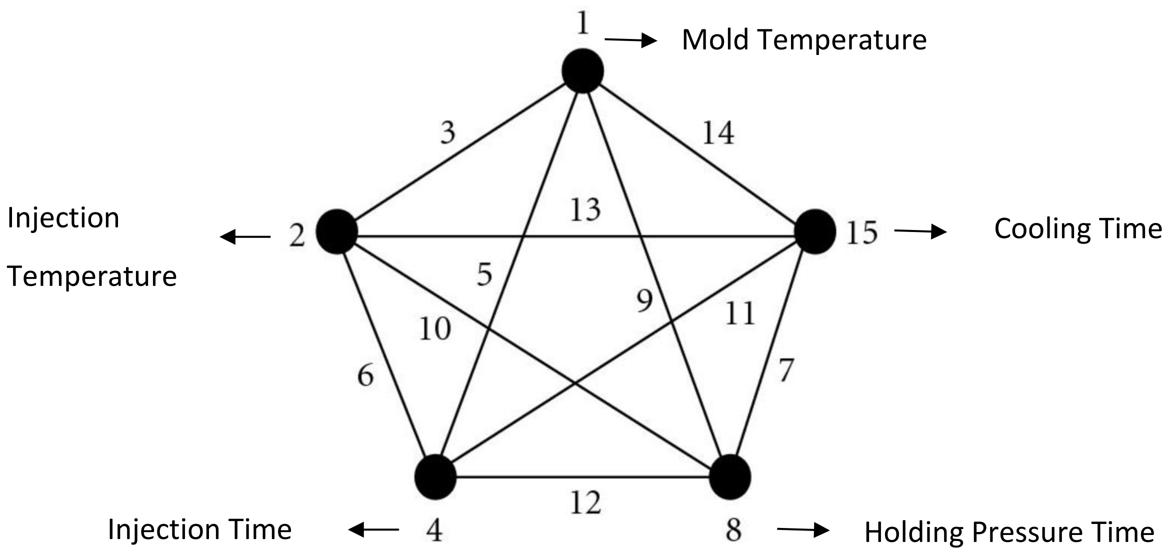


Figure 4.2 - Representation of the parameters in the orthogonal array linear graph L16.

Table 4-2 - Parameters and interactions based on the Orthogonal linear graph L16 from figure 4.2.

Number	Letter	Parameter
1	A	Mold Temperature
2	B	Injection Temperature
3	AB	Mold Temperature x Injection Temperature
4	C	Injection Time
5	AC	Mold Temperature x Injection Time
6	BC	Injection Temperature x Injection Time
7	DE	Holding Pressure Time x Cooling Time
8	D	Holding Pressure Time
9	AD	Mold Temperature x Holding Pressure Time
10	BD	Injection Temperature x Holding Pressure Time
11	AD	Mold Temperature x Holding Pressure Time
12	CD	Injection Time x Holding Pressure Time
13	BE	Injection Temperature x Cooling Time
14	AE	Mold Temperature x Cooling Time
15	E	Cooling Time

Finally, the orthogonal array was performed regarding the previous parameters (Table 4-3).

Table 4-3 -Taguchi's Orthogonal Array based on the values from table 4.1 and table 4.2.

Run	Mold Temperature	Injection Temperature	Injection Speed	Holding Pressure	Cooling Time
1	20.00	270.00	0.50	5.00	12.00
2	20.00	270.00	0.50	6.00	6.00
3	50.00	270.00	1.00	5.00	12.00
4	20.00	270.00	1.00	6.00	12.00
5	20.00	230.00	1.00	6.00	6.00
6	50.00	230.00	0.50	5.00	12.00
7	50.00	230.00	1.00	6.00	12.00

8	20.00	230.00	0.50	6.00	12.00
9	50.00	230.00	1.00	5.00	6.00
10	50.00	230.00	0.50	6.00	6.00
11	50.00	270.00	0.50	5.00	6.00
12	50.00	270.00	1.00	6.00	6.00
13	50.00	270.00	0.50	6.00	12.00
14	20.00	230.00	0.50	5.00	6.00
15	20.00.	230.00	1.00	5.00	12.00
16	20.00	270.00	1.00	5.00	6.00

4.1.2 CAE – Moldex3D

The next step was to perform the experiment following the values shown in Table 4-3). In this phase, the process was simulated using Moldex3D (Figure 4.3).

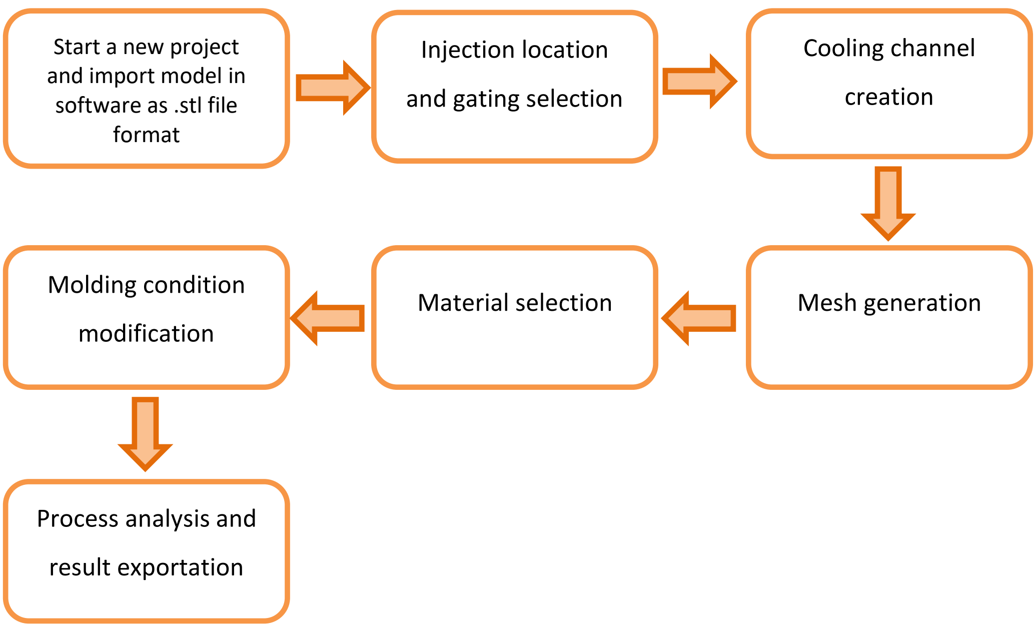


Figure 4.3 - Steps of plastic part analysis in Moldex3D software.

The mesh was generated for the part, cooling channels and feeding system using Moldex3D. It was assumed that the mold will operate with only one cooling channel circuit and for that reason all the channels were connected between each other resting only one inlet and one outlet (Figure 4.4) and (Figure 4.5).

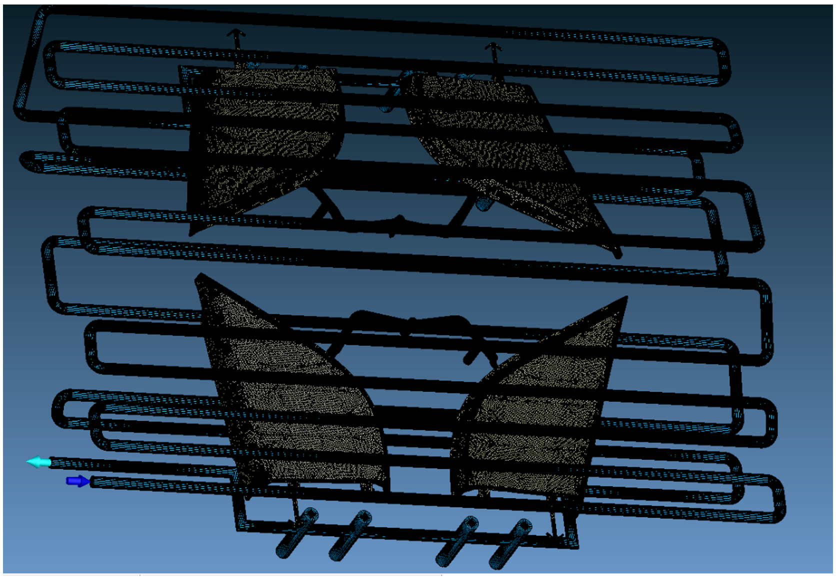


Figure 4.4 - Mesh generated for the Study. It includes four parts, 2 feeding system and the cooling system

Figure 4.5 - Zoomed view of the mesh generated.

Next, the material data was retrieved (Hostacom TRC 411N) from Moldex3D's database. In Figure 4.6 is shown the data directly from Moldex3D's database.

Polymer	PP
Grade Name	Hostacom TRC411N
Producer	LyondellBasell
Comment	15%mineral ,MFI(230,2.16)=18 g/10min ,D=1.02 g/cm3
Last modified date	2017/02/09
Process condition	Process condition
Melt temperature (minimum)	230 oC
Melt temperature (normal)	250 oC
Melt temperature (maximum)	260 oC
Mold temperature (minimum)	20 oC
Mold temperature (normal)	35 oC
Mold temperature (maximum)	50 oC
Ejection temperature	105 oC
Freeze temperature	125 oC

Figure 4.6 - Hostacom TRC 411N Datasheet from Moldex3D Database.

The values of the above-mentioned orthogonal array were used as process conditions (Table 4-3). In this case, the maximum melt temperature of Moldex3D's database is different from LyondellBasell's datasheet. For this project, the value from LyondellBasell's datasheet was used. For each run of the experiment, the process condition was changed to the values assumed by the orthogonal array (Table 4-3). Before running the program, the values were placed in Moldex3D software using the menus shown in Figure 4.7, Figure 4.8 and Figure 4.9.

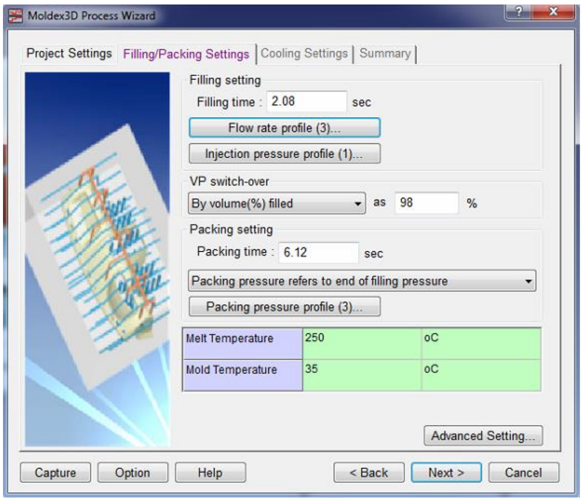


Figure 4.7 - Page 1 of process conditions modification menu.

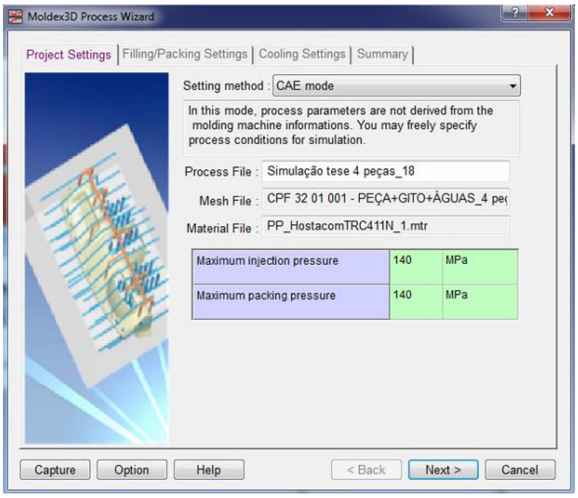


Figure 4.8 - Page 2 of process conditions modification menu.

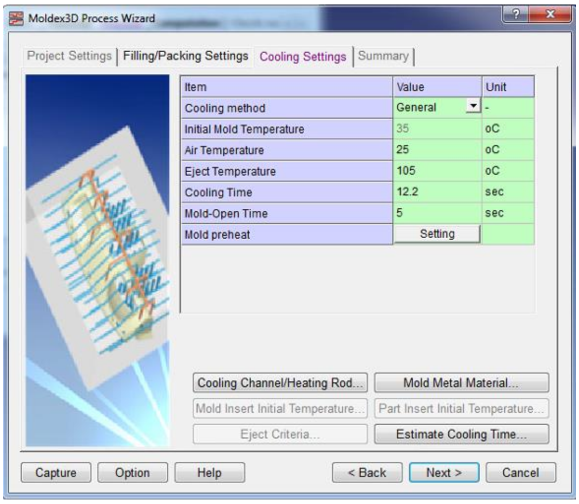


Figure 4.9 - Page 3 of process conditions modification menu.

Next, the analysis of the part proceeded. A full analysis was chosen by the operator for all runs. gave results from the analysis of the filling phase, packing phase, cooling phase and warpage were exported and analyzed by the operator.

To retrieve these results, three points from the part were chosen to measure the warpage. During the quality control, the part is measured, through a control gauge, to guarantee that there are no deviations in its critical dimensions. The three points selected (Figure 4.10 and Figure 4.11) were those previously settled by the client for the assembly phase.

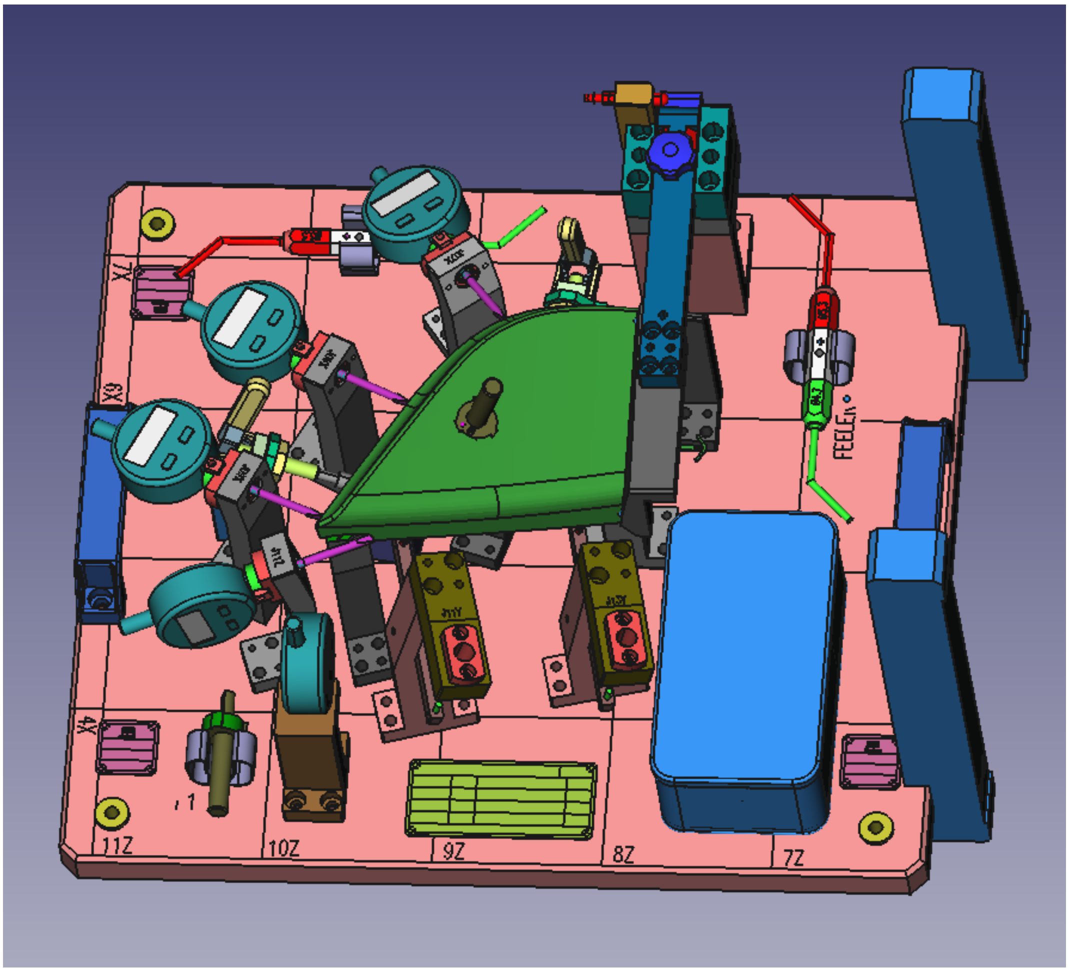


Figure 4.10 - Control Gauge of Cache Retro

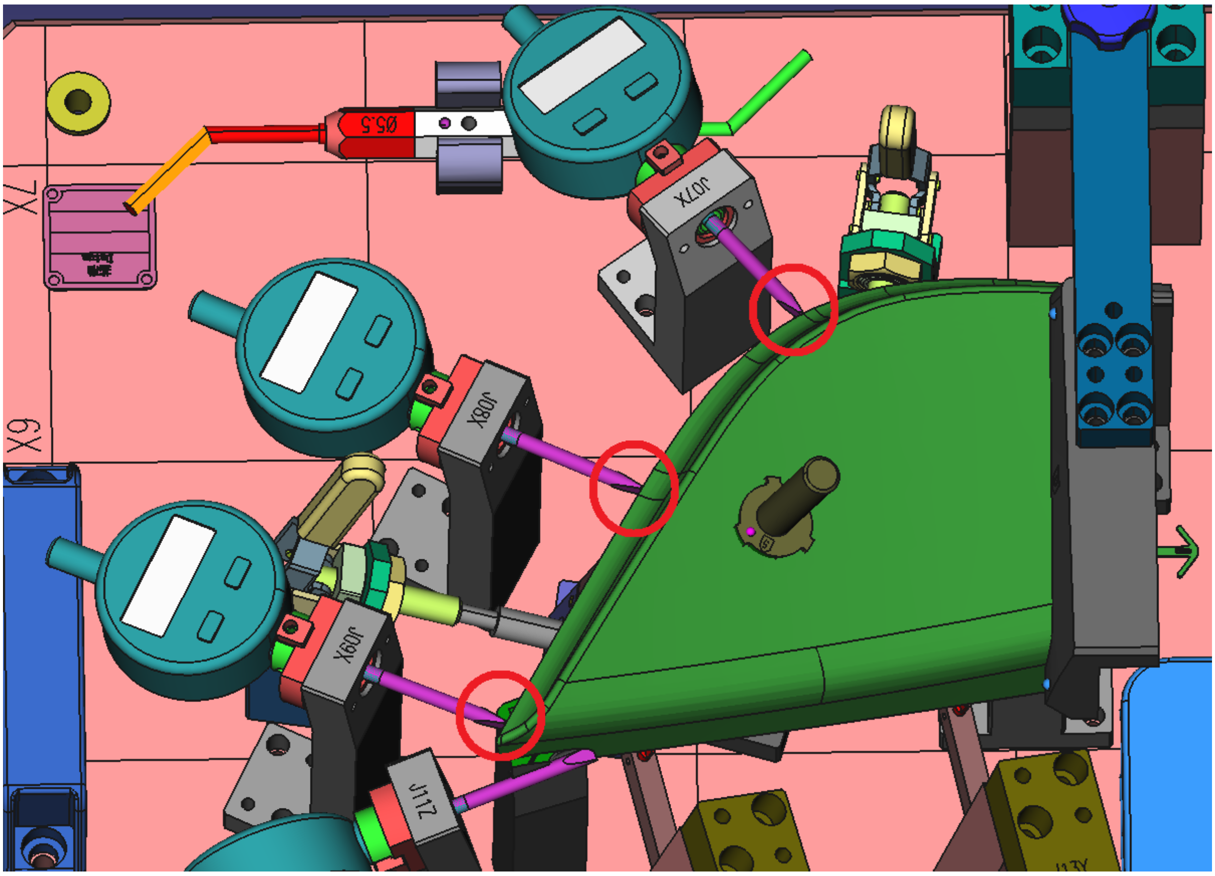


Figure 4.11 - Points studied throughout the dissertation. The points are presented in the red circles.

Table 4-4 - Points' Tolerance

Point	Tolerance
J07X	+/- 0.5mm
J08X	+/- 0.5mm
J09X	+/- 0.5mm

After the simulation, the warpage was determined for one node of each of the three points for each cavity of the mold. The warpage values were calculated as the average of the three nodes that compose each point. The same nodes and elements were used for all the 16 runs. Finally, the results were registered in the software for the statistical data analysis. The contribution of each of the parameters studied to the model explaining the warpage and the optimal condition was evaluated using ANOVA in the software DX7 – Design Expert.

4.2 Process Parameters Optimization - Experimental

4.2.1 Design of experiments – Orthogonal Array Taguchi Method

The DOE work was reduced into an orthogonal array of $L2^7$ based on the previously described (Chapter 4.1). The parameters were chosen based on the significance from the previous model. Based on the Taguchi's linear graph, there are 4 main parameters and 3 relations. (Figure 4.12 and Table 4-5)

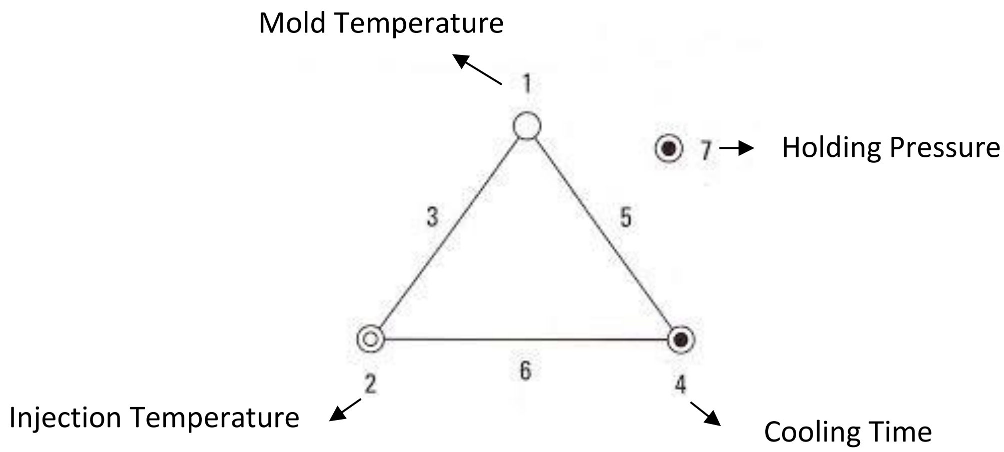


Figure 4.12 - Representation of the parameters in the orthogonal array linear graph L8.

Table 4-5 - Parameters and interactions from linear graph L_8.

Number	Letter	Parameter
1	A	Mold Temperature
2	B	Injection Temperature
3	AB	Mold Temperature x Injection Temperature
4	E	Cooling Time
5	AC	Mold Temperature x Cooling Time
6	BC	Injection Temperature x Cooling Time
7	D	Holding Pressure

With these parameters, the final design of experiments for this study is shown in Table 4-6.

Table 4-6 - Taguchi's Orthogonal Array L_8

Run	Mold Temperature	Injection Temperature	Cooling Time	Holding Pressure
1	20	270	12	5
2	20	230	12	6
3	50	230	12	5
4	50	270	12	6
5	20	270	6	6
6	50	270	6	5
7	20	230	6	5
8	50	230	6	6

4.2.2 Production of the Samples

The samples were produced in the company Maryasa in Oliveira de Azeméis using an Tederic i3200 D450 SV injection machine (Figure 4.13).

Figure 4.13 – Tederic i3200 D450 SV – Injection machine used for the samples production. [20]

The parts were produced based on the values of the orthogonal array (Table 4-7).

Table 4-7 - Orthogonal Array L_8 used to produce the parts.

Injection Temperature	Mold Temperature	Cooling Time	Holding Pressure
230	20	12	6
230	20	6	5
230	50	12	5
230	50	6	6
270	50	12	6
270	50	6	5
270	20	12	5
270	20	6	6

The mold temperature was controlled using an infrared thermometer to guarantee that the experimental settings were fulfilled. The other process parameters used for this production are shown in Appendix I. After the production, the samples were measured using a coordinate-measuring machine (CMM) (Figure 4.14 and Figure 4.15) to record the warpage values. The coordinate points of the parts were obtained using the control gauge's 3D which was imported previously into the machine's software. This measure was made for 320 parts, 160 right parts and 160 left parts. Finally, the results were registered in the software for the statistical data analysis. The contribution of each of the parameters to the model explaining the warpage, as well as the optimal condition was evaluated using ANOVA in the software DX7 – Design Expert.

Figure 4.14 - CMM Machine - Coord3 Ares NT

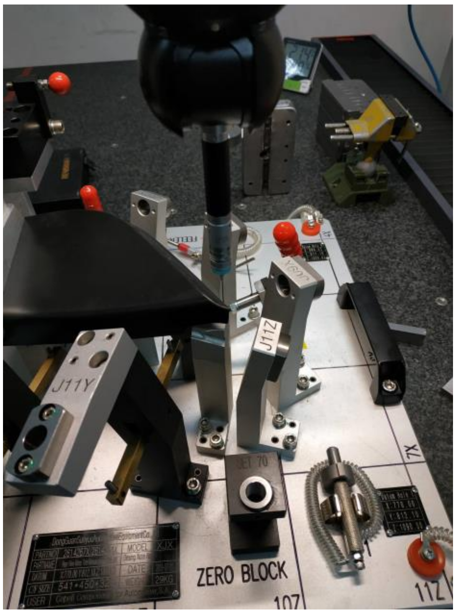


Figure 4.15 - Measurement of Point 1 in left part.

4.3 Conventional Straight-Drilled Design Optimization

4.3.1 Design of experiments – Orthogonal Array Taguchi Method

The design parameters were calculated based on the relation d = Cooling channels diameter; P = Distance between channels – 2,5 to 3,5 d; D = Distance between channels and the part – 8 to 1,5 p; (Figure 2.5), assuming a diameter of 8 or 10mm for the cooling channels (Table 4-8).

Table 4-8 - Design parameters calculated.

Parameter	Values
Diameter (d)	8 – 10 (mm)
Distance between channels (p)	24 – 30 (mm)
Distance between channels and the part (D)	27,60 – 34,5 (mm)

The parameters were chosen based on the design aspect of the cooling system (Table 4-9).

Table 4-9 - Design parameters that will be studied and their levels for the taguchi's OA.

Parameter	Levels	
Diameter (d)	8 mm	10 mm
Distance between channels (p)	24 mm	30 mm
Distance between channels and part (D)	27,60 mm	34,5 mm
Mold material	Beryllium Copper	P20 Steel
Number of circuits	1	4

Table 4-10 - Mold material Thermal Conductivity

Material	Thermal Conductivity
P20 Steel	29 – 34 W/m.K
Beryllium Copper	105 – 130 W/m.K

Additionally, two different mold materials (table ()) and different number of circuits were used to evaluate their impact in the model. Taguchi method uses an Orthogonal Array to create the experiment. For this experiment, a 2^{15} orthogonal array was chosen using five parameters as inputs and 10 relations between them (Figure 4.16, Table 4-11, Table 4-12).

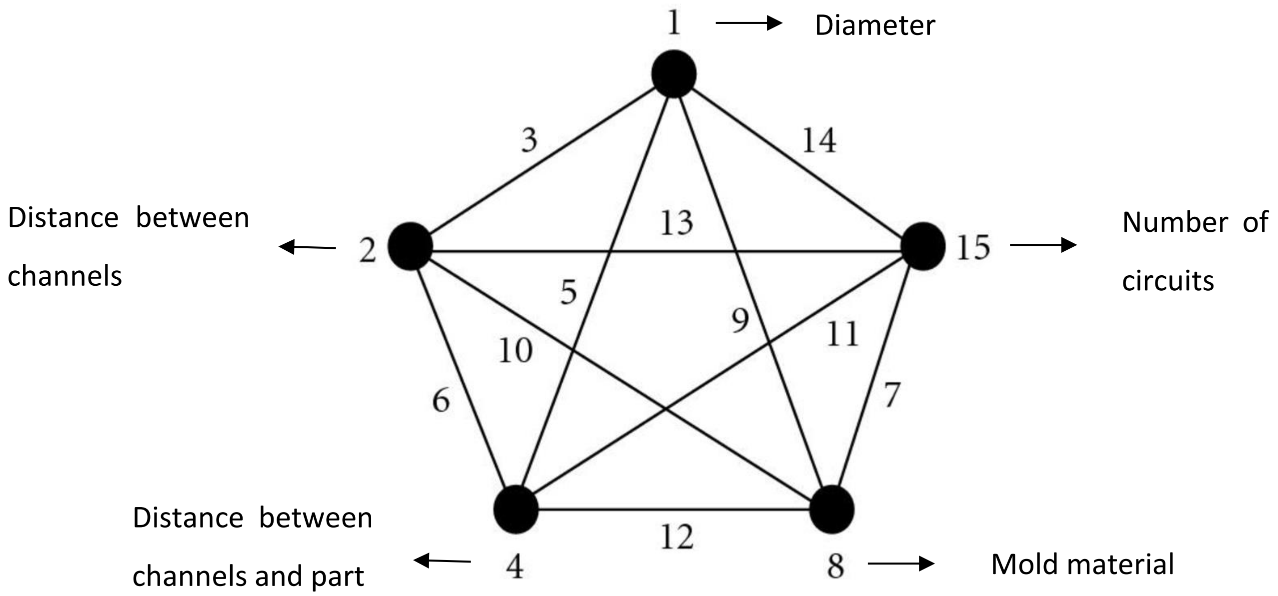


Figure 4.16 - Representation of the parameters in the orthogonal array linear graph L16.

Table 4-11 - Design Parameters and interactions for an orthogonal array L_{16}.

Number	Letter	Parameter
1	A	Diameter
2	B	Distance between channels
3	AB	Diameter x Distance between channels
4	C	Distance between channels and part
5	AC	Diameter x Distance between channels and part
6	BC	Distance between channels x Distance between channels and part
7	DE	Mold material x Number of circuits
8	D	Mold material
9	AD	Diameter x Mold material
10	BD	Distance between channels x Mold material
11	AD	Diameter x Mold material

12	CD	Distance between channels and part x Mold material
13	BE	Distance between channels x Number of circuits
14	AE	Diameter x Number of circuits
15	E	Number of circuits

Table 4-12 - Orthogonal Array L16 used for the simulation.

Run	Diameter	Distance between channels	Distance between channels and part	Mold Material	Number of circuits
1	8	30	34.5	Beryllium Copper	4
2	10	30	34.5	Beryllium Copper	1
3	10	30	27.6	P20 Steel	1
4	8	24	34.5	Beryllium Copper	1
5	10	30	27.6	Beryllium Copper	4
6	10	24	27.6	Beryllium Copper	1
7	8	30	27.6	P20 Steel	4
8	8	24	27.6	P20 Steel	1
9	10	24	34.5	P20 Steel	1
10	10	24	27.6	P20 Steel	4
11	8	24	34.5	P20 Steel	4
12	10	24	34.5	Beryllium Copper	4
13	10	30	34.5	P20 Steel	4
14	8	30	27.6	Beryllium Copper	1
15	8	30	34.5	P20 Steel	1
16	8	24	27.6	Beryllium Copper	4

4.3.2 CAE – Moldex3D

Next, the simulation was proceeded using the same model as in chapter (). The difference for this study was the use of design parameters. For that reason, it was generated one mesh for each run. Cooling channels were added inside the lifters to increase the cooling inside the pin cavities. This was possible using a system commercialized by CUMSA (Figure 4.17) being drawn using Solidworks and implemented in the 3D of the mold (Figure 4.18).

The changes in the design parameters established by the Taguchi's OA from Table 4-12 were implemented in the Cavity side of the mold (Figure 4.19).

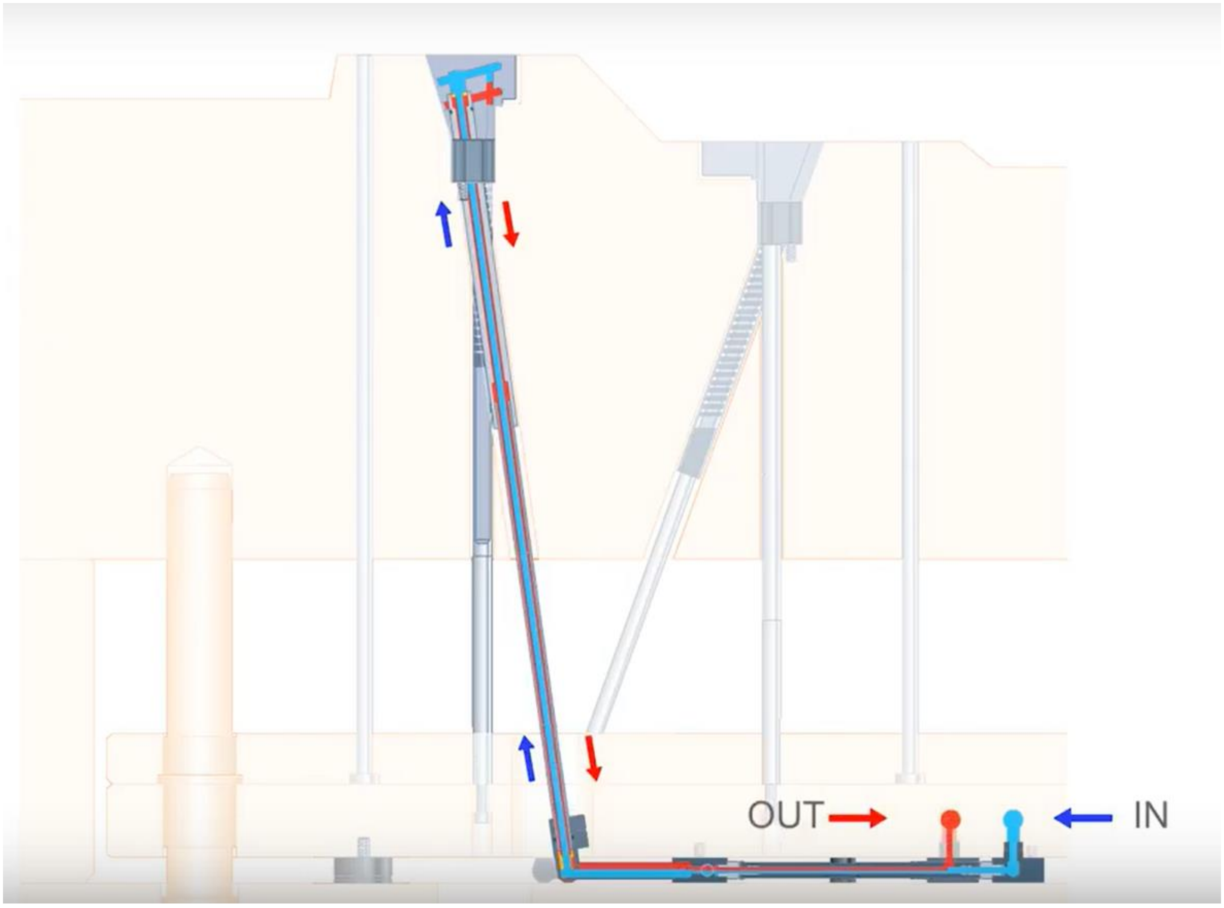


Figure 4.17 - Double Rack system with cooling feature. [21]

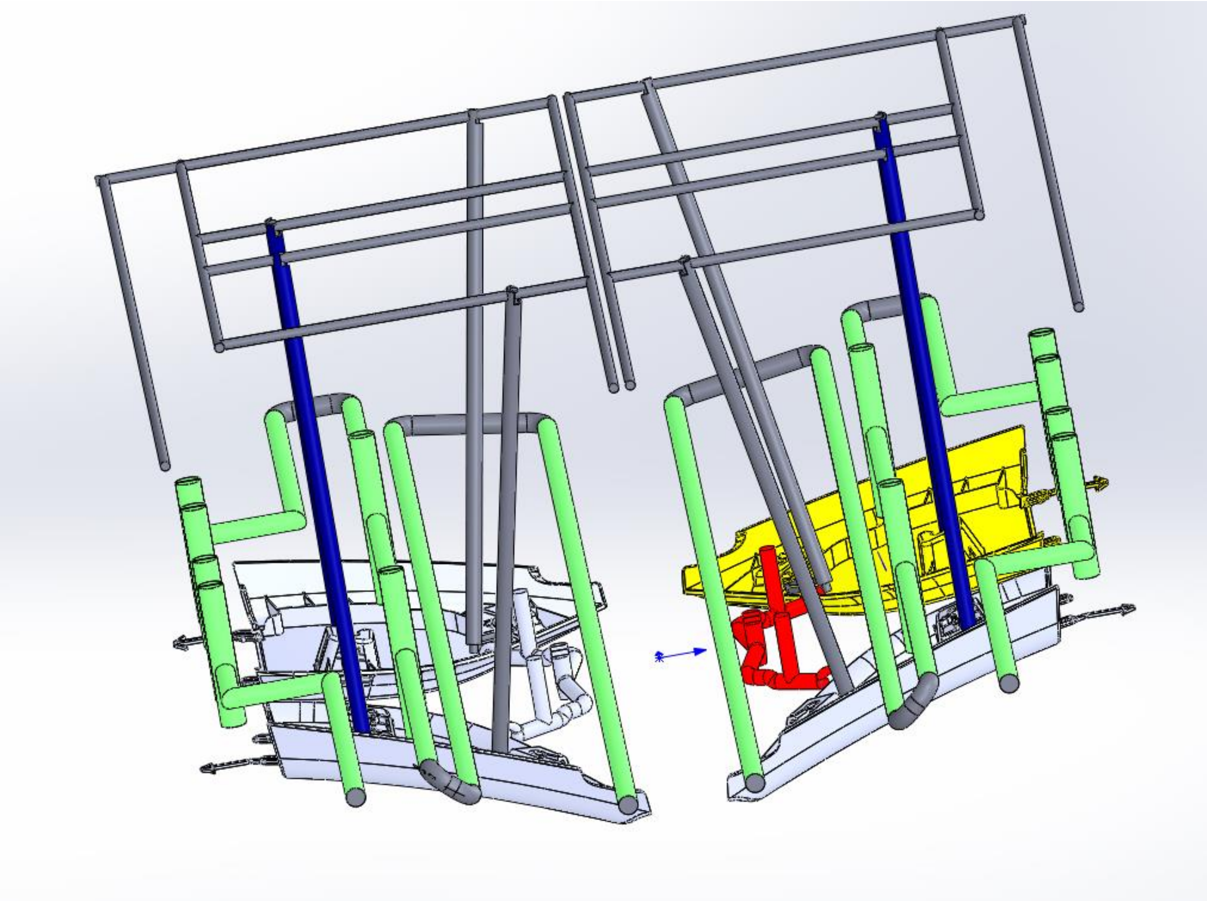


Figure 4.18 - New Core side of the mold with the double rack system with cooling feature incorporated.

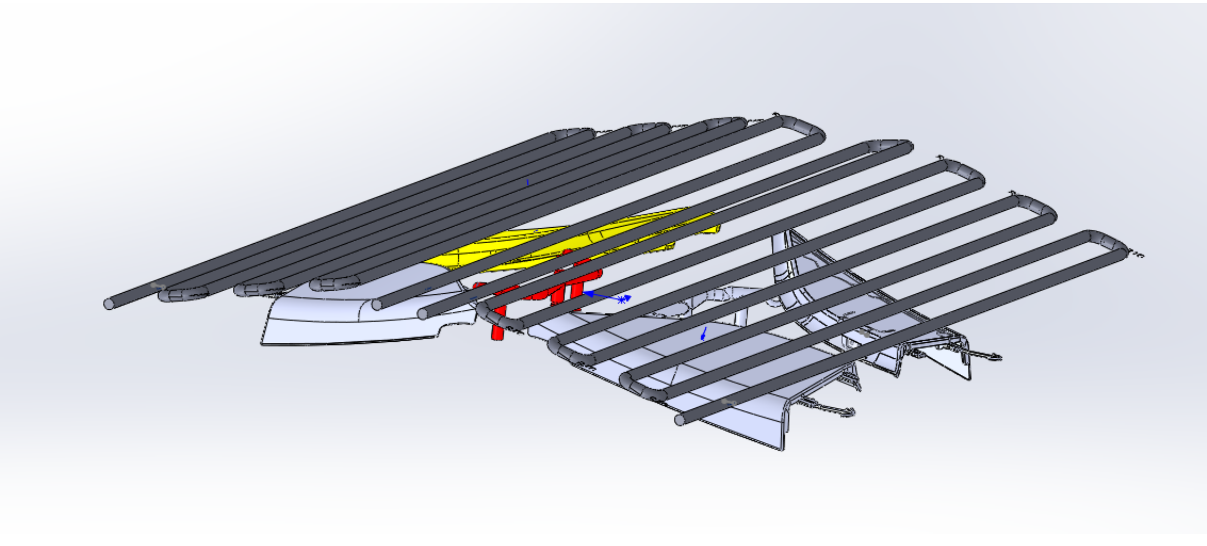


Figure 4.19 - Cavity side of the mold for this study.

The process parameters used for this study were retrieved from the results of chapter 5.1. These parameters were chosen for its optimization in simulation method (Table 4-13).

Table 4-13 - Process parameters optimized and used for simulation process.

	Mold Temperature	Injection Temperature	Injection Speed	Holding Pressure Time	Cooling Time
Simulation	50 ºC	230 ºC	0.56 s	6 s	12 s

As mentioned above, the design parameters were changed, for each run, in the cavity side of the mold. For that reason, a mesh was created always in the same way for each run.

The file with the injection system and cooling system was imported into the Moldex3D software. Inside the software, the different system was defined, and the mesh was created. In all cases, the mesh had the same number of errors. With a simple Fix Wizard feature all the errors disappeared. The mold and injection system were always the same. Finally, the mesh was generated with level 5 and saved for further analysis.

To run the simulation, the Hostacom TRC 411N material data and the process conditions were added using the values from Table 4-13.

4.4 Conformal Design Optimization

4.4.1 Design Configuration

To optimize the design configuration of the cooling system, conformal technique was applied. This technique consists of conforming the geometry of the part with the cooling channels. To achieve this, it uses AM such as Direct Metal Laser Sintering (DMLS) or Fused Deposition Modeling (FDM).

The conformal design was proposed (Table 4-14) assuming parameters optimized during conventional design optimization (Table 4-13). The process parameters are the same as in conventional system optimization.

Table 4-14 - Design parameters optimized and used for creating new conformal design.

	Diameter	Distance between channels	Distance between channels and part	Number of circuits	Material
Simulation	10 mm	24 mm	34,5 mm	4	P20 Steel

These parameters (Table 4-14) were used to create one CAD model in Solidworks software. The design conditions were guaranteed, for the cooling channels design, in the cavity side of the mold (Figure 4.20). On the other hand, some adjustments had to be made in the core side of the mold to avoid the extractor pins (Figure 4.21). On the same side, double racks with cooling feature, which were used in the conventional system optimization, remained (Figure 4.18).

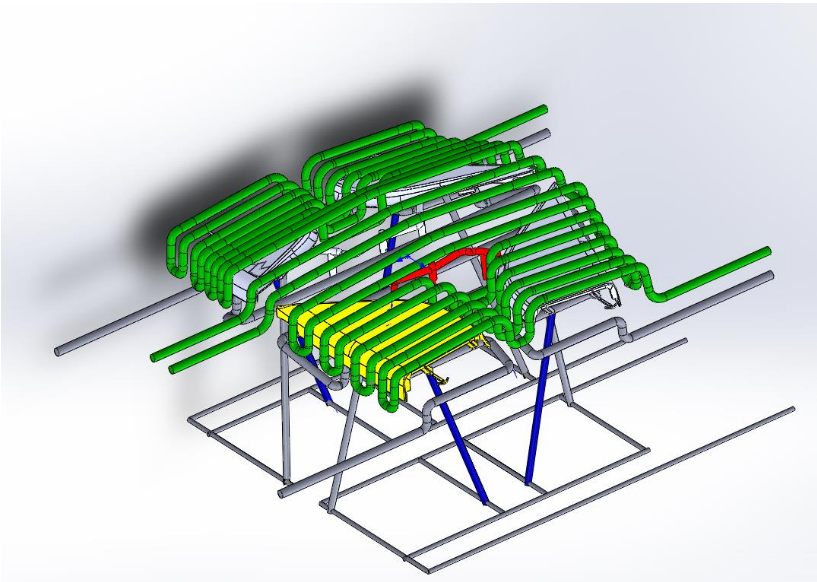


Figure 4.20 - Cavity side of the mold. Green - Conformal channels from cavity side of the mold.

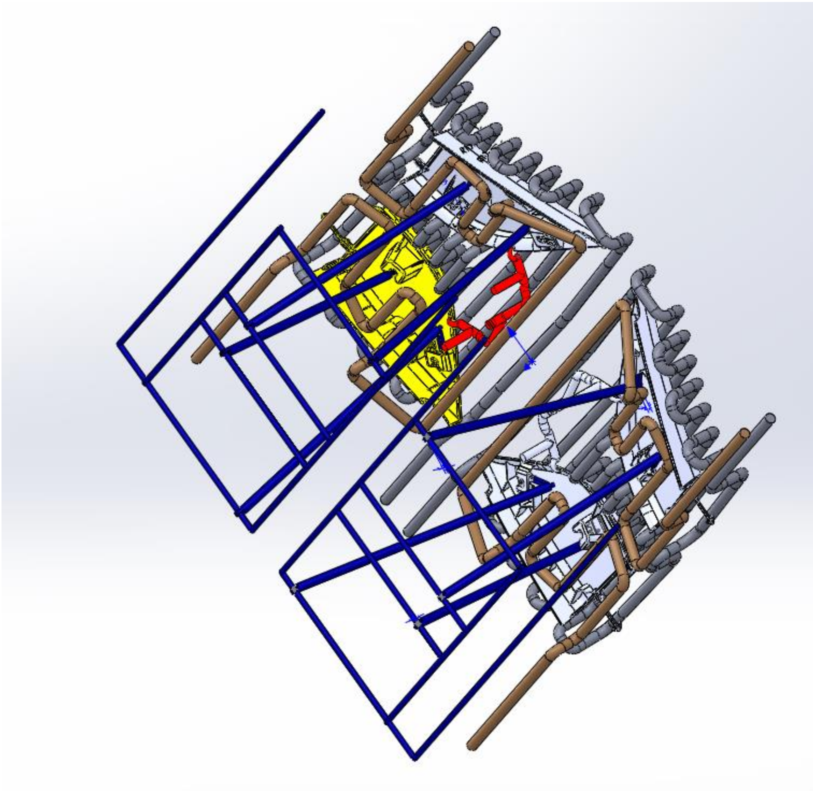


Figure 4.21 - Core side of the mold. Blue - Double racks with cooling feature; Brown - Conformal channels from core side of the mold.

4.4.2 CAE – Moldex3D

After creating the CAD model, a simulation of the process was performed using Moldex3D. In this case, only one mesh was generated with level five (Figure 4.22).

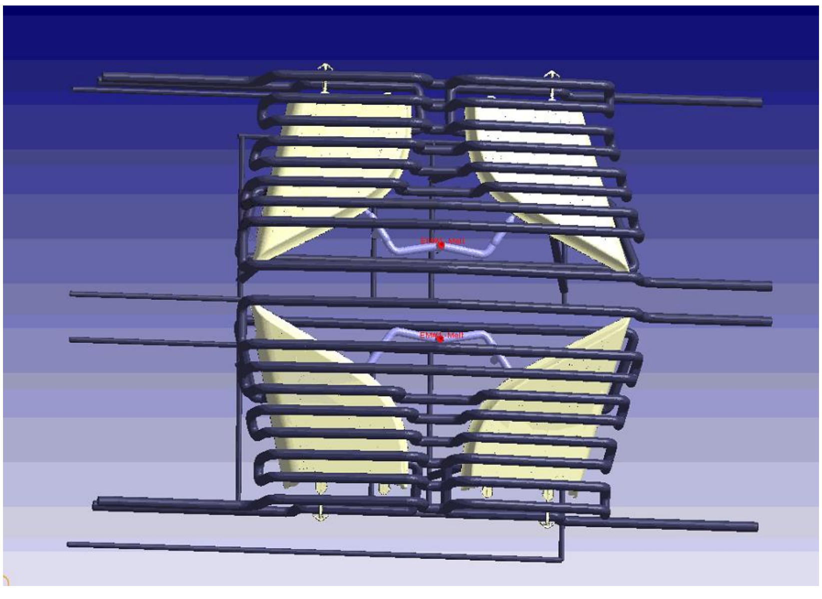


Figure 4.22 - Level 5 mesh created for the conformal design simulation.

The process parameters were defined in the software (Table 4-14) and the simulation was performed. Finally, warpage results were retrieved from the software and compared with previous optimizations. To record the warpage results, a point cloud for each zone was created.

5. RESULTS

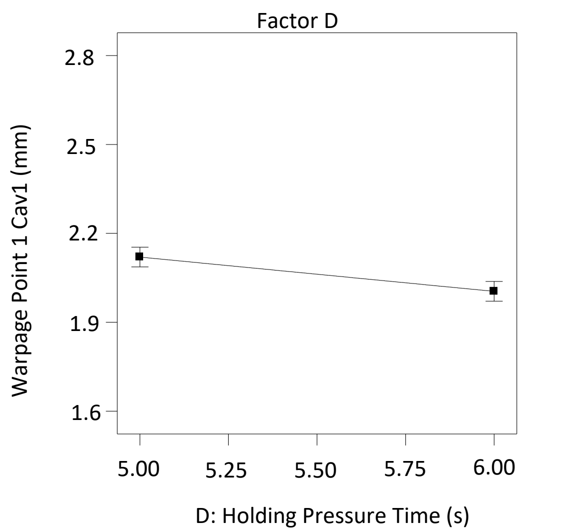
5.1 Process Parameters optimization - Simulation

As mentioned above, this study had the intention to optimize the process parameters using the software Moldex3D. Assuming the same cooling system as in the produced mold from COPEFI, the DOE was created with the values from the material datasheet (Table 5-1). A mesh was created with level 5 of complexity and the process parameters were changed, based on the Taguchi's OA, for 16 runs.

Table 5-1 - Summary of the process parameters.

Parameters	Values
Mold Temperature	20 – 50 ºC
Injection Temperature	230 – 270 ºC
Injection Time	0,5 – 1 s
Holding Pressure Time	5 – 6 s
Cooling Time	6 – 12 s

To determine the contribution of each factor, DOE and ANOVA were performed. For all responses, all the results from the ANOVA model were analyzed (Appendix II - Moldex3D Simulations and Optimization's Data). The results for response 1 are presented as an example of the analysis (Table 5-2 and Figure 5.1, Figure 5.2 and Figure 5.3).



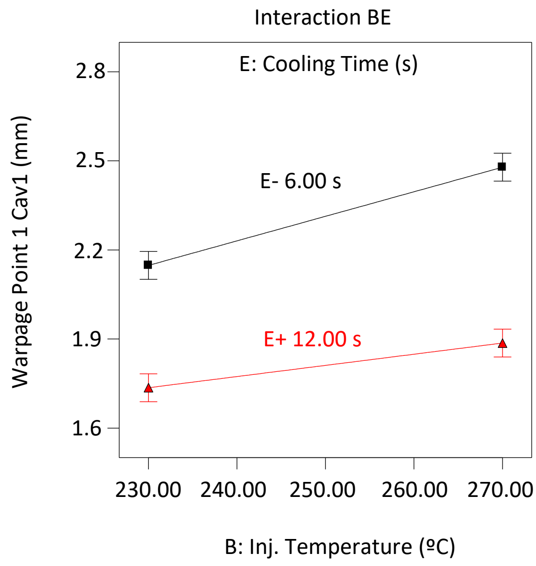


Figure 5.1 - Behavior of Factor D - Holding Pressure Time.

Figure 5.3 - Behavior of Interaction BE - Injection Temperature x Cooling Time.

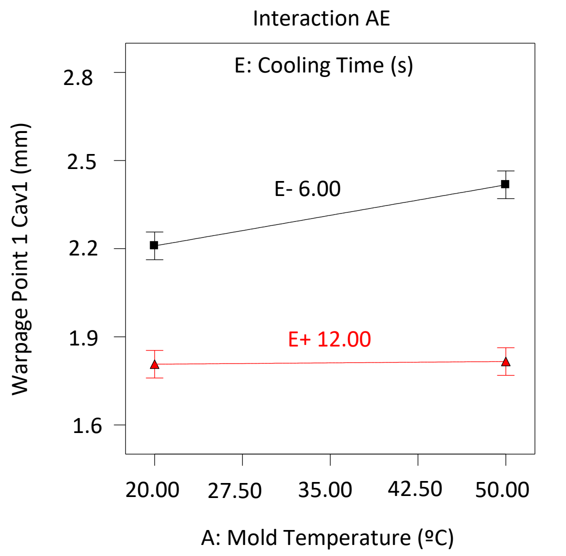


Figure 5.2 - Behavior of Interaction AE - Mold Temperature x Cooling Time.

Table 5-2 - ANOVA table for response 1 - warpage in Point 1 Cavity 1

	1		**Warpage Point 1 Cav1**				
Source	Sum of Squares	df	Mean Square	F Value	Stdized Effects	p-value Prob > F	%Contribution
Model	1.41	6	0.24	68.07		<0.0001	
A-Mold Temperature	0.047	1	0.047	13.61	0.11	0.0050	3.26
B-Inj. Temperature	0.23	1	0.23	66.92	0.24	<0.0001	16.03
D-Holding Pressure	0.054	1	0.054	15.48	-0.12	0.0034	3.71
E-Cooling Time	1.01	1	1.01	291.61	-0.50	<0.0001	69.89
AE	0.040	1	0.040	11.42	-0.099	0.0081	2.74
BE	0.032	1	0.032	9.39	-0.09	0.0135	2.25
Residual	0.031	9	3.458E-003				
Cor Total	1.44	15					

The analysis of variance for the process parameters optimization, regarding to response 1 – Point 1 cavity 1, using simulation, indicates that warpage was influenced mainly by Injection temperature (16,03%) and cooling time (69,89%) Table 5-2. When standardized effects are positive, it means that warpage increases with the increase of the factor’s value. On the other hand, if they are negative, it means that warpage decrease with the increase of factor’s value. Injection temperature had a standardized effect of 0.24 then warpage increased at 270ºC. Cooling time had a standardized effect of -0.50, then warpage decreased at 12 seconds. With these results, to decrease the point’s warpage, cooling time had to be 12 seconds and injection temperature 230ºC.

A summary of all the ANOVA analyses, for all the responses, is presented in Table 5-3.

*Table 5-3 - Summary of all ANOVA analyses. It presents the standardized effects of each factor and interaction for all runs. * is referring to p-value, representing the level of significance. * - 0.05>p>0.01, ** - 0.01>p>0.001 and *** - p < 0.001*

Resp.	A	B	D	E	AE	BE
1	**0.11****	**0.24*****	**-0.12****	**-0.50*****	**-0.099****	**-0.090***
2	**0.10****	**0.21*****	**-0.11****	**-0.46*****	**-0.098****	**-0.077***
3	**0.11****	**0.23*****	**-0.12****	**-0.50*****	**-0.099****	**-0.084***
4	**0.12****	**0.26*****	**-0.13****	**-0.54*****	**-0.086****	**-0.096***
5	-	**0.037****	**-0.030***	**-0.056****	**-0.073*****	-
6	-	**0.028***	**-0.031***	**-0.048****	**-0.067*****	-
7	-	**0.044****	**-0.027***	**-0.060****	**-0.064*****	-
8	-	**0.042****	**-0.033****	**-0.077*****	**-0.067*****	-
9	-	**0.13*****	**-0.051***	**-0.12*****	**-0.090****	**-0.038***
10	-	**0.12*****	**-0.056****	**-0.12*****	**-0.083****	**-0.037***
11	-	**0.12*****	**-0.051****	**-0.11*****	**-0.089****	**-0.038***
12	-	**0.12*****	**-0.052****	**-0.12*****	**-0.075****	**-0.036***

For each Point presented as Point 1 – responses 1 to 4, point 2 – responses 5 to 8 and point 3 – responses 9 to 12, it is possible to observe that all the factors' behavior is almost the same.

For Point 1, factors A, B, D, E, interactions AE and BE had contribution. Based on the standardized effects, when A (Mold Temperature) and B (injection Temperature) increased, warpage increased. When D (Holding pressure time) and E (cooling time) increased, warpage decreased.

For Point 2, factors B, D, E and interaction AE had contribution. Based on the standardized effects, when B (Injection Temperature) increased, warpage increased. When D (Holding pressure time) and E (cooling Time) increased, warpage decreased.

For Point 3, factors B, D, E, interaction AE and BE had contribution. Based on the difference between mean values, when B (injection temperature) increased, warpage increased. When D (holding pressure time) and E (cooling time) increased, warpage decreased.

In this study, factor C did not have contribution for any point. This meant that if the parameter were changed in the process, it would not have any effect in warpage.

After this study was performed, it was analyzed the best combination, of process parameters, to get the lowest value of warpage.

So, for this model the best combination, based on the values of warpage and the behaviors of the factors, is A – Mold Temperature = 50ºC, B – Injection Temperature = 230ºC, C – Injection Speed = 0,56s, D – Holding Pressure Time = 6s and E – Cooling Time = 12s (table ()). This combination got the following warpage results: Response 1 = 1,628 mm, Response 2 = 1,630 mm, Response 3 = 1,620 mm, Response 4 = 1,672 mm, Response 5 = 0,575 mm, Response 6 = 0,591 mm, Response 7 = 0,583 mm, Response 8 = 0,573 mm, Response 9 = 1,183 mm, Response 10 = 1,229 mm, Response 11 = 1,147 mm, Response 12 = 1,180 mm. This combination had a desirability of 98,9% (Figure 5.4).

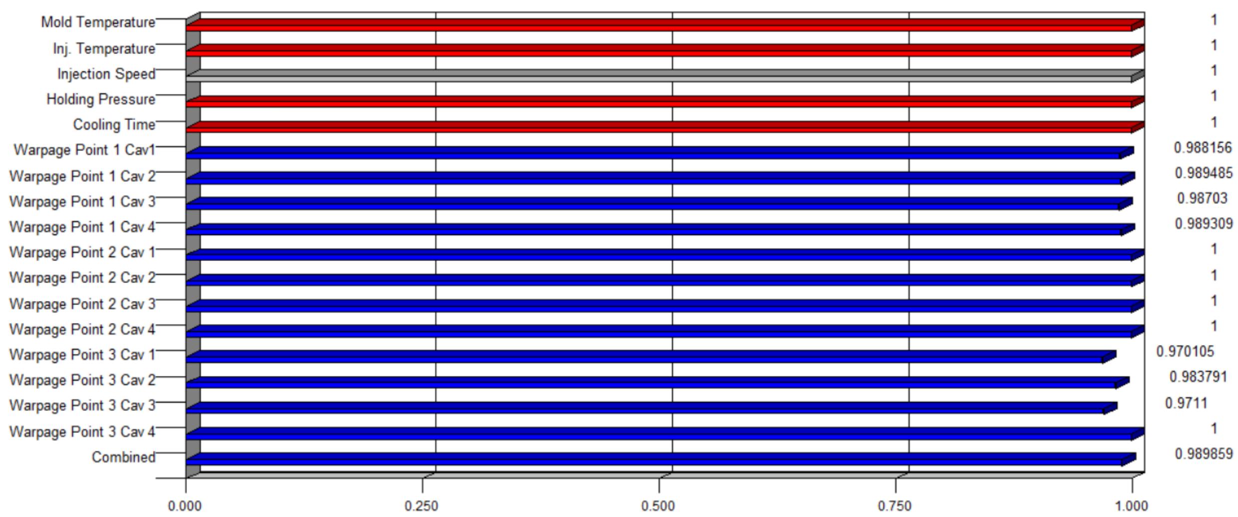


Figure 5.4 - Desirability of each response with the best combination of process parameters.

To compare the improvements between all optimizations, the max cooling time, until ejection temperature was reached, was recorded (Figure 5.5). This value was taken from the run with optimal process parameters achieved before.

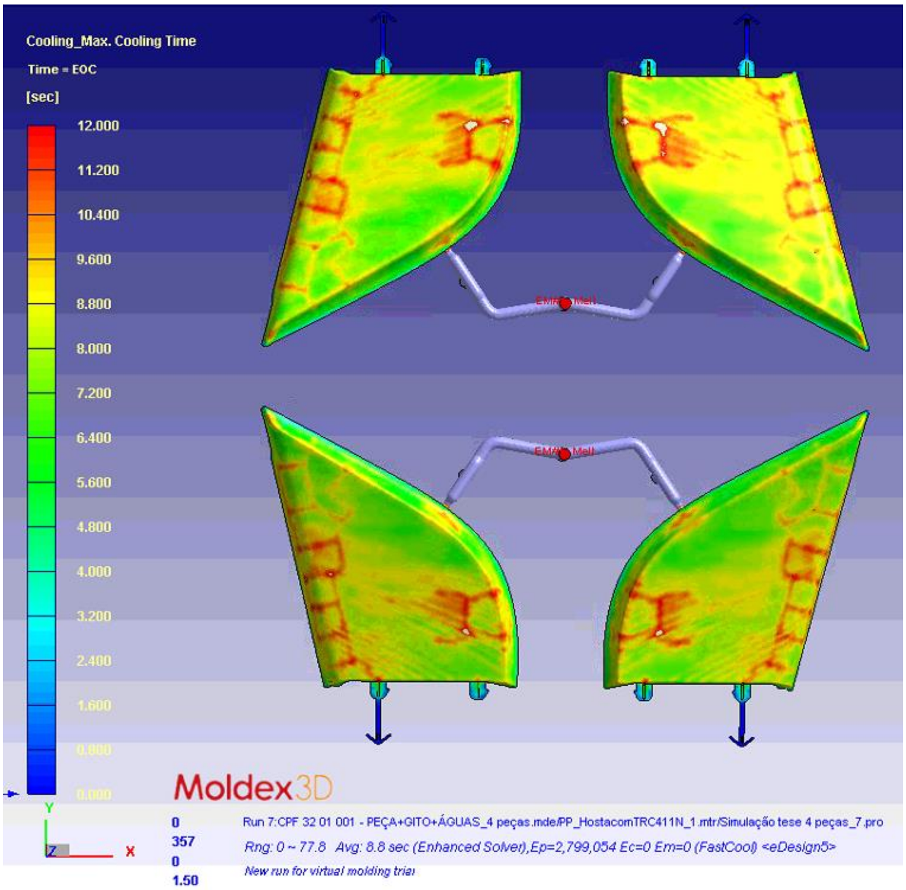


Figure 5.5 - Time to reach ejection temperature.

It was possible to observe (Figure 5.5) that with 12 sec of cooling time, almost all the part had green color, which means that those zones reached ejection temperature at around 7,2 seconds. Zones at red means that it took 12 seconds to reach ejection temperature. These zones were mainly at ribs of the part. As the ribs had more thickness than the rest of the part it was expected to take longer to cool until it reached ejection temperature. There were some zones in the part that could not achieve ejection temperature which are presented as grey color. These zones were at the pin holes which did not have any kind of cooling inside, nor around. This was expected to happen due to the non-uniform cooling system and lack of cooling channels in the extraction side of the mold.

5.2 Results - Process Parameters optimization - Experimental

As mentioned above, this study had the intention to optimize the process parameters in an industrial context. Assuming the same cooling system as in the produced mold from COPEFI, the DOE was created with the values from the material datasheet (table ()). For this study, the Taguchi's OA was lowered by one factor compared to the previous study (process parameters optimization – simulation). Factor C – Injection time was removed from the study due to its absent of contribution in the previous study. For that reason, the new Taguchi's OA had only 4 factors and was a $L2^7$ Orthogonal array (Table 5-4).

Table 5-4 - Summary of the process parameters.

Parameters	Values
Mold Temperature	20 – 50 ºC
Injection Temperature	230 – 270 ºC
Holding Pressure Time	5 – 6 s
Cooling Time	6 – 12 s

To determine the contribution of each factor, DOE and ANOVA were performed. For all responses, all the data from ANOVA model was analyzed, but it was only shown here the response 1 analysis (Table 5-5 and Figure 5.6, Figure 5.7 and Figure 5.8). The other responses are presented in appendix ().

Table 5-5 - ANOVA table for response 1 - warpage in Point 1 Cavity 1

Response	**1**	**Warpage Point 1 Cav 1**					
Source	Sum of Squares	df	Mean Square	F Value	Stdized Effects	p-value Prob > F	%Contribution
Model	17.53	5	3.51	21.16		< 0.0001	
A-Mold Temperature	4.71	1	4.71	28.41	0.49	< 0.0001	15.80
B-Injection Temperature	6.27	1	6.27	37.84	0.56	< 0.0001	21.05
E -Cooling time	4.01	1	4.01	24.21	-0.45	< 0.0001	13.47
D-Holding Pressure	1.76	1	1.76	10.65	-0.30	0.0017	5.92
AE	0.78	1	0.78	4.69	-0.20	0.0336	2.61
Residual	0.33	74	4.401E-003				
Lack of Fit	0.33	2	0.16		0.98	0.3793	
Pure Error	0.000	72	0.17				
Cor Total	17.85	79					

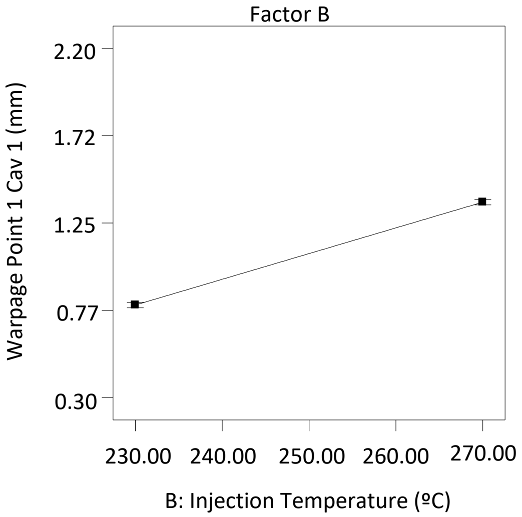


Figure 5.6 - Behavior of Factor B - Injection Temperature.

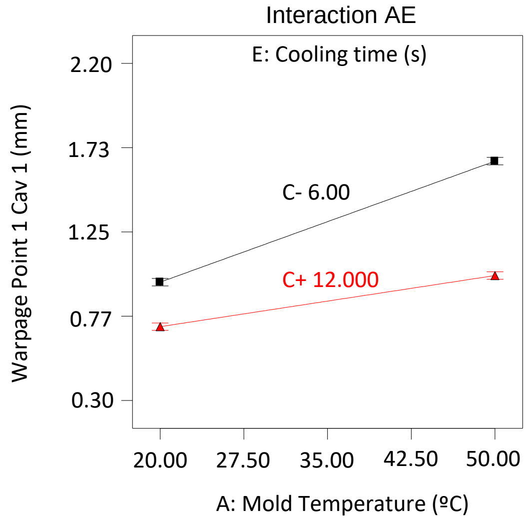


Figure 5.8 - Behavior of Interaction AE - Mold Temperature x Cooling Time.

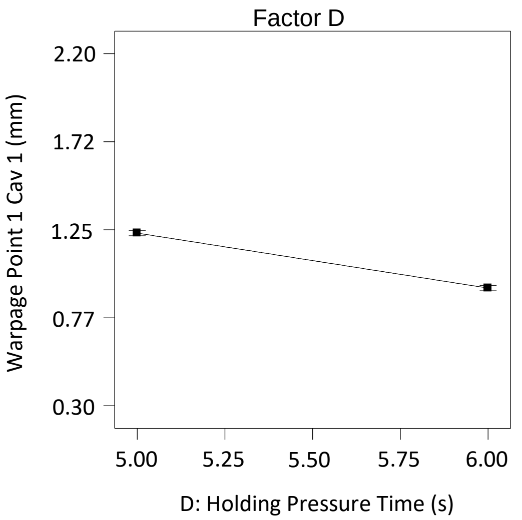


Figure 5.7 - Behavior of factor D - Hoding Pressure Time.

The analysis of variance for the process parameters optimization, regarding to response 1 – Point 1 cavity 1, using experimental method, indicates that warpage was influenced mainly by mold temperature (15,80%), Injection temperature (21,05%) and cooling time (13,47%). When standardized effects are positive, it means that warpage increases with the increase of the factor's value. On the other hand, if they are negative, it means that warpage decrease with the increase of factor's value. Mold temperature had a standardized effect of 0,49, then warpage increased at 50ºC. Injection temperature had a standardized effect of 0,56, then warpage increased at 270ºC. Cooling time had a standardized effect of -0.50, then warpage decreased at 12 seconds. With these results, to decrease the parts warpage, cooling time had to be 12 seconds, injection temperature 230ºC and mold temperature 20ºC.

A summary of all ANOVA analyses, for all the responses, is presented in Table 5-6.

*Table 5-6 - Summary of all ANOVA analyses. It presents the standardized effects, of each factor and interactions, for all runs. * is referring to p-value, representing the level of significance. * - 0.05>p>0.01, ** - 0.01>p>0.001 and *** - p < 0.001*

Resp.	A	B	E	D	AB	AE	BE
1	**0.49*** **	**0.56*** **	**-0.45*** **	**-0.30*** **	-	**-0.20** **	-
2	0.34***	-	-0.34***	-	-0.22*	-	-0.16***
3	0.28***	0.16***	-0.40***	-	-0.24***	0.13***	0.11***
4	-	0.43**	-	-0.38**	-	-	-0.56***
5	0.24***	0.30***	-0.14**	-	-0.26***	-	0.12**
6	0.28***	0.12**	-0.18**	-	-0.31***	0.11*	-0.12*
7	0.32***	0.22***	-0.15**	-0.21***	-0.23***	-	0.25***
8	0.29***	0.20**	-	-0.27***	-0.30***	-	-
9	0.53***	0.64***	-0.47***	-0.19**	-0.21**	-0.20**	-
10	0.52***	0.22*	-0.43***	-	-0.50***	-	-0.27**
11	0.57***	0.35***	-0.40***	-0.27**	-0.39***	-	0.28**
12	0.57***	0.42***	-0.30***	-0.49**	-0.33**	-	-0.36**

For each Point presented as Point 1 – responses 1 to 4, point 2 – responses 5 to 8 and point 3 – responses 9 to 12, it was possible to understand the behavior of each factor and interaction. It was only studied the parameters that contributed for all responses of the same point.

For Point 1, factors A, B and E contribution. Based on the difference between mean values, when A (Mold Temperature) and B (injection Temperature) increased, warpage increased. When E (Cooling Time) and E (cooling time) increased, warpage decreased.

For Point 2, factors A, B and interaction AB had contribution. Based on the difference between mean values, when B (Injection Temperature) increased, warpage increased. When D (Holding pressure time) and E (cooling Time) increased, warpage decreased.

For Point 3, factors A, B, E, interaction AB had contribution. Based on the difference between mean values, when B (injection temperature) increased, warpage increased. When D (holding pressure time) and E (cooling time) increased, warpage decreased.

After this study was performed, it was analyzed the best combination, of process parameters, to get the lowest value of warpage.

So, for this model the best combination, based on the values of warpage and the behaviors of the factors, is:

A – Mold Temperature = 20ºC;

B – Injection Temperature = 230ºC;

E – Cooling Time = 11,99s;

D – Holding Pressure Time = 5,99s.

This combination had a desirability of 79,9% (Figure 5.9).

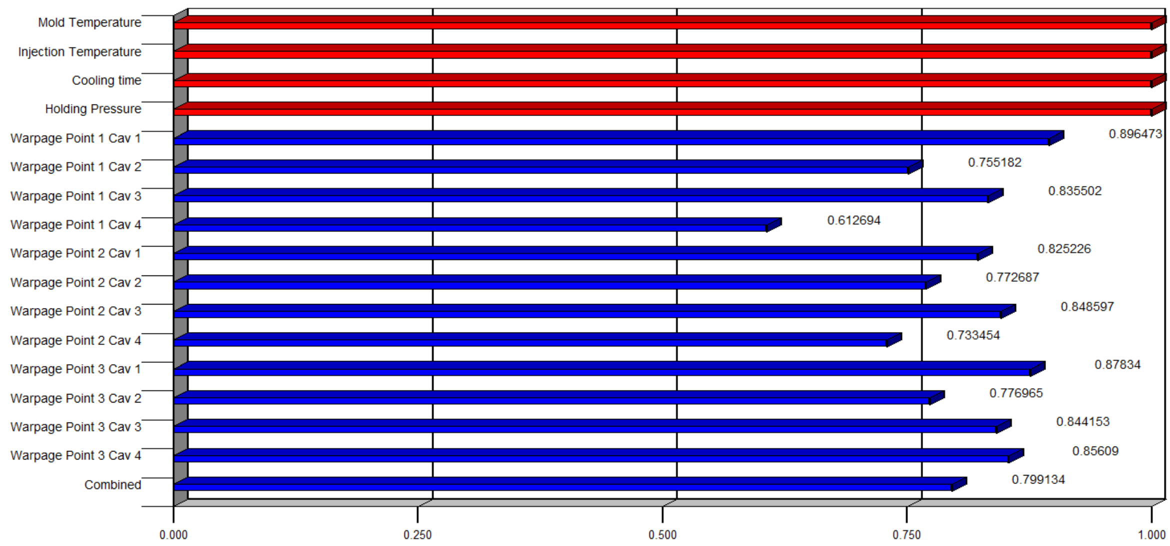


Figure 5.9 - Desirability of each response with the best combination of process parameters.

5.3 Results - Conventional Straight-Drilled Design Optimization

As mentioned above, this study had the intention to optimize the design parameters using the software Moldex3D. Assuming the same process parameters as in the previous analysis, the DOE was created with the values from Table 5-7. 16 meshes were created with level 5 of complexity and the design parameters were changed, based on the Taguchi's OA, for 16 runs.

Table 5-7 - Summary of the design parameters.

Parameters	**Values**
Diameter (d)	8 – 10 mm
Distance between channels (p)	24 – 30 mm
Distance between channels and part (D)	27,60 – 34,5 mm
Mold material	P20 Steel - Beryllium Copper
Number of circuits	1 - 4

To determine the contribution of each factor, DOE and ANOVA were performed. For all responses, all the data from ANOVA model was analyzed, but it was only shown here the response 1 analysis (Table 5-8 and Figure 5.10, Figure 5.11, Figure 5.12 and Figure 5.13).

Table 5-8 - ANOVA table for response 1 - warpage in Point 1 Cavity 1

Response	**1**		**Warpage Point 1 Cav 1**				
Source	Sum of Squares	df	Mean Square	F Value	Stdized Effects	p-value Prob > F	% contribution
Model	1,79E-02	5	3,57E-03	5,97		0.0082	
B-Distance channels	6,89E-03	1	6,89E-03	11,52	-0.042	0.0068	28.90
AC	2,76E-03	1	2,76E-03	4,61	-0.026	0.0574	11.56
AE	2,40E-03	1	2,40E-03	4,02	-0.025	0.0729	10.07
BE	3,36E-03	1	3,36E-03	5,63	-0.029	0.0391	14.11
CD	2,45E-03	1	2,45E-03	4,10	0.025	0.0705	10.28
Residual	5,98E-03	10	5,98E-04				
Cor Total	2,38E-02	15					

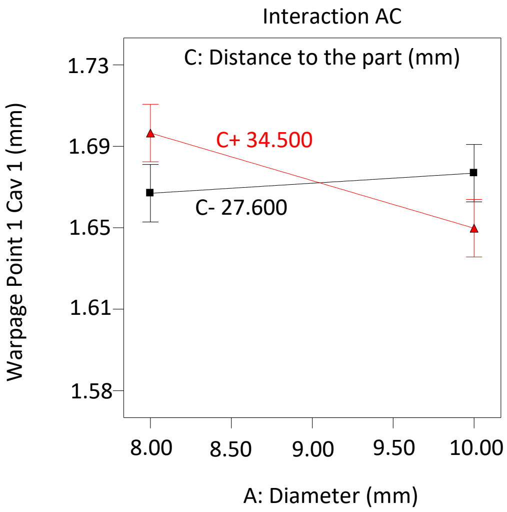


Figure 5.10 - Behavior of Interaction AC - Diameter x Distance to the part.

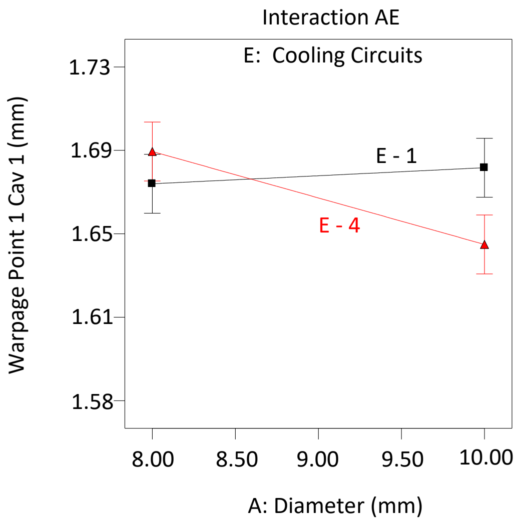


Figure 5.11 - Behavior of interaction AE - Diameter x Cooling circuits.

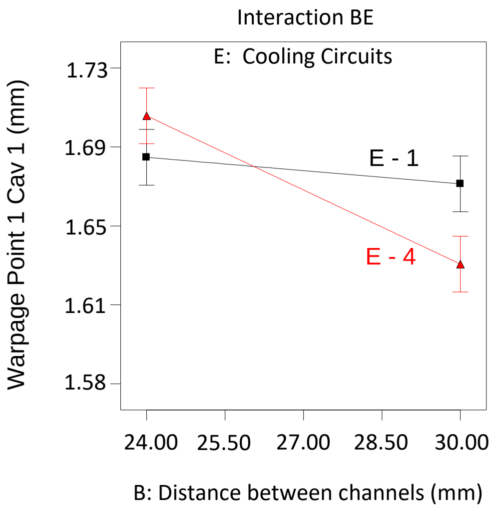


Figure 5.12 – Behavior of interaction BD - Distance between channels x Mold Material.

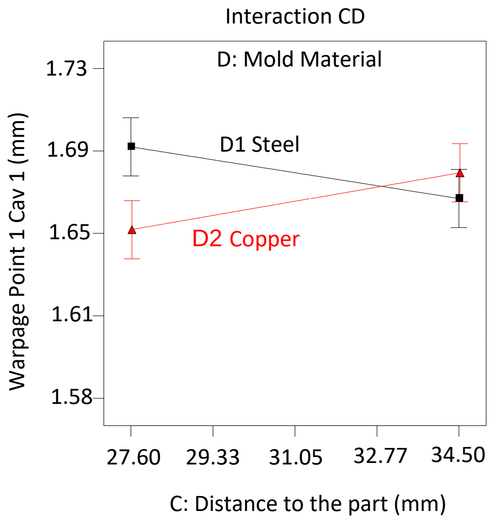


Figure 5.13 - Behavior of interaction CD - Distance to the part x Mold Material.

The analysis of variance for the design optimization, regarding to response 1 – Point 1 cavity 1, using conventional cooling channels, indicates that warpage was influenced mainly by the distance between channels (28,90%)(Table 5-8). When standardized effects are positive, it means that warpage increases with the increase of the factor's value. On the other hand, if they are negative, it means that warpage decrease with the increase of factor's value. Distance between channels had a standardized effect of -0,042, then warpage decreased at 30mm. With these results, to decrease the parts warpage, distance between channels had to be 30mm.

A summary of all the ANOVA analyses, for all the responses, is presented in Table 5-9.

For each Point presented as Point 1 – responses 1 to 4, point 2 – responses 5 to 8 and point 3 – responses 9 to 12, it was possible to understand the behavior of each factor and interaction. It was only studied the parameters that contributed for all responses of the same point.

For Point 1, none of the factor had significant contribution. This means that independently of the changes of factors' values, there were not improvements in warpage.

For Point 2, factor D had contribution. Based on the difference between mean values, when D (Mold Material) was copper, warpage increased and when it was steel, warpage decreased.

For Point 3, factor D had contribution. Based on the difference between mean values, when D (Mold Material) was copper, warpage increased and when it was steel, warpage decreased.

After this study was performed, it was analyzed the best combination, of process parameters, to get the lowest value of warpage.

So, for this model the best combination, based on the values of warpage and the behaviors of the factors, is:

A – Diameter = 10mm;

B – Distance between channels = 25,44mm;

C – Distance from the part to channels = 34,50mm;

D – Mold Material = Steel;

E – Number of systems = 4.

This combination had a desirability of 83,8% (Figure 5.14).

*Table 5-9 -Summary of all ANOVA analyses. It presents the standardized effects, of each factor and interactions, for all runs. * is referring to p-value, representing the level of significance. * - 0.05>p>0.01, ** - 0.01>p>0.001 and *** - p < 0.001*

Factor	A	B	C	D	E	AB	AC	AD	AE	BD	BE	CD	CE	DE
1	-	-0.042**	-	-	-	-	-0.026*	-	-0.025*	-	-0.029*	0.025*	-	-
2	-	-	-	-	-	-	-0.031*	-	-0.046*	-	-0.032*	-	-	0.037**
3	-0.036**	0.020**	0.020**	0.020**	-0.017*	-	-	-	-0.026**	-	-	0.046***	-	-
4	-0.018*	-	-	-	-0.036**	-	-	-	-0.027**	-	0.019*	0.026*	-0.020*	-
5	-	-	-	0.045***	-	-	-	-	-	-	-	-	-	-
6	-	-	-	0.048***	-	-	-	-	-	-	-	-	-	-
7	-	-	-	0.042***	-	-	-	-	-	-	-	-	-	-
8	-	-	-	0.040***	-	-	-	-	-	-	-	-	-	-
9	-	0.054***	-	0.054***	-	-	-	-	-	-	-	0.020*	-	-
10	-	0.070**	-	0.057**	-	0.031**	-	-	-	-	-	-	-	-
11	-	-	-	0.050***	-	-	-	0.020**	-	-	-	-	-	0.017*
12	-	0.015*	-	0.041**	-	-	-	-	-0.015*	0.016*	0.018*	-	0.020**	0.040***

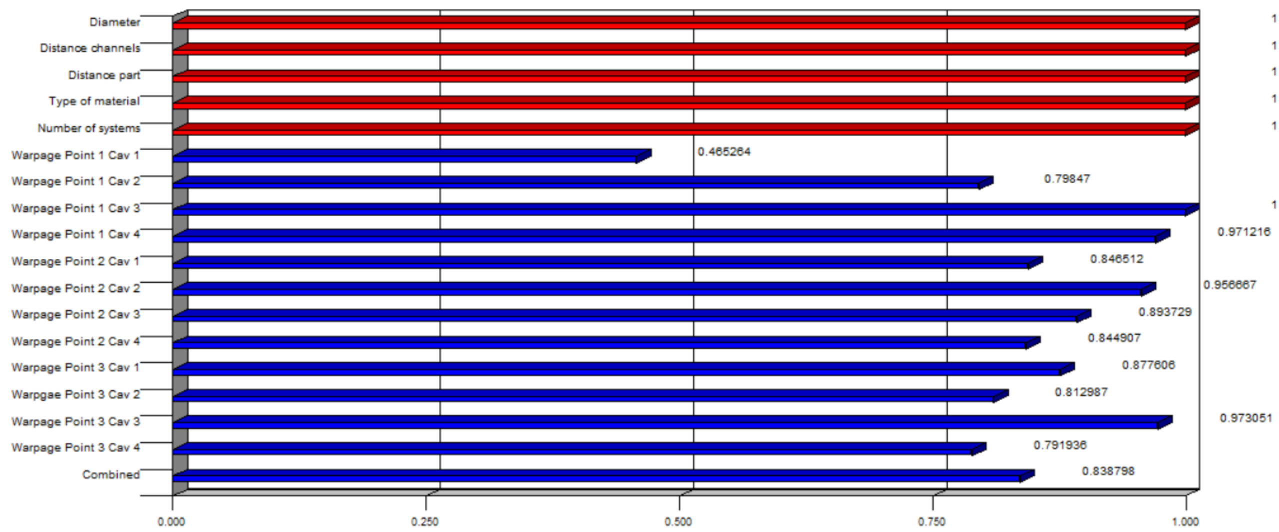


Figure 5.14 - Desirability of each response with the best combination of process parameters.

In order to compare the improvements between all optimizations, the max cooling time, until ejection temperature was reached, was recorded (Figure 5.15)

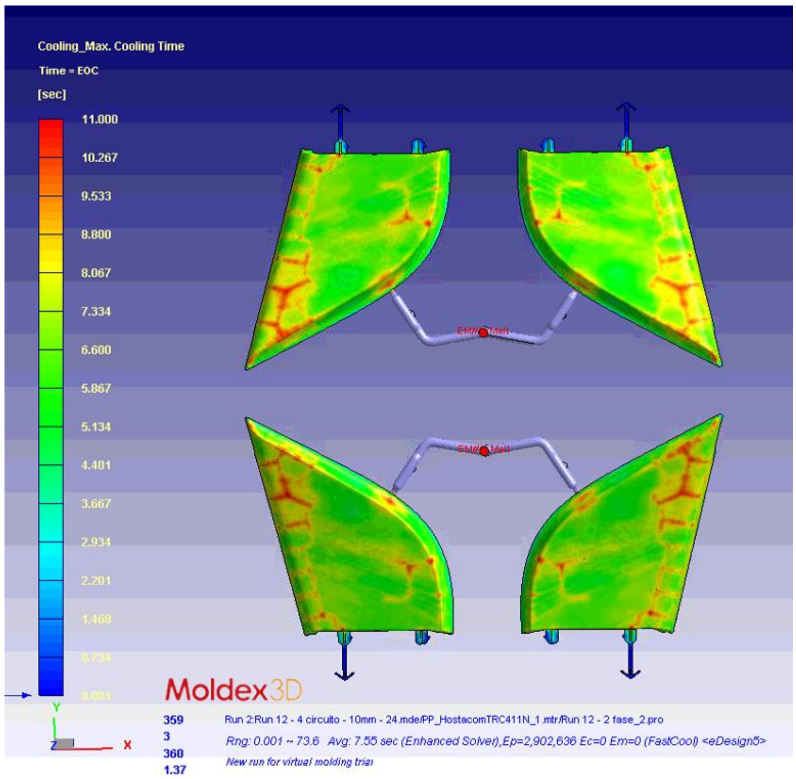


Figure 5.15 - Time to reach ejection temperature.

It was possible to observe (Figure 5.15) that with 12 sec of cooling time, almost all the part had green color, which means that those zones reached ejection temperature at around 6.6 seconds. Zones at red means that it took 11 seconds to reach ejection temperature. These zones were mainly at ribs of the part. As the ribs had more thickness than the rest of the part it was expected to take longer to cool until it reached ejection temperature. Note that, adding the double racks with cooling feature improved cooling inside pin holes. In the previous analysis, pin holes took 12 sec to reach ejection temperature and, in this case, it took 7,33 seconds. There were some places in the part, especially in the vertex, that was still red on the ribs. This happened due to the reduced quantity of cooling channels on the extraction side of the mold.

5.4 Results – Conformal Cooling Design Optimization

To determine if the new conformal design improved warpage, a simulation with optimized process parameters and design parameters was performed.

In this simulation, the results of point's warpage were: Point 1 Cavity 1 = 1.655 mm, Point 1 Cavity 2 = 1.648 mm, Point 1 Cavity 3 = 1.652 mm, Point 1 Cavity 4 = 1.640 mm, Point 2 Cavity 1 = 0.609 mm, Point 2 Cavity 2 = 0.611 mm, Point 2 Cavity 3 = 0.612 mm, Point 2 Cavity 4 = 0.613 mm, Point 3 Cavity 1 = 1.169 mm, Point 3 Cavity 2 = 1.138 mm, Point 3 Cavity 3 = 1.201 mm, Point 3 Cavity 4 = 1.204 mm.

In order to compare the improvements between all optimizations, the max cooling time, until ejection temperature was reached, was recorded (Figure 5.16)

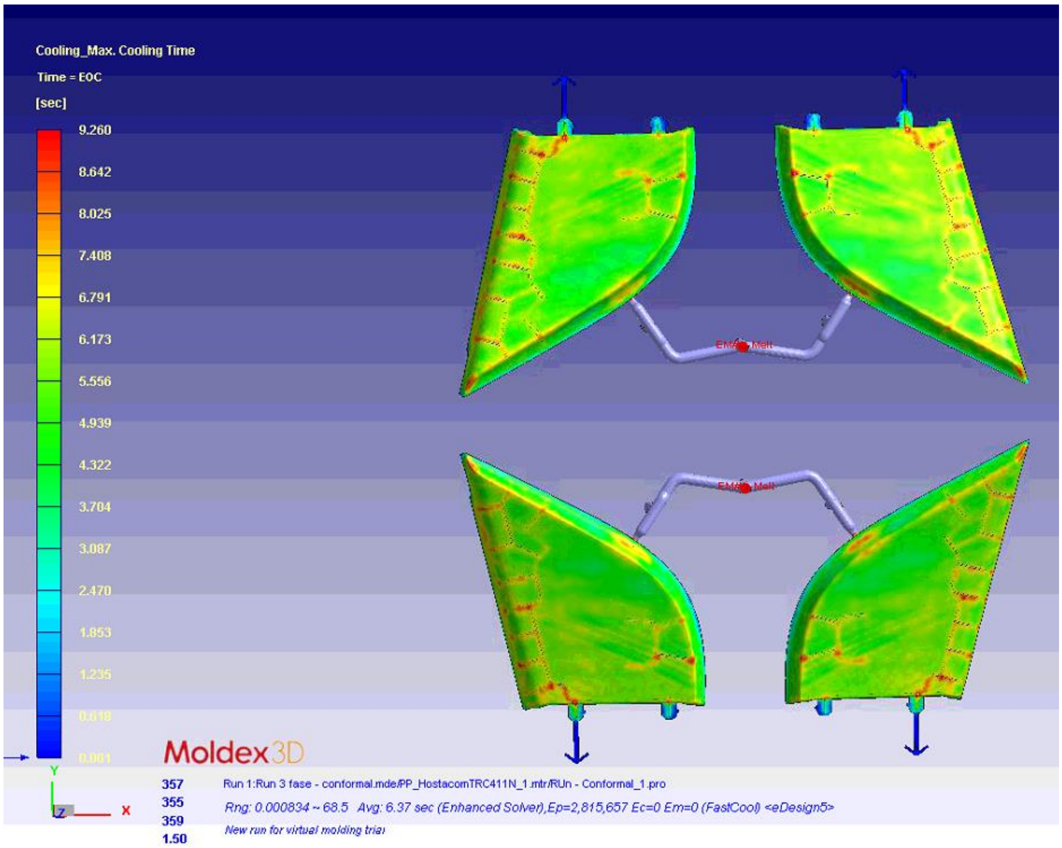


Figure 5.16 - Time to reach ejection temperature.

It was possible to observe (Figure 5.16) that with 12 seconds of cooling time, almost all the part had green color, which means that those zones reached ejection temperature at around 5.55 seconds. Zones at red means that it took 9.26 seconds to reach ejection temperature. These zones were mainly at ribs of the part. As the ribs had more thickness than the rest of the part it was expected to take longer to cool until it reached ejection temperature.

6. DISCUSSION

6.1 Process Parameters Optimization – Simulation Vs Experimental

In this work it was demonstrated that, for both optimizations, cooling time and injection temperature had the highest contribution to warpage. It was expected to decrease warpage with the increase of cooling time since the part remains a longer time inside the mold. It would guarantee the cooling constricted to the mold walls [22][23]. On the other hand, cooling time significance decreased with the decrease of injection temperature. Assuming a lower injection temperature, cooling time had lower significance to warpage, as the part reached the extraction temperature sooner. Although, if the injection temperature was higher, with 6 seconds of cooling time, there could be a possibility of the part not reaching extraction temperature. This meant a free cooling of the part outside the mold which would able warpage to form unevenly. Despite the lower cooling time significance, with lower injection temperatures, warpage was lower when cooling time was higher as the part would be extracted at lower temperature than extraction temperature. This meant that warpage would be formed evenly inside the mold [22].

For this part of the work it was expected to verify similar results between simulated and experimental work. As the results were both the same, it was possible to accept the simulation process for the next optimizations.

6.2 Conventional Straight-Drilled Design Optimization Vs Conformal Design Optimization

In this part of the work it was demonstrated that conventional straight-drilled cooling channels had a better result, to improve warpage, than conformal cooling channels. It went against what was expected as in literature conformal cooling channels usually gets better results [24][25][26]. One possible justification for this result is the fact that in literature authors do not always consider the complexity of the extraction system. In this work it was considered the extraction system as a priority and for that reason the cooling channels were drastically influenced by the position of the extractors. Due to this constrain the design was not symmetric between fixed and movable plates of the mold. As the warpage was influenced by temperature gradients, this asymmetric design could affect considerably the part's warpage [27][28]. It assumes that a higher temperature gradient increases warpage which meant that when it were added more channels and conformed to the part's geometry, only on the fixed plate of the mold, the cooling was even higher, on one side of the part, than in conventional design, increasing the difference of temperature from side-to-side of the part.

The conventional straight-drilled cooling channels optimization did not have any significant changes between all the runs. The factor that contributed more for the warpage decrease was the mold material but with small changes in warpage value, around 1 to 2% improvement. In this experiment, the mold material with better results was steel which supported the previous assumption of increasing the temperature gradient with a better cooling, assuming that it had asymmetric design, as it increases the difference of temperature between bottom and top of the part. This meant that if the design were made using the theoretical intervals, whatever the value used in this work, the cooling would be better to decrease warpage. The temperature gradient decreased with the introduction of cooled extractors to compensate the lack of cooling in the moving side of the mold.

The conformal cooling channels optimization used the same design parameters of conventional straight-drilled cooling channels optimization and the process parameters of the previous work. The results demonstrated that there was not any improvement in warpage value. On the other hand, there were an improvement in the maximum time to reach ejection temperature compared to the other designs. It was expected to perform this way, as the cooling is more effective and faster than the other designs [27].

6.3 Current Mold Vs Conventional Straight-Drilled Design Optimization Vs Conformal Design Optimization

Comparing all the cooling channels designs and process parameters optimizations, it was possible to determine which one had the best warpage results (Table 6-1). In this work, conformal cooling channels design was the worst design to improve warpage. Next came the current design with process parameters optimization. Finally, conventional cooling design was the best design to improve warpage.

Conventional cooling channels design had an improvement between 3 to 7% for point 1, 3 to 4% for point 2 and 3 to 12% for point 3.

Conformal cooling channels design had a major improvement in the maximum time to reach ejection temperature of 17% comparing to conventional cooling channels design optimization and 24% comparing to the current mold design.

Table 6-1 - Comparison Between Optimizations

Responses	Current Mold	Conventional Design Optimization	Conformal Design Optimization
Point 1 Cavity 1 (mm)	1.628	1.592	1.655
Point 1 Cavity 2 (mm)	1.630	1.617	1.648
Point 1 Cavity 3 (mm)	1.620	1.584	1.652
Point 1 Cavity 4 (mm)	1.672	1.567	1.640
Point 2 Cavity 1 (mm)	0.575	0.568	0.609
Point 2 Cavity 2 (mm)	0.591	0.570	0.611
Point 2 Cavity 3 (mm)	0.583	0.565	0.612
Point 2 Cavity 4 (mm)	0.573	0.568	0.613
Point 3 Cavity 1 (mm)	1.183	1.108	1.169
Point 3 Cavity 2 (mm)	1.229	1.087	1.138
Point 3 Cavity 3 (mm)	1.147	1.127	1.201
Point 3 Cavity 4 (mm)	1.180	1.151	1.204
Max. Time to reach ejection temperature (s)	12	11	9.2

7. CONCLUSION

In this thesis an optimization of the cooling channels design, to improve warpage from a case study part, was proposed. The design of experiments and ANOVA methods were used to study which process and design parameters would contribute more for the parts' warpage. A comparison between experimental and simulated results was performed to validate the software MOLDEX3D. Next, a DOE was performed and analyzed using ANOVA method to find the optimized process parameters within an interval of values previously defined. After the validation of the software and process parameters optimized, a new cooling design using conventional straight-drilled cooling channels was studied through a DOE and analyzed by ANOVA using theoretical values. Finally, another cooling design was proposed using conformal cooling channels was studied by means of a DOE and analyzed by ANOVA method applying the previous optimized process parameters and optimized design parameters.

Results demonstrated that experimental and simulated work presented the same behavior and the factors, which contributed more to warpage, were cooling time and injection temperature. The way that each factor influenced warpage was the same meaning that MOLDEX3D was validated and was able to be used in the next work. In this case, increasing cooling time would decrease warpage and decreasing injection temperature would, as well, decrease warpage.

Regarding conventional straight-drilled cooling channels optimization, results concluded that mold material was the factor that had the biggest contribution in warpage. For any values used in the other factors, there were not significant contribution. It was concluded, as well, that conventional optimization had better warpage results than the previous model, which meant that for every value used in conventional design it would be better for warpage.

For the conformal cooling channels optimization, the results presented a decrease in warpage results. One possible cause was the asymmetric design of cooling channels between moving and fixed side of the mold as the temperature gradient raised.

As a conclusion, the optimization was successful using conventional straight-drilled cooling channels, with the optimized process parameters. Cooling time was the factor that contributed the most to the optimization with a 70% contribution.

8. FUTURE WORK

For future work is proposed:

I. Apply this model to a part with a less complicated geometry in order to study a symmetric cooling design;
II. Produce a tool with the optimized cooling channels in order to verify the simulated results;
III. Apply this method of process optimization to all tools from COPEFI in order to improve parts quality;
IV. Test this method for other parts defects, such as, sink holes, shrinkage, voids, and others;
V. For a better study, in the future, the tool should have temperature and pressures sensors in order to assess at more trustworthy results in experimental phase;

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APPENDIX

Appendix I

Technical Data Sheet

Hostacom TRC 411N NAT

Polypropylene Compounds

Product Description

Hostacom TRC 411N NAT is a 15% talc filled PP copolymer compound with high flowability, good impact/stiffness balance, offering low odour and low emissions performances.
The use of colour masterbatch with this specific natural base is offering good scratch performances in final part.
The product is available as natural, pellet form.

Regulatory Status

For regulatory compliance information, see *Hostacom* TRC 411N NAT Product Stewardship Bulletin (PSB) and Safety Data Sheet (SDS).

This grade is not intended for medical, pharmaceutical, food and drinking water applications.

Status	Commercial: Active
Availability	Europe
Application	Automotive Parts; Instrument Panels; Interior Automotive Applications
Market	Automotive
Processing Method	Injection Molding
Attribute	Ductile; Good Abrasion Resistance; Good Colorability; Good Processability; Good Stiffness; Good Surface Finish; High Flow; High Impact Resistance; Low Density; Low Temperature Impact Resistance; Low to No Odor; Low VOC Emission; Scratch Resistant; UV Resistant

Typical Properties	Nominal Value	Units	Test Method
Physical			
Melt Flow Rate, (230 °C/2.16 kg)	19	g/10 min	ISO 1133-1
Density, (23 °C)	1.02	g/cm³	ISO 1183-1/A
Mechanical			
Flexural Modulus, (23 °C, Tech. A)	1800	MPa	ISO 178/A1
Impact			
Charpy Impact Strength - Notched, (23 °C)	30	kJ/m²	ISO 179-1/1eA
Thermal			
Deflection Temperature Under Load, (0.45 MPa, Unannealed)	90	°C	ISO 75B-1, -2

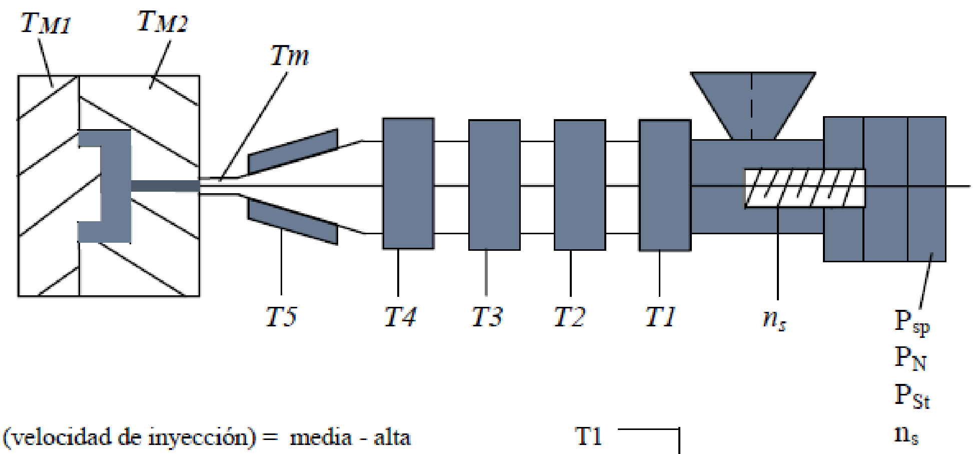
Figure 0.1 - Material Datasheet

lyondellbasell

Información de producto

Inyección de Hostacom y Hifax

Valores orientativos de transformación por inyección.



Vi (velocidad de inyección) = media - alta
Pi (presión de inyección) = 750-1200 bar
Tm (temperatura de masa) = 200-270°C
TM1/TM2 (temperatura del molde) = 20 - 50 °C

T1, T2, T3, T4, T5 → 200-270 °C

Tiempo máximo de permanencia en cilindro: no es problemático, pero depende de la temperatura empleada: por ej. con temp. de masa 240 – 260°C hasta 20" la degradación no es excesiva, a 280°C y 5" la degradación ya es importante.
Presión inyección = P_{sp} = 750 – 1200 bars
Presión mantenimiento = P_N = 50-70% presión de inyección.
Contrapresión de llenado (P_{st}) y velocidad de giro de husillo (n_s) según necesidad.
Tipo boquilla: abierta o cerrada

Otras consideraciones:
Prever salidas de gases en el molde (0.01-0.02 mm).
La transformación con máquinas provistas de desgasificación no presenta problemas.
En caso de realizarse secado previo: 2h-3h a 80 - 100°C.
Evitar el contacto del material fundido con la piel.

Figure 0.2 - Material Datasheet

MARYASA

ORDEM DE ENSAIO N : 309
CLIENTE COPEFi
MOLDE Nº
DESCRIÇÃO MiRROR TRiM /CACHERETRO

DADOS DE REGISTO

DATA 25/11/2019
HORA INICIO 10:00
MÁQUINA INJ 450 TON. M. PRIMA PP-HOSTACOM TRC411N HORA FIM __:__
FORÇA DE FECHO UTILIZADA 450 l. BAR T. CICLO 55 SEG.

TEMPERATURAS	DOSAGEM FUSO 100 MM
BICO 220 GRº	CONTRA PRESSÃO 8 BAR
RESISTÊNCIA SEGUINTE 215 GRº	VELOCIDADE DE ROTAÇÃO 55 MM
RESISTÊNCIA SEGUINTE 210 GRº	DESCOMPRESSÃO 7 BAR
RESISTÊNCIA SEGUINTE 200 GRº	TEMPERATURA MOLDE Nº GRUPOS
RESISTÊNCIA SEGUINTE 195 GRº	MACHO 40 Nº 1
RESISTÊNCIA SEGUINTE ____ GRº	CAVIDADE 40 Nº 1

CANAIS QUENTES

Nº1 220	Nº4 220	Nº7	Nº10
Nº2 220	Nº5	N8º	Nº11
Nº3 220	Nº6	Nº9	Nº12

1ª INJECÇÃO | PERFIL: SIM ___ NÃO X		2ª INJECÇÃO ALMOF. REAL 15,1 MM	
1ª VELOCIDADE 40	1ª PRESSÃO 120 BAR	1ª VELOCIDADE 10	1ª PRESSÃO 55 BAR
2ª VELOCIDADE	2ª PRESSÃO BAR	2ª VELOCIDADE 10	2ª PRESSÃO 45 BAR
3ª VELOCIDADE	3ª PRESSÃO BAR	3ª VELOCIDADE 10	3ª PRESSÃO 35 BAR
4ª VELOCIDADE	4ª PRESSÃO BAR	4ª VELOCIDADE	4ª PRESSÃO BAR
5ª VELOCIDADE	5ª PRESSÃO BAR	5ª VELOCIDADE	5ª PRESSÃO BAR
TEMPO INJ 2,3 SEG	TEMP. ARREF. 20 SEG	ENT. 28 MM	TEMPO 3+3+3 SEG

MACHO ___ VALVE GATE ___ | FECHO	MACHO ___ VALVE GATE ___ | ABERTURA
TEMPO ___ FICHA SEGURANÇA ___	TEMPO ___ FICHA SEGURANÇA ___
TEMPO ___ SEG CABO ___	TEMPO ___ SEG CABO ___
COTA/MOLDE ___ MM	COTA/ MOLDE ___ MM
PRESSÃO ___ BAR	PRESSÃO ___ BAR
VELOCIDADE ___ BAR	VELOCIDADE ___ BAR
OBS:	OBS:

ABERTURA MOLDE ___ MM	FECHO| SEGURANÇA ___ MM|BAR ___
1ª ___ MM BAR ___	1ª ___ MM BAR ___
2º ___ MM BAR ___	2º ___ MM BAR ___
3º ___ MM BAR ___	3º ___ MM BAR ___
4º ___ MM BAR ___	4º ___ MM BAR ___
TIPO DE LIGAÇÃO AR ABERTURA ___	TIPO DE LIGAÇÃO AR ABERTURA ___
1ª ___ MM BAR ___	1ª ___ MM BAR ___
2º ___ MM BAR ___	2º ___ MM BAR ___

OBS:

AFINADO POR: Ricardo

MOD009/R00
Elaborado por: DS
Aprovado por: MS

Página 1 de 1

Edição n.º 1
08/03/2019

Figure 0.3 - Process Parameters. Process parameters used in the production of the parts.

Appendix II - Moldex3D Simulations and Optimization's Data

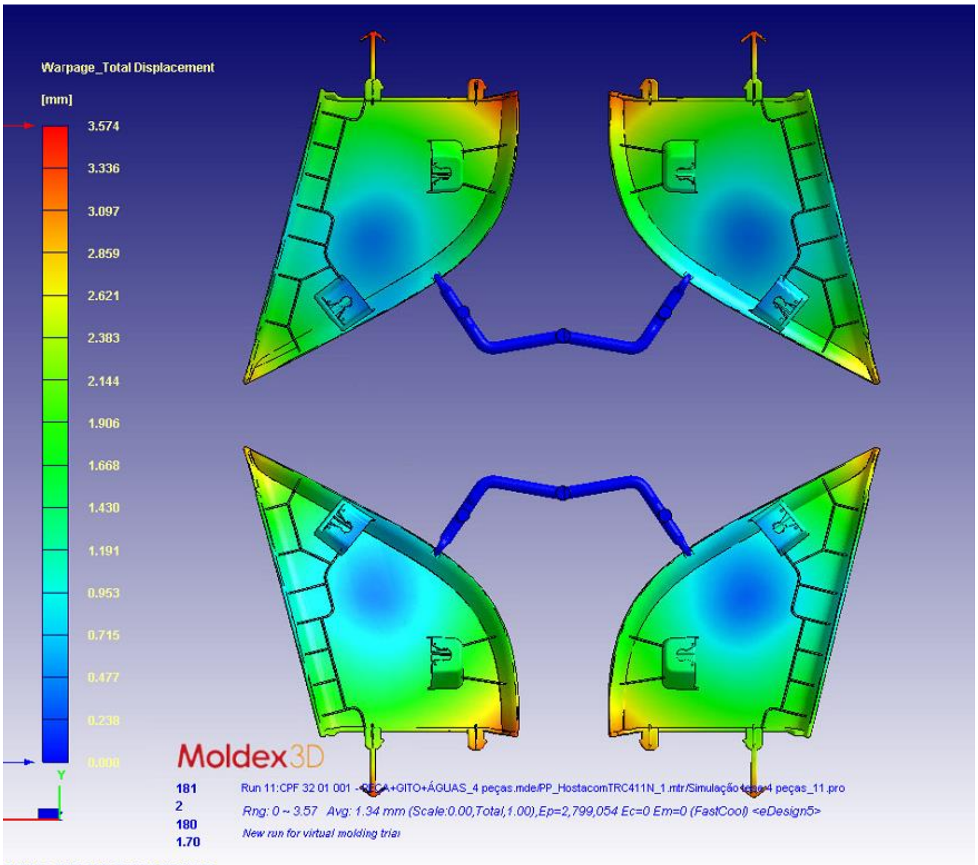


Figure S2 - 1 - Worst Run for Conventional Process Optimization.

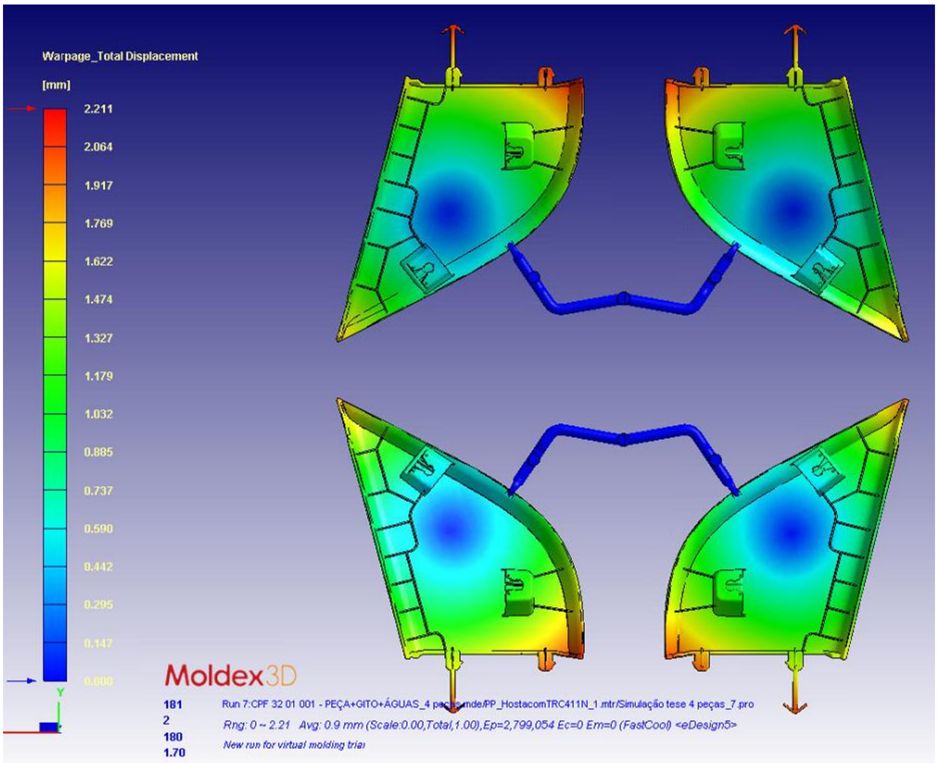


Figure S2 - 2 - Best Run for Conventional process Optimization.

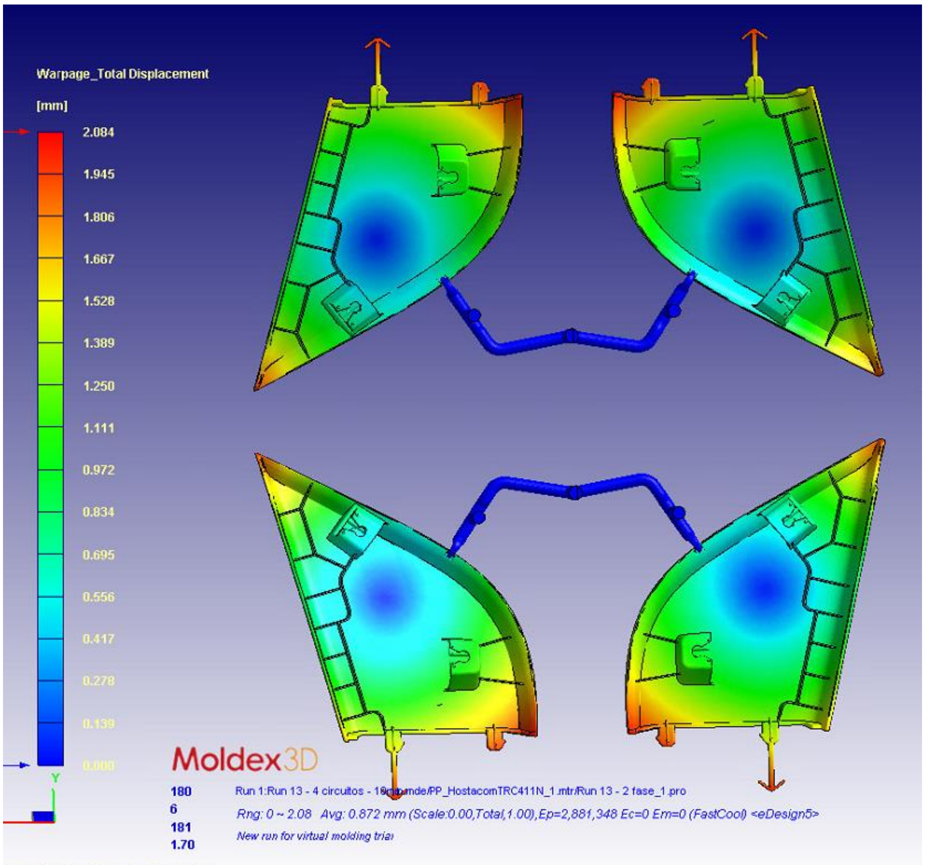


Figure S2 - 3 - Worst Run for Conventional Design Optimization.

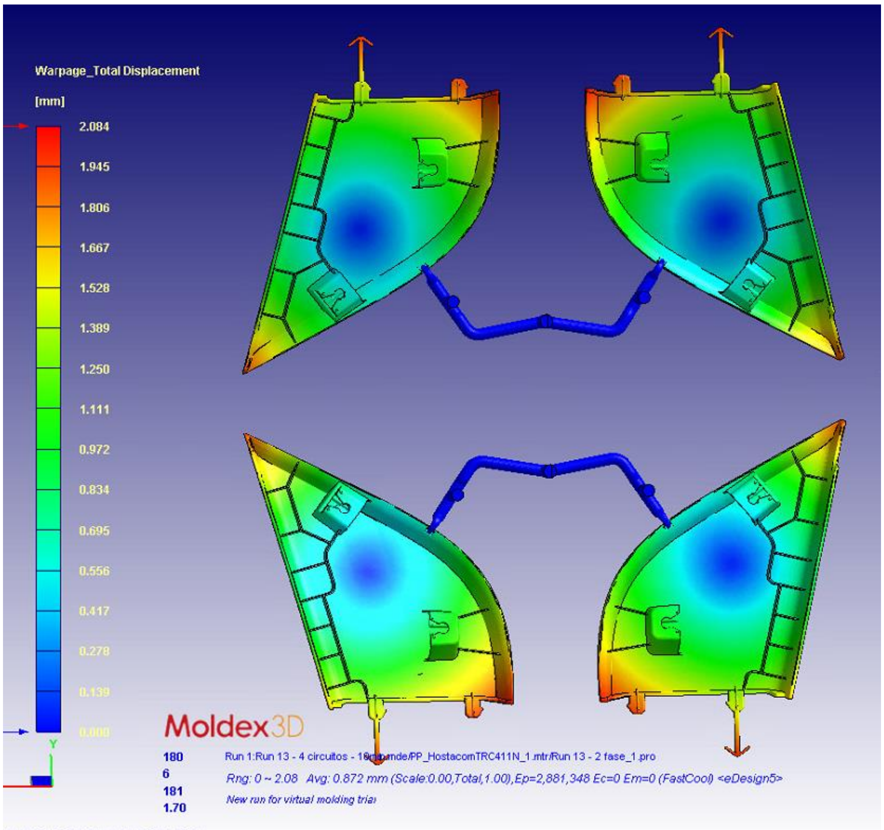


Figure S2 - 4 - Best Run for Conventional Design Optimization

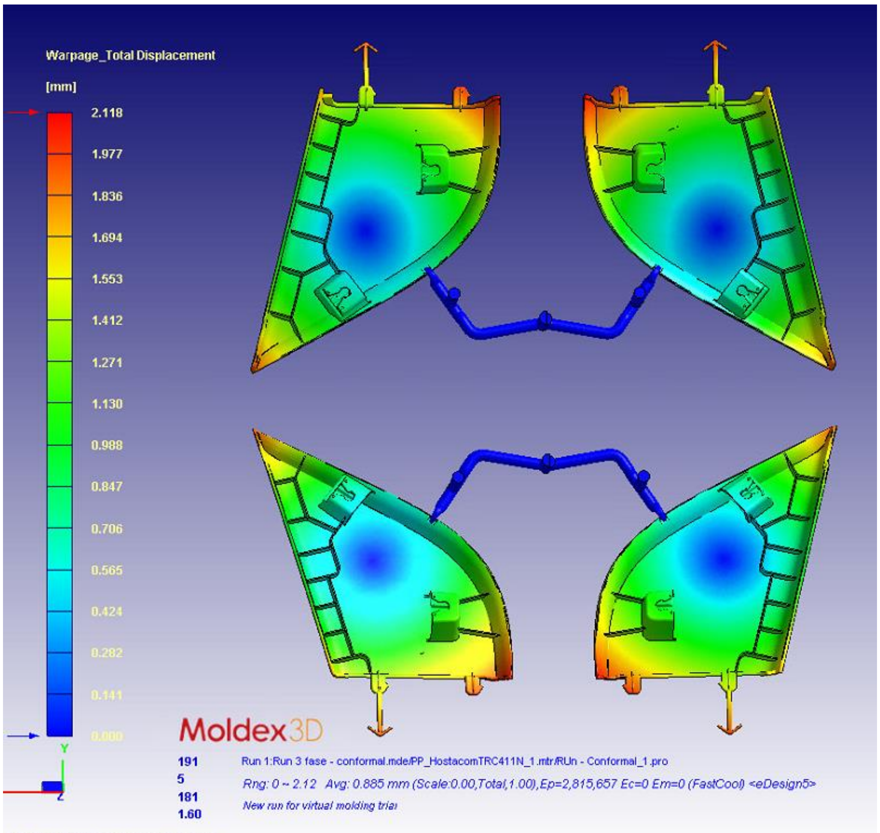


Figure S2 - 5 - Conformal Design Optimization

Table S2 - 1 - Conventional Optimization Data

		Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Response 1	Response 2	Response 3
Std	**Run**	**A:Mold Temperature**	**B:Injection Temperature**	**C:Injection Speed**	**D:Holding Pressure Speed**	**E:Cooling Time**	**Warpage Point 1 Cav1**	**Warpage Point 1 Cav 2**	**Warpage Point 1 Cav 3**
5	1	20.00	270.00	0.50	5.00	12.00	1.914	1.765	1.889
6	2	20.00	270.00	0.50	6.00	6.00	2.294	2.100	2.271
15	3	50.00	270.00	1.00	5.00	12.00	1.973	1.819	1.954
8	4	20.00	270.00	1.00	6.00	12.00	1.805	1.669	1.782
4	5	20.00	230.00	1.00	6.00	6.00	1.967	1.824	1.963
9	6	50.00	230.00	0.50	5.00	12.00	1.765	1.633	1.751
12	7	50.00	230.00	1.00	6.00	12.00	1.672	1.547	1.657
2	8	20.00	230.00	0.50	6.00	12.00	1.783	1.645	1.759
11	9	50.00	230.00	1.00	5.00	6.00	2.301	2.134	2.300
10	10	50.00	230.00	0.50	6.00	6.00	2.158	1.337	2.155
13	11	50.00	270.00	0.50	5.00	6.00	2.706	2.504	2.692
16	12	50.00	270.00	1.00	6.00	6.00	2.502	2.285	2.466
14	13	50.00	270.00	0.50	6.00	12.00	1.851	1.707	1.839
1	14	20.00	230.00	0.50	5.00	6.00	2.164	1.995	2.153
3	15	20.00	230.00	1.00	5.00	12.00	1.722	1.613	1.723
7	16	20.00	270.00	1.00	5.00	6.00	2.411	2.206	2.388

	Response 4	Response 5	Response 6	Response 7	Response 8	Response 9	Response 10	Response 11	Response 12
Run	Warpage Point 1 Cav 4	Warpage Point 2 Cav 1	Warpage Point 2 Cav 2	Warpage Point 2 Cav 3	Warpage Point 2 Cav 4	Warpage Point 3 Cav 1	Warpage Point 3 Cav 2	Warpage Point 3 Cav 3	Warpage Point 3 Cav 4
1	1.983	0.698	0.669	0.698	0.711	1.645	1.565	1.550	1.458
2	2.407	0.671	0.628	0.683	0.708	1.675	1.595	1.572	1.504
3	2.075	0.639	0.606	0.648	0.667	1.555	1.510	1.474	1.423
4	1.863	0.707	0.684	0.707	0.712	1.588	1.503	1.497	1.411
5	2.048	0.643	0.602	0.643	0.675	1.493	1.431	1.412	1.344
6	1.839	0.608	0.580	0.612	0.629	1.448	1.406	1.375	1.311
7	1.745	0.606	0.582	0.611	0.621	1.396	1.347	1.325	1.267
8	1.843	0.674	0.648	0.668	0.683	1.563	1.483	1.481	1.387
9	2.418	0.754	0.711	0.749	0.788	1.640	1.594	1.560	1.495
10	2.240	0.668	0.634	0.671	0.701	1.544	1.493	1.460	1.404
11	2.802	0.797	0.747	0.802	0.840	1.837	1.778	1.735	1.667
12	2.628	0.753	0.707	0.758	0.793	1.734	1.676	1.642	1.581
13	1.934	0.605	0.573	0.614	0.630	1.503	1.461	1.418	1.349
14	2.264	0.658	0.664	0.664	0.694	1.579	1.512	1.490	1.424
15	1.781	0.687	0.650	0.668	0.695	1.508	1.456	1.444	1.351
16	2.553	0.725	0.683	0.732	0.764	1.689	1.620	1.590	1.531

Table S2 - 2 - Experimental Optimization Data

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3	Response 4
Std	**Run**	**A:Mold Temperature**	**B:Injection Temperature**	**C:Cooling time**	**D:Holding Pressure**	**Warpage Point 1 Cav 1**	**Warpage Point 1 Cav 2**	**Warpage Point 1 Cav 3**	**Warpage Point 1 Cav 4**
4	1	20.00	270.00	12.00	5.00	1.0584	0.5688	0.8577	0.6674
2	2	20.00	230.00	12.00	6.00	0.3727	0.4864	0.2454	0.5826
6	3	50.00	230.00	12.00	5.00	0.8435	1.1291	0.9947	0.8708
8	4	50.00	270.00	12.00	6.00	1.1638	0.7609	0.9337	0.5387
3	5	20.00	270.00	6.00	6.00	1.0691	1.132	1.1839	0.9231
7	6	50.00	270.00	6.00	5.00	2.1624	1.1884	1.1859	1.791
1	7	20.00	230.00	6.00	5.00	0.8636	0.742	0.9885	0.4806
5	8	50.00	230.00	6.00	6.00	1.1345	1.2286	1.2824	0.2556

	Response 5	Response 6	Response 7	Response 8	Response 9	Response 10	Response 11	Response 12
Run	**Warpage Point 2 Cav 1**	**Warpage Point 2 Cav 2**	**Warpage Point 2 Cav 3**	**Warpage Point 2 Cav 4**	**Warpage Point 3 Cav 1**	**Warpage Point 3 Cav 2**	**Warpage Point 3 Cav 3**	**Warpage Point 3 Cav 4**
1	1.08	0.7813	1.322	1.1403	1.4825	1.0453		
2	0.33	0.3744	0.4215	0.4501	0.3967	0.4485	2.0232	1.6468
3	0.84	1.1623	1.2142	1.4093	1.1325	1.7607	0.7353	0.775
4	0.95	0.7627	1.2401	0.9535	1.4144	1.0501	1.9734	2.1676
5	0.99	1.0944	1.052	1.1208	1.5229	1.7316	1.9387	1.3988
6	1.07	1.0494	1.3071	1.2991	2.2242	1.7627	1.8835	1.8269
7	0.61	0.6333	1.0618	0.8176	0.9083	0.8871	2.3188	2.5473
8	1.10	1.0202	1.358	1.0449	1.6564	1.6292	1.6906	1.2068