UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Ingegneria Industriale

Corso di Laurea Magistrale in Ingegneria dei Materiali

# CONFORMAL COOLING ANALYSIS FOR A COMPLEX PIECE IN MOLDFLOW

**Relatore: Prof. Massimo Guglielmi**

**Correlatori: Prof. Inês da Fonseca Pestana Ascenso Pires**
**Prof. Bárbara Perry Pereira Alves Gouveia Almeida**
**Prof. Rui Manuel Dos Santos Oliveira Baptista**

**Laureanda: Eleonora Caneve**

Anno Accademico 2022 - 2023

Dedicated to my family.

# Acknowledgments

Il primo pensiero è nella mia lingua madre, perchè è in italiano che voglio ringraziare le persone più importanti. Non sarei qui se non avessi avuto il sostegno della migliore famiglia del mondo. Mi hanno visto prendere la decisione di partire in piena pandemia per due anni in un paese estero di cui non conoscevo nulla e dove non conoscevo nessuno. Mi hanno sostenuta nel processo di selezione, accompagnata nei primi passi di questa esperienza, e poi sostenuta durante ogni momento di questa avventura. Mi hanno visto felice, mi hanno visto triste, mi hanno visto spaventata... Mi hanno visto innamorarmi della città che è diventata la mia seconda casa. E nonostante le paure e preoccupazioni mi hanno lasciato prendere il volo.

The next thought goes to all the friends that have come and left in these two years. People from every country that have crossed my path and became part of this experience. They have permitted me to discover new ideas, new cultures, and new horizons. They have been the colors with which I have painted this story.

E por último, mas não menos importante, aos Portugueses, a Lisboa e a Portugal. Lisboa foi a minha casa por dois anos. As ruas cheias, o tráfico da grande cidade, o Tejo, e o cheiro a bacalhau e pastéis de nata. Sem a vitalidade desta cidade nada disto seria possível. Ao meu amor, que só chegou há um ano nesta aventura mas que tornou tudo mais colorido e à minha nova família portuguesa, que cuidou de mim quando tive saudades da minha que estava longe.

To each and every one of you - Grazie, Thank you, Obrigada!

Este trabalho foi desenvolvido no âmbito do projeto S4Plast – Sustainable Plastics Advanced Solutions, Projeto Mobilizador Nº 46089, Ref. POCI-01-0247-FEDER-046089, no âmbito do programa PORTUGAL 2020, e cofinanciado pela União Europeia através do FEDER

## Abstract

Conformal Cooling (CC) will define the future of injection molding and mold manufacturing. By creating CC channels that follow the unique geometry of an injection molded part, engineers can better optimize their cooling lines. The results are reduced costs and increased profits.

The following work is part of a bigger project (S4PLAST- ”Sustainable Plastics Advanced solutions) where, in collaboration with the Erofio company, the need for more accurate injection molding simulation of parts with complex CC systems is being assessed. Being CC a relatively new technology, software programs are still under development.

This thesis project is intended to simulate the initial steps of the development of new complex pieces. The main goal is to study the possible ways to import already existing geometries and data into Moldflow, try to run and eventually correct errors and problems in the analysis, and in the end, obtain results that can be used for the development of the optimal production conditions. This project is intended to understand the limits of Moldflow analysis on systems that require CC.

This thesis goes in-depth on the feasibility study of Moldflow analysis on systems that require CC in order to be able to simulate numerically the cooling system as close to reality as possible.

This project determined that it is possible to simulate the injection molding process for complex pieces that require CC circuits in Moldflow. However, Moldflow seems to be in its infancy for the simulation of CC systems with major problems, especially when importing complex geometries. Regarding the company-provided piece, Moldflow analysis results suggest that it is not possible to produce the piece with the geometries and set of parameters given by the company.

**Keywords:** Injection molding, Moldflow, Conformal cooling, Cooling system, Cooling channels, Cool analysis, Import procedure.

## Resumo

Conformal Cooling (CC) definirá o futuro da moldagem por injeção e fabricação de moldes. Ao criar canais CC que seguem a geometria única do molde de uma peça moldada por injeção, engenheiros podem otimizar melhor as linhas de refrigeração. Os resultados são uma redução de custos e aumento de lucros.

O seguinte trabalho está enquadrado no projeto S4PLAST (Sustainable Plastics Advanced Solutions) onde, em colaboração com a empresa Erofio, está a ser avaliada a necessidade de simulação de moldagem por injeção mais precisa de peças com sistemas CC complexos. Sendo CC uma tecnologia relativamente nova, os programas de software ainda estão em desenvolvimento.

Este projeto de tese tenciona a simular os passos iniciais do desenvolvimento de novas peças complexas. O objetivo principal é estudar as possíveis formas de importar geometrias e dados já existentes para o Moldflow, tentar executar e eventualmente corrigir erros e problemas na análise e, no final, obter resultados que possam ser utilizados para o desenvolvimento das condições de produção ideais. Este projeto visa entender os limites da análise do Moldflow em sistemas que requerem CC.

Esta tese é um estudo aprofundado de viabilidade da análise Moldflow em sistemas que requeiram CC tentando simular numericamente os canais de refrigeração o mais próximos da realidade quanto possível.

Este projeto concluiu que é possível simular o processo de moldagem por injeção de peças complexas que requerem circuitos CC no Moldflow. No entanto, o Moldflow parece estar na sua infância para a simulação de sistemas CC, com grandes problemas principalmente na importação de geometrias complexas. Relativamente à peça fornecida pela empresa, os resultados da análise em Moldflow sugerem que não é possível produzir a peça com as geometrias e conjunto de parâmetros fornecidos pela empresa.



**Palavras-chave:** Moldagem por injeção, Moldflow, Refrigeração conformal, Sistema de refrigeração, Canais de refrigeração, Análise de refrigeração, Procedimento de importação.

## Sommario


Il raffreddamento conforme (Conformal cooling, CC) ha il potenziale per definire il futuro dello stampaggio a iniezione e della produzione di stampi. Creando canali CC che seguono la geometria del pezzo, gli ingegneri possono ottimizzare molto più facilmente le linee di raffreddamento. I risultati sono costi ridotti e maggiori profitti.

Il seguente lavoro fa parte di un progetto più ampio (S4PLAST- "Sustainable Plastics Advanced solutions") dove, in collaborazione con l'azienda Erofio, si stanno studiando soluzioni alla necessità di simulazioni più accurate dello stampaggio ad iniezione di parti con sistemi CC complessi. Essendo CC una tecnologia relativamente nuova, i software di simulazione sono ancora in fase di sviluppo.

Questo progetto di tesi è pensato per aiutare Erofio a simulare le fasi iniziali dello sviluppo di nuovi pezzi con geometria complessa. L'intento principale è quello di studiare le possibili modalità di importazione in Moldflow di geometrie e dati già esistenti, cercare di eseguire ed eventualmente correggere errori nell'analisi e, infine, ottenere risultati che possano essere utilizzati per lo sviluppo delle condizioni di produzione ottimali. Questo progetto ha quindi lo scopo di comprendere i limiti dell'analisi in Moldflow di sistemi che richiedono CC.

Questa tesi approfondisce lo studio di fattibilità dell'analisi Moldflow su sistemi che richiedono CC, al fine tentare di simulare questi canali in modo più vicino possibile alla realtà.

Questo progetto definisce che è possibile simulare il processo di stampaggio a iniezione per pezzi complessi che richiedono circuiti CC in Moldflow. Tuttavia, il software sembra essere ancora in fase di sviluppo per la simulazione di sistemi CC, con grossi problemi soprattutto nella procedura di importazione. Per quanto riguarda il pezzo fornito dall'azienda, i risultati dell'analisi Moldflow suggeriscono che non è possibile produrre il pezzo con le geometrie e l'insieme di parametri forniti.



**Parole chiave:** Stampaggio a iniezione, Moldflow, Raffreddamento conforme, Sistema di raffreddamento, Canali di raffreddamento, Analisi di raffreddamento, Procedura di importazione.

# Contents

# List of Tables

# List of Figures

# Nomenclature

### Greek symbols

$\nu$ Viscosity $(m^2 * s^{-1})$

$\rho$ Density $(kg * m^{-3})$

### Roman symbols

$A$ Surface area $(m^2)$

$C_f$ Surface friction factor

$C_p$ Specific heat $(J * Kg^{-1} * K^{-1})$

$d$ Cooling channel diameter $(m)$

$h_C$ Contact heat transfer coefficient $(W * m^{-2} * K^{-1})$

$k_{st}$ Thermal conductivity of the mold $(W * m^{-1} * K^{-1})$

$L$ Cooling channel length $(m)$

$\Delta P$ Pressure drop $(Pa)$

$R_a$ Surface roughness of the channel wall $(m)$

$Re$ Reynolds number

$s$ Part thickness $(m)$

$T_C$ Coolant temperature $(K)$

$t_C$ Cooling time $(s)$

$T_E$ Ejection temperature $(K)$

$T_i$ Initial temperature of the cavity $(K)$

$T_M$ Melt temperature $(K)$

$T_W$ Mold temperature $(K)$

$V$ Volume of the cavity $(m^3)$

$x$ Pitch between two neighboring cooling channels $(m)$

# Acronyms

**3D** Three Dimensional.

**AM** Additive Manufacturing.

**BEM** Boundary Element Method.

**CAD** Computer-Aided Design.

**CC** Conformal Cooling.

**CFD** Computational Fluid Dynamics.

**DD** Dual Domain.

**DMLS** Direct Metal Laser Sintering.

**DOE** Design Of Experiment.

**FEM** Finite Element Method.

**L-PBF** Laser Powder Bed Fusion.

**RPI** Relatório de Parâmetros de Injeção.

# Chapter 1

# Introduction

The following work is intended to go in-depth on the feasibility study of Moldflow analysis on systems that require Conformal Cooling (CC).

This work is part of a bigger project (S4PLAST- "Sustainable Plastics Advanced solutions) where in collaboration with Erofio company it was found the need for more accurate injection molding simulation of parts with complex cc systems. In that context, this thesis aims to study the possible ways to import already existing geometries and data in Moldflow, try to run and eventually correct errors and problems in the analysis, and in the end obtain results that can be used for the development of optimal production conditions. At the current moment, the company uses Moldex as analysis software for the simulation of the injection molding process over pieces that present some complicated geometries or that require intricated cooling systems, but the results are not in line with what was obtained in the experimental trials. The hope is to be able to find a way to use Moldflow for these analyses, avoiding great money and time losses for the company in the attempt to find the optimal production conditions by experimental trials.

After a quick introduction to the company that produces this piece, a detailed description of the piece is presented and completed with a brief introduction to the cooling system and mold that the company has already developed.

## 1.1 Quick overview on the company: Erofio

The Erofio Group specializes in providing solutions for the thermoplastic injection industry, using the best technology available for the design, production, and quality control in the supply of molds and plastic injection products. The group's companies excel in accuracy and quality, investing in technology, equipment, and training of their employees.

The company can follow the whole injection molding process from the design of the piece to the design and construction of the mold, up to the final injection once the mold has been calibrated to obtain the correct tolerance and quality specifications for the final piece. The customer is followed from the beginning to the end of the whole process. This has been made possible thanks to the creation of two


Figure 1.1: Presentation of the company logo (on the left) and main goals (on the right) as presented on the company site.

separate divisions of the company:

- Erofio SA (Toolmaking division) - founded in 1990, starting the manufacture of molds for the electronics, home appliances, and automobile industries. The evolution and demand of the various markets led to a firm commitment to the certification of their management and production activities. The company is proudly certified ISO 9001:2015. Their growth is supported by adequate financial management, attention to the updating of knowledge and technologies and a qualified and experienced team, sharing the goals of growth and consolidation, and a loyal customer base due to the continuity of good service provision. In 2021 they also founded the additive manufacturing unit.
- Erofio Atlântico SA (Plastic division) - With the need to validate the molds made at Erofio SA, in 2000, Erofio Atlântico SA is found. The simple validation of molds has then become effective production in time, establishing lasting relationships with the customers, who now trust the company to produce their plastic components. Also, Erofio Atlântico SA is certified ISO 9001 (quality) and also IATF 16949 (quality for automotive) extending their customers in the automotive industry.

Nowadays, following the increasing interest in CC channels, the company is implementing this new technique in the construction of its molds. The complicacy of this process has forced the company to integrate its manufacturing power with an additive manufacturing unit and also to contact Instituto Superior Técnico for some help in the research. It is also a goal of this thesis to give feedback to the company on the results obtained with this work, to facilitate subsequent analysis that the company will have to perform.

## 1.2 Description of the piece

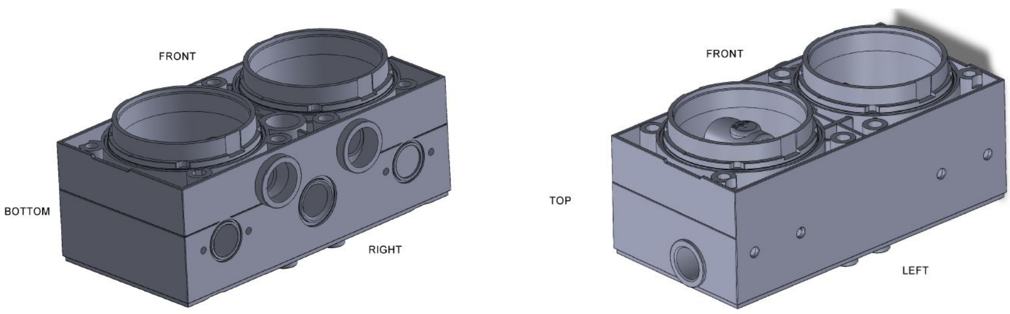
The piece under study is part of a medical device produced by Erofio spa. The company is starting the production of this piece and, due to its complexity, the trials that the company had to face before obtaining the final version of the mold have been multiple. This work aims to understand the methodology used by Moldflow for the numerical simulation of such complex CC channel systems. If representing this situation in Moldflow is possible and the analysis is run correctly, then a comparison between the obtained analytical results and the effective results from the attempts of the company in the last months may be analyzed at the end of this work or will be left as a future development for the current project.

Being involved in a sanitary environment it has to fit and hold in place the filters perfectly, and this restricts the dimensional tolerances to the very minimum.


Figure 1.2: Hospital air purifier machine in which the piece will work as filter's holder.

For the same reason, the material has to have all the specifications for medical fluid contact, and it also needs to stand any sterilization procedure that is necessary for its use. Being a filter for gases, it has to be taken into consideration that the pressures it is subjected to are very high. The specification given to the company is that the filter has to stand around 70 bars of pressure during validation tests. In figure 1.2 the air purifier is represented.

The piece has big dimensions, as shown in figure 1.5, so to reduce its weight, its thickness, and to permit its production a whole set of thin ribs has been thought to keep the shape. These ribs are built to maintain the structure of the piece and give mechanical stability to it, but they also are the main reason for the need for CC. A geometry with multiple holes as the one under observation does not allow traditional cooling channels to reach the inner surfaces of the piece to cool them down (figure 1.4). The distance of the cooling channels from the center of the piece is forcefully maintained by the presence of the ribs. Only a CC system or a very complex system of baffles will permit to cool down properly a piece of such complexity.




(a) Front-Bottom-Right view (b) Front-Top-Left view

Figure 1.3: Perspective view of the piece from two different angles. Emphasis is given in these views to show the filter seats on what is called the front side of the piece.

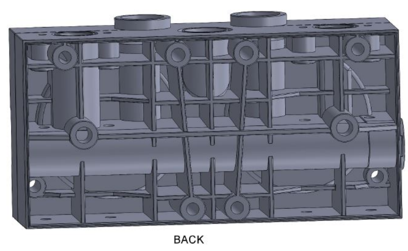



Figure 1.4: Perspective view of the back of the piece. This is the side that will be cooled by the CC system due to the presence of structural ribs.

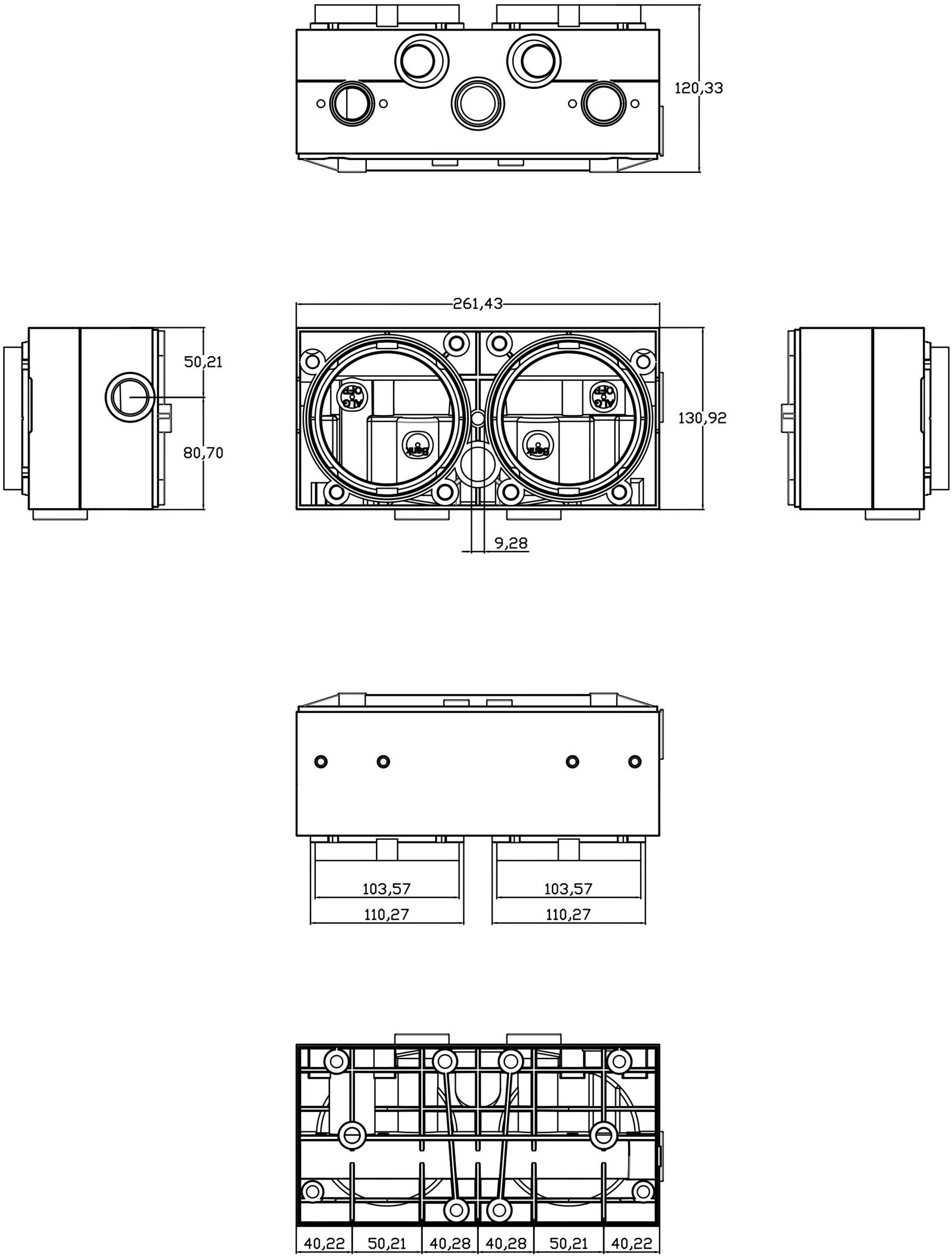
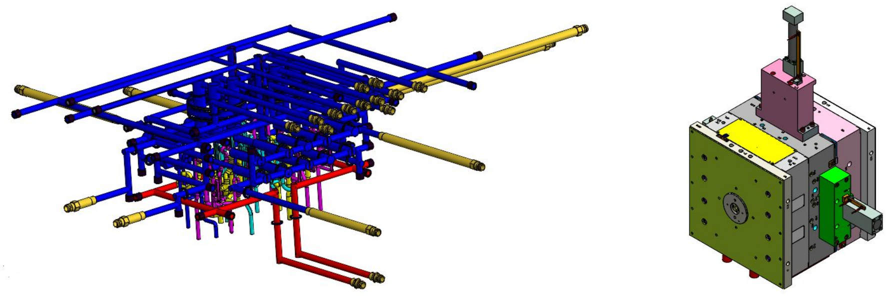



Figure 1.5: Projection view of the piece and dimensions.

To cool down this piece, the company has already developed a complicated cooling system that puts together some traditional cooling channels and some CC channels. The cooling system is represented in figure 1.6(a) and the mold is represented in figure 1.6(b).



(a) Cooling system

(b) Mold

Figure 1.6: Solidworks file geometry view of the cooling channels and mold defined by the company for the piece under study.

One important thing to mention: the piece went through some changes in geometry during the study. This has been an attempt to try to solve some of the problems that, from the very beginning, have been found by the observation of the analysis results. The variations thought for the solution have been found to be in alignment with what the company applied. This not only assures that the comparison between the results of the software analysis and the experimental results is still valid but also confirms that the software can point out defects that the part has had since the very beginning of the study.

## 1.3 Organization of the Document

This chapter has been written to be a general introduction to the case study that has been assigned. After this introduction, in chapter 2, it is necessary to go a little more in-depth into the CC to start understanding the challenges of this specific technology that is necessary for the assigned piece. Chapter 3 will then be spent describing all the initial steps of any Moldflow analysis. The software must have a correctly imported and meshed piece, a properly placed gate, and a functioning runner system to use as a base file for all the following steps. Fill and Pack analysis will follow.

After having obtained the base file for the geometry of the cavity, it is time to proceed with the cooling system and cooling analysis. Chapter 4 contains a detailed description of all the attempts to import the cooling system into Moldflow from external files with a relative explanation of the problems that have been faced during the study. Once one functioning solution for the representation of the cooling channels has been found, the chapter proceeds with the explanation of the Boundary Element Method (BEM) cooling analysis and the Finite Element Method (FEM) cooling analysis. Results and comparisons constitute the final paragraphs of the chapter.

The following chapter, chapter A, is spent over the complete Fill+Pack+Cool+Warp analysis and then in chapter 5 the conclusions for the whole project are treated and reported.

# Chapter 2

# Conformal Cooling

Injection molding is a well-known plastic-forming process using molds; it does not involve only plastic materials nowadays, but the focus will be kept on this category of materials. In this process, synthetic resins are heated and melted and then injected into the mold where they acquire the designed shape and then cool down until proper solidification before demolding. With injection molding, diversely shaped parts, including those with complex shapes, can be sequentially and quickly manufactured in large volumes. Therefore, injection molding is used to manufacture commodities and products in a wide range of industries. [1] In the last decades a new way of cooling has been studied and implemented due to its benefits over the process: conformal cooling.

To be able to develop the following project correctly, and consequently understand it, it is necessary to have a clear idea of the functioning of the traditional injection molding process and its variations due to the application of conformal cooling. A brief paragraph will be spent on the traditional method, followed by a detailed description of what conformal cooling is and an in-depth analysis of the state of the art of this fairly new type of system.

At the end of the chapter, some paragraphs are spent explaining what an injection machine is and how it works, and then an introduction to the mold.

## 2.1 Introduction on injection molding

The injection-molding process is usually divided into the following 4 steps:

- Clamping/Mold Close: The two halves of the mold are clamped shut with enough force that the mold will stay closed as the material is injected.
- Injection: The polymer shot is injected.
- Pack and Hold: More polymer is injected to increase the polymer density and compensate for shrinkage as the plastic cools down.
- Cooling: The polymer is cooled down to the ejection temperature. The screw turns and is retracted as the next shot is prepared.
- Ejection/Mold Open: Once it has cooled, the part is ejected, and the process starts again.

The type of machine involved determines some very important parameters for the final result of both the injection and the software analysis, so it is important to describe it properly.

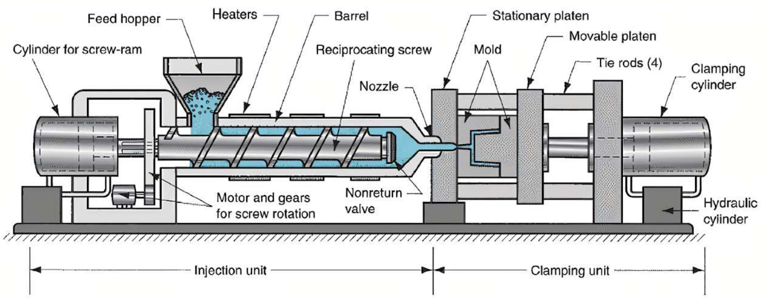



Figure 2.1: General scheme of the structure of an injection molding machine, single screw. [2]

Each injection molding machine can be divided into three main sections [3]:

- Machine base unit - Often referred to as the machine "bed". This provides a mounting frame for the clamp and injection units. The prime functions of any machine base unit must be dimensional stability, accuracy, and strength.
- Injection unit - The basic function is that of melting and preparation of the polymeric resin and pressurizing and feeding the molten resin to the mold under controlled conditions. In this unit, the parameters of the molten material have to be set up.
- Clamp unit - To inject the molten resin into the mold under considerable pressure, the mold must be sufficiently clamped together to resist the applied injection force. Under-clamping would result in the mold being forced apart creating flashes about the split line. Apart from providing sufficient clamping force for the mold, the clamping unit is also utilized for mold opening, closing, and sometimes component ejection when required.

The specific machine used in this project will be described later in the report (section 3.1.2). All the necessary parameters have been found in the producer data sheet, and they will be presented in the mentioned paragraph.

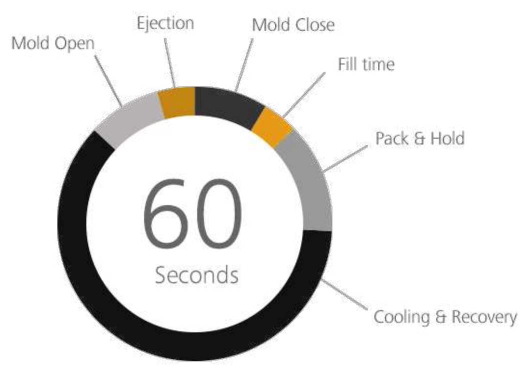



Figure 2.2: Timeline division example of a common injection molding cycle. [4]

All in all, the entire injection process can take anywhere from 2 seconds to 2 minutes [5] on average, which can be subdivided into the fractions of duration represented in figure 2.2. It is clear how reducing the cooling time means an improvement in the injection molding efficiency. And an increase in efficiency will mean a higher profit on the piece produced. How does it easily influence the cooling time? Through the design of an efficient cooling system for the piece.

It is known from practice that the cooling system's purpose is to ensure uniform cooling of the molded product to eject the product within a short time. The layout of the cooling channel plays an important role in the injection molding quality as well as the production cycle (cost) of a product.

During the injection molding process, the cooling channel is used to control mold temperature, of which the fluctuation has a direct influence on product shrinkage, deformation/warpage, dimensional stability, mechanical strength, residual stresses, and surface quality/glossiness. These overall effects will determine the final quality of this product.

Until recently, cooling channels were primarily manufactured in straight lines, due to the limitations of standard tool-making techniques. Hot spots within a design had to be addressed by including targeted bubblers or baffles whose main function was to reach difficult locations with the flux of coolant liquid to enhance the cooling process in these areas. In extreme cases, the mold half had to be split into smaller sections, with half of the cooling channel profile machined into each mating section before recombining the sections into the final mold. This not only significantly increased the tooling cost, but often shortened the life of the mold. Straight-drilled channels cannot provide optimal cooling since their layouts are limited by the cavity shape (to prevent interference between the cavity and channels) and the drilling process. [6]

From the observation of these problems and the attempt to find a solution, Conformal Cooling (CC) was invented, and interest in this way of designing cooling channels has gained interest among researchers and industries since then.

## 2.2 Definition of Conformal Cooling

Conformal cooling (CC) is the process of using coolant channels in plastic injection mold tools which closely follow, or conform with, the shape of the part being molded. They differ from standard cooling channels in that they are not confined to the line-of-sight, straight holes that are created from conventional drilling or milling. CC channels follow the twists and turns of complex part designs, and so offer much better cooling efficiency and faster cycle times. [7] No longer restricted to straight lines, CC channels can also incorporate different cross-sectional shapes that are appropriate for different areas of the part, but the more complex their shape, the more complex is also their production.

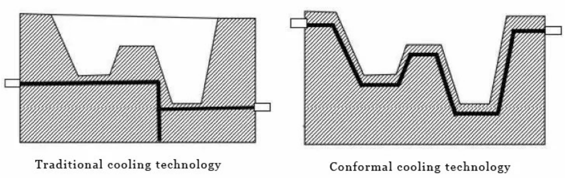



Figure 2.3: Schematic view of the main difference between Traditional cooling and CC. The differences are many more, but the main one is the way CC follows the shape of the piece while the traditional is restricted to straight lines.

Conformal channels allow the coolant to access all part locations uniformly, making the cooling process efficient and consistent. Reviewed journal articles specify that CC cycle time reductions range from 15% [8] to 50% [9]. Improvement levels depend on many factors, including part geometry, CC design, and cooling channel parameters. Mold designers can optimize channel sizes and locations as well as the coolant temperature and flow rate and, since mold designs can be split up into regions by proximity and peak temperature, they can generate parameters that benefit each localized area instead of proposing sub-optimal, uniform values across the whole mold. [10]

Efficient cooling achieved by CC prevents the overall part from reaching as high temperatures as conventional cooling channels; this helps reduce the cycle time and the amount of part shrinkage. This is not only beneficial to the part produced but also to the mold itself which will last longer with more efficient cooling. [10]

CC channels were proposed in the 1990s, and they have been studied thoroughly in the past couple of decades, but they can't be considered a common cooling method still, due to the difficulty of production of these types of molds.

### 2.2.1 Main advantages and disadvantages of CC

Both traditional and CC channels have their advantages and disadvantages as any production procedure in this world. Some of them though may determine the final choice depending on the specific case. The characteristics of each single production case have to be determined before choosing which type of procedure to apply, and the list of the main pros and cons can then be compared to understand which solution can be the best.

The main advantages and disadvantages of CC are reported here and can be used as a primal decision step for each case studied.

Advantages of CC: [11]

1. CC channels can follow the contours of the part surface providing a better cooling capability
2. Uniform cooling reduces part warpage
3. Ability to cool hot spots which may be difficult using drilled holes
4. The process requires fewer drilled holes and frees up space for lifter and slide locations
5. The channels provide drastically reduced coolant pressure and allow operation with smaller, more energy-efficient pumps
6. Tests have shown reductions in part cooling times up to 30% from conventional cooling techniques
7. Quicker de-mold times allow increased mold, press throughput, and press utilization rates

Disadvantages of CC [7]:

1. 3D printing for the creation of the mold is more expensive than conventional CNC machining
2. 3D printing requires more careful engineering of the geometries of the mold
3. Because of the careful engineering required to get the best results, preparing a 3D-printed tool takes more time than a conventional counterpart
4. It may involve using sophisticated analysis software like Moldflow® to determine the optimal design for drawing away heat most efficiently
5. Tool size is limited to the size of the print bed, which on most printers is smaller than a standard machined counterpart

6. There are fewer choices of raw materials, so common tool steels like NAK80 or P20 aren't available as a print media

### 2.2.2 Design and Optimization of the conformal cooling channels

An optimal design of CC channel networks is important to produce parts quickly, reliably, and more efficiently. Many methodologies and algorithms for designing CC channels have been proposed by researchers to enable the intelligent and optimal design of CC systems. However, despite the progress made in CC design, several obstacles still exist in front of mold designers and engineers, mainly because there exists no standard and uniform taxonomy and framework for CC system designs. Each part needs a unique and specific design. [6]

The goals in the design and optimization of CC channels are to ensure uniformity in the temperature distribution, reduce the cooling time needed to reach the ejection temperature, and minimize shrinkage and part warpage. Since the mold reaches a steady-state heat transfer and temperature condition after a certain number of cycles, and almost the totality of the heat to be transferred is known to be transferred to the coolant the simple energy balance principle can be applied to roughly evaluate the cooling time as shown in 2.1. [6]

$$t_C = \frac{[C_p(T_M - T_E)]\rho \frac{s}{2} x}{T_W - T_C} \left\{ \frac{1}{2\pi k_{st}} \ln \left[ \frac{2x \sinh(2\pi \frac{y}{x})}{\pi d} \right] + \frac{1}{0.03139\pi Re^{0.8}} \right\} \tag{2.1}$$

Based on this formula and more advanced fluid dynamic ones the study can proceed with the design and optimization of the shape and dimension of the cooling channels. Multiple procedures have been studied to obtain the best result: experimental procedures, Design Of Experiment (DOE), CC line and surface, expert algorithms, modular design, topology optimization, etc. All these formulas used for the study and optimization are the ones also implemented in Moldflow for the study of injection molding situations.

Another possible way of studying these problems is to effectively produce the mold with various versions of the cooling channel, study the products obtained, and optimize by experimental results the shape of the cooling system from what is observable in the pieces produced. This second method is not only time-consuming but also extremely expensive, being the molds very complicated to produce by themselves. This is why intensive research is currently undergoing to try to find the best way to run numerical simulations that can perfectly represent the reality of the process.

This work's aim is not to get into the optimization of the cooling channels for this piece but to define and validate a methodology to properly simulate the CC system. Still, a brief mention of the methodologies of design of these channels seemed important to understand the complexity of this type of process and to set a mention for the methodologies that are implemented into the software used for the analysis, Moldflow.

### 2.2.3 Evaluation of the performances of the conformal cooling channels

There has been a great interest in how to evaluate the performance of the conformal cooling (CC) system. Although the heat and mass transfer taking place in CC channels can be clearly described by physical and mathematical equations as seen in section 2.2.2 in a simplified form, it is a difficult challenge to solve these equations due to their high complexity and non-linearity.

Numerical simulation methods such as Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) are commonly used tools to obtain solutions for these problems. Various commercial software packages, such as Moldflow, Ansys, and COMSOL Multiphysics, have been employed to conduct simulations on thermal, mechanical, and fluid flow analysis. [6]

Moldflow is the software of choice to run the analysis, while the company proceeds to research the best cooling configuration by experimental procedures. Finding a way to run these performance evaluations without the need for experimental methods will help the company decrease the costs of production of the piece, but a comparison between these numerical simulation results, if found, and their experimental ones will be necessary to validate the results obtained.

The first and most important point in these simulations, for them to be correctly representing the reality of the problem, is to set the parameters of the simulation correctly. All the parameters inserted have to be the same used for the experimental attempts. All these data have been given by the company throughout the time of the work and will be listed in the following chapters while going in-depth into this specific case.

When obtained the results then there is the need to read these results and accurately interpret them. All these parameters and results will be analyzed and described in chapters 3 and 4 of this thesis, to understand more in-depth their meaning and their usefulness in terms of performance evaluation.

### 2.2.4 State of the art of modeling for conformal cooling systems.

Most of the research on conventional cooling systems for injection molding has been directed toward optimal cooling system design to improve the effectiveness and efficiency of cooling ([12], [13]) or have been applied to pieces with simple geometries, and the main focus has been applied to prove the higher efficiency of CC over traditional systems ([14], [15], [16]).

For the first mentioned case Au and Yu [12] presented a scaffolding architecture for conformal cooling design for rapid plastic injection molding. Wang and Yu [13], on the other hand, perfectioned a system to design a conformal cooling system for simply shaped pieces automatically; the procedure can be seen in figure 2.4. All these attempts to find a way to draw conformal cooling channels automatically are extremely helpful in terms of the development of the CC systems, but they are still far from the piece complexity that is needed for the system assigned.

The comparison between traditional and CC on the other hand has some interest in the development of this thesis. But also for this case, the geometries that have been found in the literature are quite far from the current situation. Mohamed and Masood [14] studied a simple water jar and compared cooling efficiencies between four different cooling systems. Also, Marquez and Sousa [15] tried the

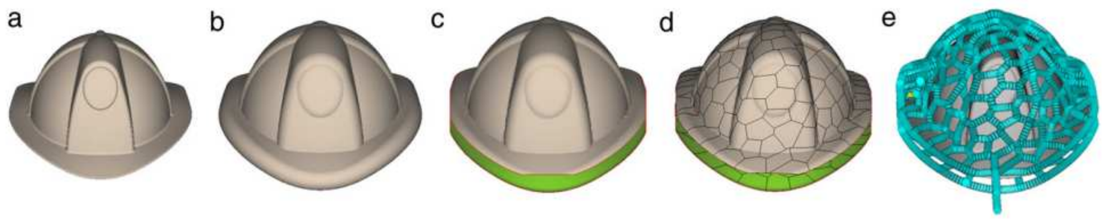



Figure 2.4: Overview of the cooling circuit generation algorithm: (a) a given model to be fabricated by rapid tooling, (b) the offset surface of the given model, (c) the separated offset surface serving as the conformal surface, (d) the refined discrete CVD, and (e) the resulting conformal cooling circuit. [13]

same comparison over a different piece. To be noticed is always the simple geometry of the piece that then results in a relatively easy conformal cooling system. Also, some attempts have been made to obtain and study porous molds in which the flux of the coolant is inside the porous structure of the mold itself [16]. Shu and Zhang [17] not only compared the two cooling methods but also referred to the mold production methods but the studied system is die casting.

(a) Piece from [14]

(b) Piece from [15]

Figure 2.5: Pieces that have been used in literature for comparison of different types of the cooling system.

It is relevant to mention the software in use for this case study. The defined software for this work will be Moldflow, with the aid of Solidworks for the reading and correction of the geometrical files shared by the company. Moldflow is not the only software that can be implemented, and under many aspects also not the most common to be found in the literature. ANSYS and Moldex (that is the software used by the company to study the system in parallel to this study) are much more frequently found.

Moldflow analysis in I-DEAS was used by Dimla et al. in 2005 to find the best position for the runner. ABM Saifullah and SH Masood analyzed ‘part cooling time’ using ANSYS thermal analysis software 2007. In 2009, the same group used MPI simulation software for part analysis and compared results for conventional and square section conformal cooling channels; concluding conformal channels render 35% less cooling time than conventional ones. A thermal-structural FEA analysis was performed by Saifullah et al. in 2012 by coupling results from ANSYS Workbench and Autodesk Moldflow Advisor in terms of temperature and stress distribution. [16]

It is easy to notice how the literature does not present cases with very complex pieces for these systems. Two things contribute to this lack of literature: confidentiality agreements with companies that produce these pieces and the long time needed to obtain results over these complicated systems. The implementation of these systems is still under development. The application of CC over complicated shapes is even more under constant study due to the challenges in terms of simulation and manufacturing. Being CC new, companies are usually the owners of this know-how, so they may be averse to sharing this knowledge. Also, the time needed to study these systems is directly proportional to their complexity. So, for very complex geometries, the time necessary to reach some results is much more than for simple ones, and also the analysis of the results becomes much more complicated.

## 2.3 Main characteristics and production processes for the mold

Fundamental to the creation of any piece by injection molding is the development of the relative mold. In the mold, the cavity has to be planned to give the final piece the correct dimensions, a proper cooling system has to be carved, a venting system has to be created if necessary, and all the other necessary inserts for correct closure, opening and extraction have to be inserted. The molds are very complex items, and they constitute the main core for the injection molding process. Their production is extremely expensive and delicate due to their complexity.

### 2.3.1 Production methods for the conformal cooling molds

While the design of CC channels is an important problem in itself, manufacturing the internal channels poses its unique challenges. Most CC network designs, optimized for cooling efficiency, possess complex three-dimensional shapes that are difficult (or impossible) to be realized using conventional machining techniques such as drilling. Designers thus need to turn to modern technologies such as Additive Manufacturing (AM). [6]

This case is no different than any others, and an AM-produced insert is needed. Several methods have been proposed to fabricate CC molds since the late 1990s. These methods can be summarized as follows:

- casting
- welding
- U-groove milling
- laminated tooling
- AM, divided into categories as seen in figure 2.6

Moreover, surface quality and dimensional accuracy of cooling channels affect the cooling performance. Thus, surface finishing using mechanical methods and the combination of additive/subtractive manufacturing were also proposed to improve the surface quality and dimensional accuracy of the additively manufactured mold insert. [6]

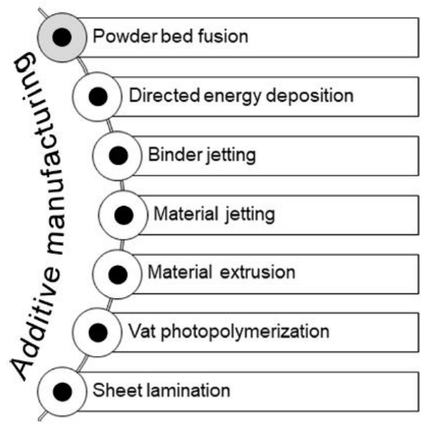



Figure 2.6: Additive manufacturing process categories according to ISO/ASTM 52900:2015. [18]

From all the previously mentioned, the powder-based AM are for sure the ones with the better prospects for the future. But a few side effects on the material need to be considered due to the production technique. Several trade articles, including Mayer (2005) [19], indicate that CC molds can withstand roughly one million injection molding cycles, the same number of cycles as conventionally manufactured molds. Research has been conducted to validate their equivalence; however, there have not been many journal publications on the subject. [10]

Among these powder-based methods, Direct Metal Laser Sintering (DMLS) is the most common and the one used by the company in question so it will be described a little more in-depth. It should be noted that both scientific and popular literature use different names for the Laser Powder Bed Fusion (L-PBF) process. The most well-known terms used are selective laser melting (SLM), direct metal laser sintering (DMLS), LaserCusing, direct metal laser melting (DMLM), and laser metal fusion (LMF). However, one must clearly understand that these are only different commercial names for the same process, and they will be used alternatively in the following paragraphs as synonyms. [18]

#### 2.3.1.1 Conformal insert - Laser Powder Bed Fusion

As already seen, not the whole mold is made of the same material and with the same process. Parts of the mold are produced with traditional methods, and others are produced with more advanced processes as L-PBF. The conformal insert under observation is produced by Laser powder bed fusion, then heat treated through precipitation hardening (aging) to a hardness of 49HRC.

For simplicity on the analysis and setup of the software parameters, it has been decided to simplify the mold study and consider the whole mold as made in the same way, with the AM procedure. To better understand the real case scenario it is necessary to describe in more depth the manufacturing process for the conformal insert since all the mold will be considered as made with the same process, and then understand what are the main differences between the CC insert and the traditional parts.

The DMLS process works by laser-sintering parts of the bed of powder. The building platform is shifted down after each cross-section layer of powder is micro-welded, and the re-coater blade moves across the platform. The process is repeated until the build is complete. After the process is finished, the powder is removed, as we can see in figure 2.7, and followed by the appropriate heat-treat cycle to relieve any stresses. Parts are then removed from the platform and support structures and then finished with any needed beading blasting and deburring. Final DMLS parts are at near 100% density. [20]

Figure 2.7: Product extraction of a DMLS process. Act of eliminating the excess powder to see the final product before detachment from the base. The complexity of the shapes that are possible to be obtained is clear in the image.

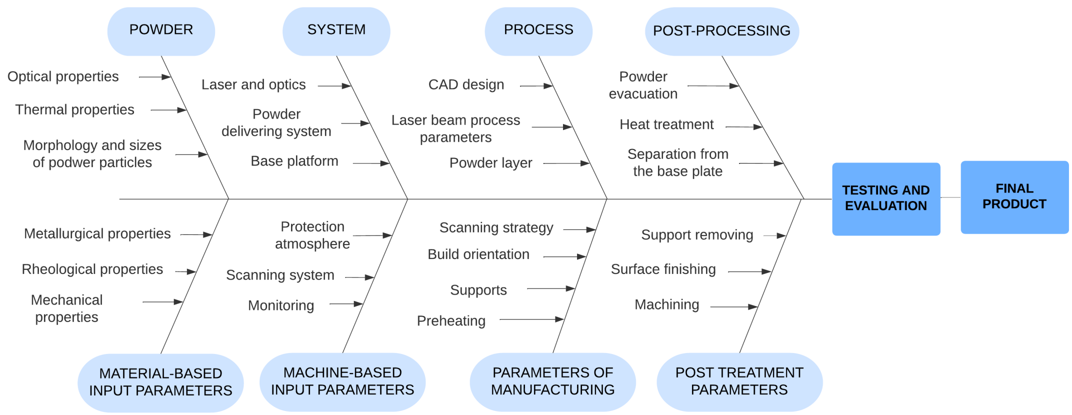



Figure 2.8: Main parameters influencing the quality of LPBF components, divided by categories. [18]

There are several advantages to this method. First, laser sintered CC does not replace existing processes; it complements them. It opens up possibilities that can stretch design creativity and bring in new business. What's more, conformal cooling is a proven technology. Over the past few years, benchmarks of CC against traditional processes have documented significant reductions in two of the most important cost drivers of injection molding: cooling times and scrap rates. [21]

But with the many advantages also some challenges and problems occur. The main one is the number of parameters that can influence the final result, and consequently the complicacy in obtaining optimality. All parameters that can influence the result are listed in a fishbone diagram in figure 2.8.

# Chapter 3

# Injection molding simulation of parts with complex geometries

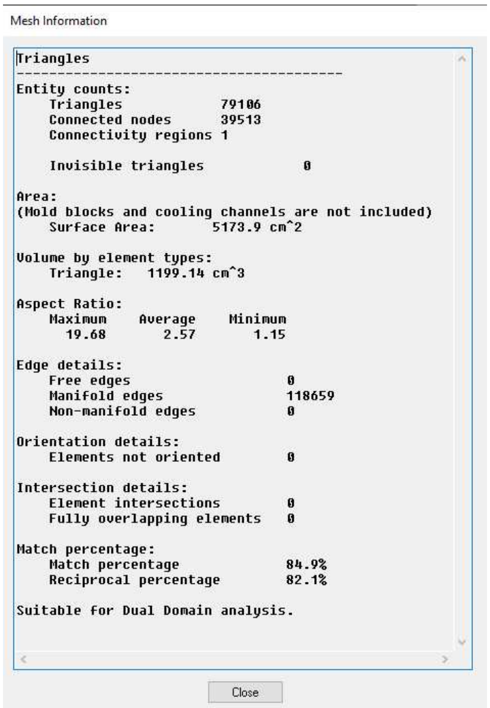
The import and mesh of the piece is just the initial step of the extensive process that ends with the complete analysis in Moldflow. It can be foreseen from the beginning how challenging the study of very complicated pieces may be. Nevertheless, it is also a stage of extreme importance for the correct prosecution of the study. If the suitable piece mesh is achieved in this stage, the following steps will be more straightforward since the piece is the central point of the Moldflow study. Anything else depends on the correct representation of its geometry inside the software.

Complementary to the piece import and mesh, to correctly set up the base for any following analysis, is the definition of the correct gate location and relative runner system. All these parts can be considered as one singular piece since they all are parts of the mold. The only way to understand if this procedure is correct is to run the fill and fill+pack analysis. The results of these analyses will be essential to know how Moldflow perceives the piece and runner geometries after the import from Solidworks. All this will be analyzed in the following chapter.

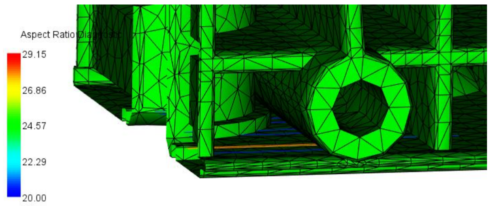
## 3.1 Piece mesh

Before importing the assigned piece, it is always necessary to observe the piece geometry in Solidworks to spot geometrical defects that can compromise the import and the mesh. From the observation of the piece, it can be immediately noticed that the complex ribs structure on the rear part will give major cooling concerns, and it is here that the company is trying to apply the Conformal Cooling (CC). By observing the Solidworks piece file, no other problems are recognizable.

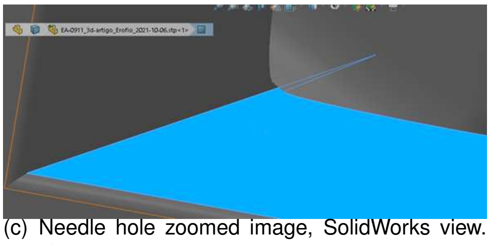
Then, it is necessary to import the piece alone, in Moldflow, and mesh it to start observing problems that were impossible to spot by eye. Dual Domain (DD) mesh is used for the first trial. A careful observation of the characteristics and issues of this type of mesh will give much information about how to change the piece's geometry before proceeding with the Three Dimensional (3D) mesh. Any present defect is much easier to spot and fix with this type of mesh.




(a) Mesh analysis results from Moldflow for the DD mesh of the piece.




(b) Aspect Ratio analysis result in Moldflow, also in this case for the DD mesh obtained for the piece.



(c) Needle hole zoomed image, SolidWorks view. A defective junction between elements in the piece created this hole in the geometry.

Figure 3.1: DD mesh analysis results. Figure a) shows the mesh information obtained through the mesh analysis wizard. Figure b) illustrates the results from the aspect ratio analysis. One critical area of the piece is shown in detail. Figure c) illustrates a needle hole found in the initial piece geometry through the mesh analysis.

A preliminary study was carried out before the beginning of this project for two main reasons: to start the theoretical research necessary for understanding this complex subject and start gaining knowledge about the system itself. For it, DD mesh was applied to obtain faster results in the analysis. This initial implementation helped a lot with the mesh correction procedure. The problems spotted were:

- HIGH ASPECT RATIO: The general recommendations from the Autodesk Moldflow guide in this case are:
  - 20:1 for triangular elements in Midplane and DD meshes.
  - 30:1 for triangular elements in a DD mesh that will be converted to a 3D mesh.
  - 50:1 for tetrahedral elements in a 3D mesh. The limit has been extended to 100:1 recently.

  In figure 3.1(a), it is shown that the mesh obtained in this study has a good quality and the aspect ratio is lower than 20. Some critical points were found between the holding screw's seats and the external structure of the piece and corrected to reach this result. This can be seen in figure 3.1(b).
- One point in the structure is found to have an extremely high aspect ratio, and it is not located, as all the others, near the screw's seats. Also, an error is printed by Moldflow: ** WARNING 305400 ** Sharp hole in surface geometry of the tetrahedral mesh at node 38235. This point was found to be a needle hole created while designing the piece in Solidworks and merging different piece structures. The rear of the major front hole, the filter holder, was merged with the rear fin structure to create the final geometry of the piece and the approximation of the position gave a non-precise

contact between the two surfaces, creating the hole. This problem has been solved by covering the hole through the SolidWorks sketch feature. See figure 3.1(c).

Once all these initial problems have been solved for the DD mesh, it is necessary to convert the DD into the 3D and solve, through the repair wizard, any eventual problem left on the piece.

### 3.1.1 Material for the piece

Table 3.1: Properties of DOMAMID 6LVG30H2 BK in comparison with DOMAMID 6LVG35H2 BK. The first is the material used for this study, found directly in the Moldflow database. The second is the material used by the company. Its properties have been found in the data-sheet from the producer.

| | 6LVG30 (Moldflow) | 6LVG35 (Company) | Units |
|---|---|---|---|
| MECHANICAL PROPERTIES | | | |
| Stress at break | 175/115 | 200/125 | MPa |
| Tensile Modulus | 9500/6800 | 11200/6700 | MPa |
| Yield stress | 175/115 | 200/125 | MPa |
| Strain at break | 3.0/3.0 | 3.0/6.0 | % |
| Flexural Modulus, 23° | 7800/4800 | 9800/6200 | MPa |
| Charpy notched impact strength (+23°) | 10.0/18.0 | 13.0/23.0 | kJ/m2 |
| Charpy impact strength (+23°) | 70/65 | 85/95 | kJ/m2 |
| PHYSICAL PROPERTIES | | | |
| Molding shrinkage - normal | 1.1 | 0.25-0.45 | % |
| Molding shrinkage - parallel | 0.3 | 0.75-0.95 | % |
| Density | 1360 | 1420 | Kg/m3 |
| THERMAL PROPERTIES | | | |
| Melting temperature (10℃/min) | 221 | 221 | ℃ |

The material chosen for the production of this piece is: PA6 GF35 (Domamid 6 LV G35 H2 BK) This material is a Polyamide-6 from the group Domo. It is a particular type of polyamide with low viscosity (LV) and 35% glass fiber (G35). The specification H2 means heat stabilized, and BK indicates the color black of the polymer.

The material used for the study is Domamid 6 LV G30 H2 BK. The only difference is the content of glass fibers from the one used by the company. This material has only 30 % glass fiber in it and consequently, the mechanical properties are slightly different, but the difference should not disturb the analyses enough to obtain invalid results. Table 3.1 lists the main characteristics of the material that will be used for the analysis in Moldflow compared with the material used by the company.

### 3.1.2 Injection machine

The machine used by the company is a Krauss Maffei with 650 tonnes of maximum clamping (internal code EA010).

In table 3.2 are listed all the main characteristics of the machine used by the company; all the data come from the technical data sheet of the machine [22], found on the site of the producer. Usually, the relevant data for the machine are present in the datasheet but the inputs necessary for Moldflow, when creating a user-defined machine, do not match precisely with them. For this reason, the right side of 3.2

indicates the list of data needed to set a user-defined Moldflow machine, while the list of data to obtain from the data sheet is listed on the left.

Table 3.2: Data from the machine data sheet and necessary conversions. The machine can be edited by following the path: $>$Study task panel $>$Process settings $>$Process settings wizard $>$Advanced options $>$Injection molding machine $>$Edit

| Datasheet properties | Value | Unit | Moldflow requirements and conversions | |
|---|---|---|---|---|
| DESCRIPTION | | | | |
| Trade name | | | KM 575/650 CX | |
| Manufacturer | | | Krauss Maffei | |
| Data source | | | Company site | |
| Data last modified | | | September 2007 | |
| Data status | | | Confidential | |
| INJECTION UNIT | | | | |
| Machine screw diameter | 80 | $mm$ | 80 | $mm$ |
| Stroke volume | 1810 | $cm^3$ | | |
| Maximum machine injection stroke | | | 360 | $mm$ |
| Maximum machine injection rate | 498 | $cm^3/s$ | 498 | $cm^3/s$ |
| L/D ratio of the screw | 22.5 | | | |
| Length of the screw | 1800 | $mm$ | | |
| Filling control | | | Stroke vs ram speed | |
| HYDRAULIC UNIT | | | | |
| Maximum machine injection pressure | 2205 | $bar$ | 220.5 | $MPa$ |
| CLAMPING UNIT | | | | |
| Maximum machine clamp force | 5750/6500 | $KN$ | 650 | $tonne$ |
| Maximum mold opening stroke | 1150 | $mm$ | | |
| Minimum mold height | 600 | $mm$ | | |

Since some of the data in the datasheet usually do not match the inputs required by Moldflow, some conversions and evaluations are necessary. For example, the datasheet of the machine used by the company does not specify the maximum injection stroke but gives both the diameter of the screw and the maximum stroke volume. A simple formula can be applied for the conversion.

$$d = diameter = 80mm = 8cm$$

$$A = area = \pi \frac{d^2}{4} = 50.265cm^2$$

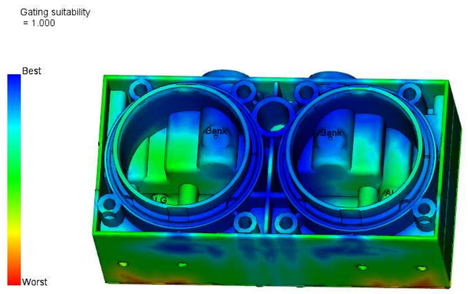
$$V = volume = As = 1810cm^3$$

$$s = stroke = \frac{V}{A} = 36.03cm = 360mm$$

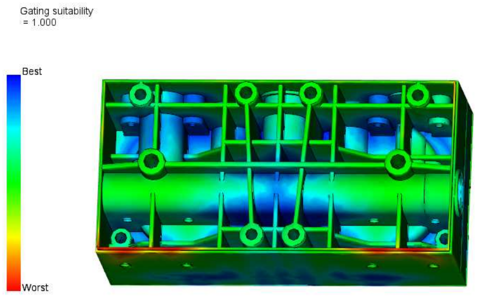
Knowing how to insert the parameters of the machine used into Moldflow is extremely important to obtain final results that might be comparable with the real case scenario. In some rare cases, the machine involved may already be in the Moldflow database, and in this case, this process is not necessary. For all the other cases, the specific machine will not be present, and the described procedure needs to be followed.

## 3.2 Gate location analysis

Once the main DD and 3D mesh problems were solved, an analysis for the best gate location was run in Moldflow although the company had already set the actual gate location. The actual gate location has been checked only after the first run of the gate location analysis to see if Modflow can correctly identify feasible gate locations in a piece of such complexity. The results obtained are shown in figure 3.2




(a) Gate suitability. The Front surface of the piece. The best gate locations are indicated in blue.



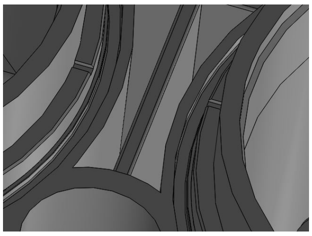

(b) Gate suitability. Back of the piece. The rib structure on the piece's rear part prevents having a good injection point on this side.

Figure 3.2: Gate location analysis results in terms of Gate Suitability. a) Front view with best gate location. b) Back view with no possible gate location.

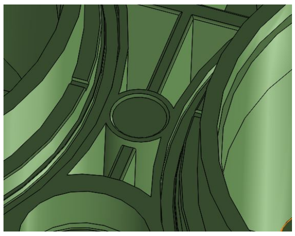
The best location for the gate is on the front side of the piece (following the references defined in chapter 1). Experts usually suggest injecting big and complex pieces in the center of the geometry; this will shorten the molten path that the polymer has to travel to reach the farthest points in the piece. In this case, the central point is occupied by a thin rib of about 3 millimeters of thickness, which prevents us from using this point as an injection point as it is.

After this first result, it is essential to look at what the company did to solve this issue, and whether it found the best way to deal with it. They chose to change the piece's geometry in the central point by creating more space for the polymer to flow. The result of the modification can be observed in figure 3.3 where the company's final geometry is shown in comparison with how it has been decided to modify the piece for this specific project. The two geometrical variations are not the same, so it is important to show both of them.

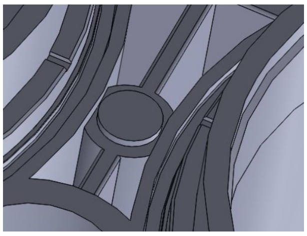
The difference is small enough not to give any difference in the analysis result. Unfortunately, the last updated model received from the company was not usable due to some unsolvable defects on the Solidworks file. An attempt to solve these Computer-Aided Design (CAD) model problems to permit the



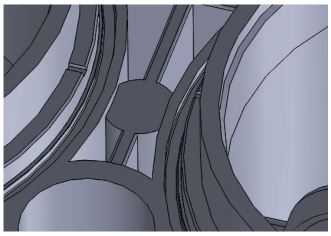
(a) Suggested area for best gate location. Central thin rib on the front of the piece that will not allow correct filling.



(b) Company alteration of the geometry



(c) First gate location modification attempted in this project - FAILED to mesh properly



(d) Second gate location modification attempted in this project - DEFINITIVE for the study

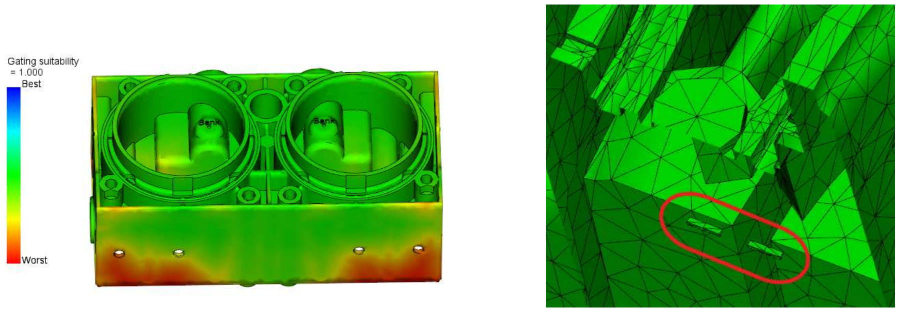
Figure 3.3: Gate location modification to permit correct piece filling and still maintain the software gate location recommendation. Visual comparison of the geometry alterations. a) Suggested location from the software. b) Company solution to the incorrect filling. c) First attempted solution for this project. The software was not able to mesh the geometry. d) Second and definitive solution.

upload in Moldflow was made, but nothing has been successful, so the initial file has been modified to obtain a geometry as near as possible to the definitive geometry from the company.

After obtaining these results and choosing the gate in figure 3.3(d) as the definitive one, another gate location analysis is run to check if the change in geometry has produced the desired effect. In figure 3.4(a) the analysis now indicates any point of the front surface of the piece as an available gate location. Here it is important to notice the scale used by the software: the best locations, which would be represented in blue in the figure following the Moldflow scale on the left of the picture, are nowhere to be found on the surface of the piece. No visible area of the surface is indicated in color blue, while usually, Moldflow scales are built to describe precisely the situation from minor to major limit of the values that represent the result. This gives a possible hint for the presence of a defect in the geometry since the scale indicates a value for the best location that is then not shown anywhere in the final result. To notice that the system is not able to evaluate the best position for the gate, and even further no flow resistance indicator analysis is evaluated by the system, is not a sign to be left hanging while beginning to analyze a new piece. All need to be perfectly working, and there is the need to ensure that Moldflow is reading all the information given in the right way before proceeding, otherwise, the software will have problems running the analysis later or the results obtained will not be feasible solutions for comparison with the real experimental process.

To proceed, it is necessary to check the whole geometry of the piece again, in search of possible reasons for this problem. A void is found in the piece, which has probably been created while trying to enlarge the gate location, and the system sees this void as the best gate position (figure 3.4(b)). All this permits to see how important it is to carefully analyze each result obtained, especially with these complicated pieces whose defects cannot be easily spotted.

Once identified the problem, it is solved by recreating the previous geometrical variation differently in Solidworks, and then the piece is carefully checked for any other defect. None has been spotted.

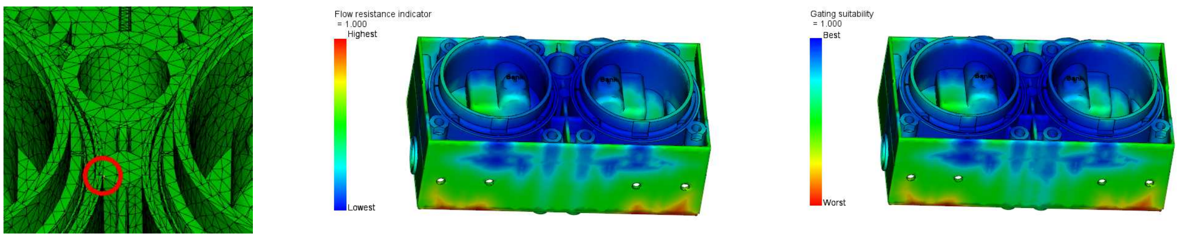



(a) New gate location analysis after the alteration of the piece's geometry. The best location, which should be represented in blue, can't be found.

(b) Geometrical voids found in the structure. Their presence was spotted with the previously described gate analysis. The position of the best node for gate location is found here for this case.

Figure 3.4: New gate location analysis result after the first alteration of the geometry. Still, the results show some problems. a) Gate suitability with no best point shown. b) Geometrical voids found by analyzing the geometry in search of the best gate location.

The study for the piece is restarted from the beginning; first the Dual Domain mesh and corrections, then the 3D mesh and correction till it is possible to run the gate location analysis on this new and improved geometry again. Immediately, the results obtained confirm the absence of further defects because both the flow resistance indicator and gate suitability are shown correctly for the piece, and the results are in concordance with the expected. The suggested gate location is now at NODE 2638 on the surface of this geometric modification, and both the flow resistance and the best gate location suggest that spot as the optimal location.




(a) Suggested gate location on the new attempt, NODE 2638 indicated by the red circle.

(b) Flow resistance indicator.

(c) Gating suitability.

Figure 3.5: Attempt to run the gate location analysis on the new modification of the piece geometry. a) Best node suggested. b) Flow resistance indicator. c) Gating suitability.

The advanced gate locator algorithm was used for all the previous analyses (Advanced Gate Locator recommends up to 10 gate locations for the study, based on minimized pressure. The number of gates to be analyzed can be specified here. It is not required to specify Material properties or Process Settings conditions [23]). For completeness of the study, the final results of the other analysis method available in Moldflow are described here. The Gate region locator method recommends a gate location for the study based on balanced flow. The Material properties or Process Settings conditions can be specified if wanted. [23] This result is shown in figure 3.6.

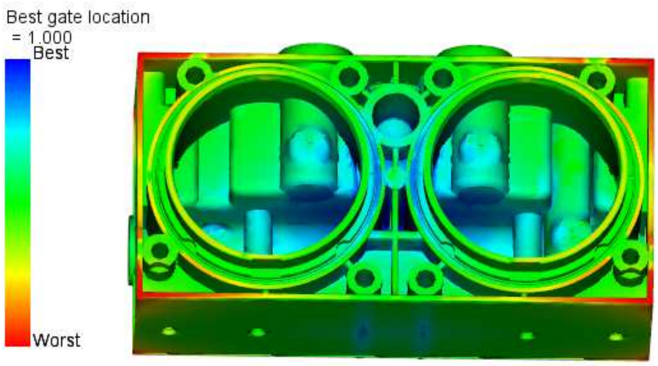
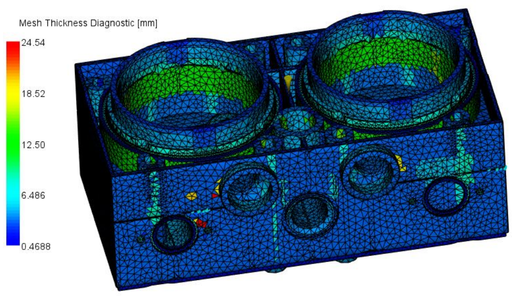


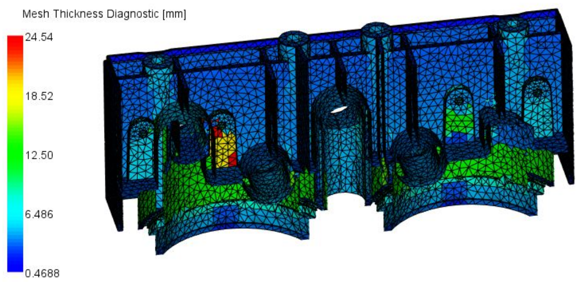

Figure 3.6: Gate analysis with the gate region locator method

All the previous comments on thickness for the gate locator analysis and all future references to properties and problems that depend on the local thickness of the piece are determined by careful observation of the results of the Thickness Diagnostic tool available in Moldflow. During Dual Domain mesh creation, at the very beginning of the study for this case, the distance between matching surfaces is calculated. This distance corresponds to the part thickness. After Dual Domain mesh creation, it is important to review the thickness and make any required adjustments before running an analysis. In this case, since the company already set the geometry, no variations have been applied to the piece. This result has just been used for pointing out local defects and problematic areas. [24]

In figure 3.7 the results of this diagnostic are shown, and it can be seen that the variation of thickness for this piece is quite high for an injection molding. The thickness varies between a minimum of 0.47mm and a maximum of 24.54 mm with two orders of magnitude variation between them.




(a) View of the piece




(b) Section view of the highest thickness points

Figure 3.7: Diagnostic thickness result. a) Complete view. b) Section view to highlight the thickest point.

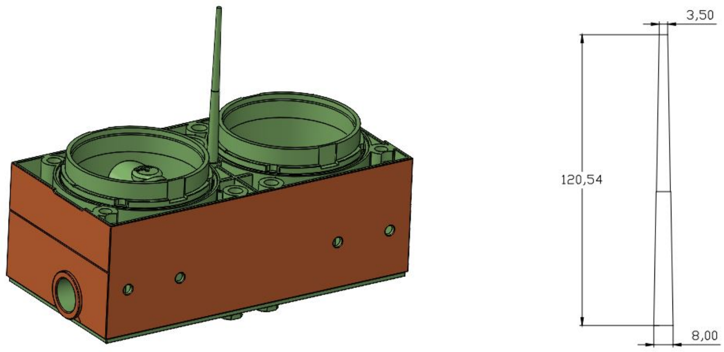
Not only the variation in thickness is very high but also the highest thickness is one order of magnitude bigger than the top dimension of the sprue that is used for the system. The sprue geometry has not been described yet and only will be described in the apposite section 3.3.1.

## 3.3 Fill analysis

The following paragraphs aim to describe in depth the second stage of any Moldflow analysis: the fill analysis. To do so, it is necessary to take a look at what a filling analysis is, how it works and how the software simulates it, and all the parameters that are needed to make it work and give proper results. Also part of this second step, in the progress of the study, is the Fill+Pack analysis that Moldflow makes available. This second stage complements the results obtained in the first and gets into a more deep understanding of the behavior of the system. For any analysis that has been run in this project, it was necessary to review the available theoretical literature. [25], [26], [23]

### 3.3.1 Runner system

No mention has already been made of the runner system, and for the first fill analysis, the runner system will not be considered. But for the following, more detailed, analysis the consideration of the runner system is necessary. The runner system used in this specific case is a cold runner composed of one simple sprue that goes from the orifice of the injection unit to the gate area for the piece.




(a) View of the whole piece with the runner system

(b) Sprue that composes the runner system of the piece, with dimensional quotes

Figure 3.8: Geometrical properties of the runner system for the piece, a) positioning, b) dimensions.

As previously indicated when talking about the thickness, the top dimension of the sprue is only 3.5 mm while the maximum thickness analyzed in the part is 24.54 mm. This goes against any possible recommendation present in theory. Usually, the injection tip of the sprue should always be slightly bigger than the biggest thickness found in the piece, with variations depending on the type of piece involved. But also for very complex pieces, it is a good recommendation to maintain these two dimensions as near as possible to each other to permit correct polymer flow in terms of quantity. Even before the run of the analyses, the problems start to show.

### 3.3.2 Preliminary fill analysis

The first fill analysis is conducted to check the correct mesh representation of the piece.

Once the meshed model is ready, the optimal position for the gate is identified, and the runner system is simulated, there is the possibility to start the initial step of the injection molding process in Moldflow: the fill analysis. The first analysis is left to run with the software's default settings to check that the mesh is appropriate for the study and that the temperatures set are correct for the filling of the piece. The focus this time is on the representation of the piece and not the results obtained.

The company has given a set of parameters, and the expected results have to be obtained from them. The company applied multiple sets of parameters while trying to find the optimal production method through experimental trials. Only the last set will be taken into consideration and presented for this project. In 3.3 the important parameters that will be used as inputs for a second fill analysis are listed. The analysis will help define how the Solidworks geometry is perceived by Modflow, and also how much time the software evaluates to reach complete piece filling.

After this first analysis aimed to check the system, multiple ones have been run, but the results will not be discussed in depth since they are not necessary to fulfill the project requirements.

Table 3.3: Set of parameters, given from the company, used as the setup for the fill analysis

| SETTINGS | Value | Units |
|---|---|---|
| Material | Domamid 6 LV G35 H2 BK | |
| Injection time | 3.14 | s |
| Packing time | 30 | s |
| Cooling time | 145 | s |
| Packing pressure | 50 | MPa |
| Mold temperature | 90 | ℃ |
| Melt temperature | 260 | ℃ |
| Cooling liquid | pure water | |
| Cooling °T (channels 2,3,4,16) | 60 | ℃ |
| Cooling °T (other channels) | 70 | ℃ |

### 3.3.3 Fill analysis with the company parameters

Once the company shared the machine setup sheet (figure 3.9), Moldflow can be set to simulate what the company has experienced. Also, being now in possession of all the important information about the setup, it is possible to describe exactly the machine used, as seen in section 3.1.2.

For completeness of the study, a simple fill analysis is run, and the results are shown briefly. The only modification necessary to pass from the Relatório de Parâmetros de Injeção (RPI) to the Moldflow interface for fill analysis is to convert the position of the screw from a volume in $cm^3$ to a linear position in $mm$.

$$A = area = 50.265cm^2$$

$$V = volume = Ap = (1400; 750; 250; 0)cm^3$$

$$p = position = \frac{V}{A} = (278; 149; 50; 0)mm$$

1 Unidade Horinzontal

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DOSAGEM | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Descompressão | |
| Dosagem | cm^3 | 0 | 1400 | | | | | | | cm^3 | cm^3/s |
| Velocidade | rot / min | 80 | 80 | | | | | | | 42 | 100 |
| Contrapressão | [bar] | 100 | 100 | | | | | | | | |
| | | | | | | | | | Tempo | [s] | 35,6 |
| INJECÇÃO | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Posição | cm^3 | 0 | 250 | 750 | 1400 | | | | | | |
| Velocidade | cm^3/s | 200 | 450 | 450 | 450 | | | | | | |
| Pressão | [bar] | 1800 | | | | | | | | | |
| | Pressão | max. | [Bar] | 626 | Comutação | | 195 | | Tempo Injec. | [s] | 3,14 |
| COMPACTAÇÃO | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Tempo | [s] | 0 | 30 | | | | | | | | |
| Pressão | [bar] | 500 | 500 | | | | | | | | |
| | | | | Almofada | | | 14,1 | | TEMPO ARREFECIMENTO | [s] | 145 |
| | | | | | | | | | CICLO TOTAL | [s] | 198 |

Figure 3.9: Machine setup sheet with data received from the company. It contains all the necessary info for the described filling analysis.

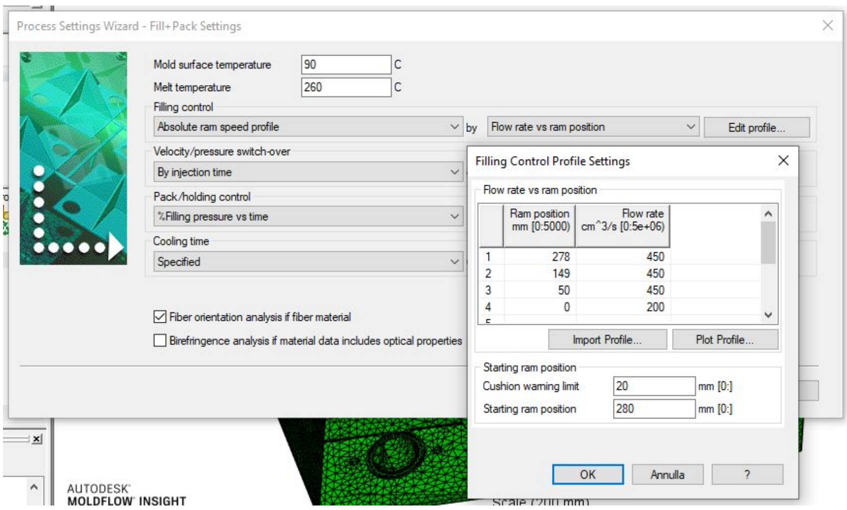



Figure 3.10: First set of parameters inserted for the fill analysis. The Moldflow parameters can now be edited by following the path: >Study task panel >Process settings >Process settings wizard >Mold surface temperature = 90 >Melt temperature = 260

The first thing to notice in the result log is the presence of some warnings about the mesh.

1. ** WARNING 304920 ** There is an insufficient refinement of the tetrahedral mesh in some areas, which may affect solution accuracy. Inspect with the "Node layer number" plot and consider improving the mesh. [For the 10 tetrahedral refinement layers requested, the node layer number is expected to reach 6 at the part centerline.]

2. ** WARNING 304930 ** The node layer number on the part centerline is 5 or less for 56.2 percent of the part.

3. ** WARNING 304940 ** The node layer number on the part centerline is more than one less than requested (i.e. 4 or less) for 16.4 percent of the part.

These errors occur whenever the 3D mesh refinement is not ideal in some areas of the model due to CAD geometry thickness differences. [27] The procedure indicated in the Autodesk Moldflow guide has

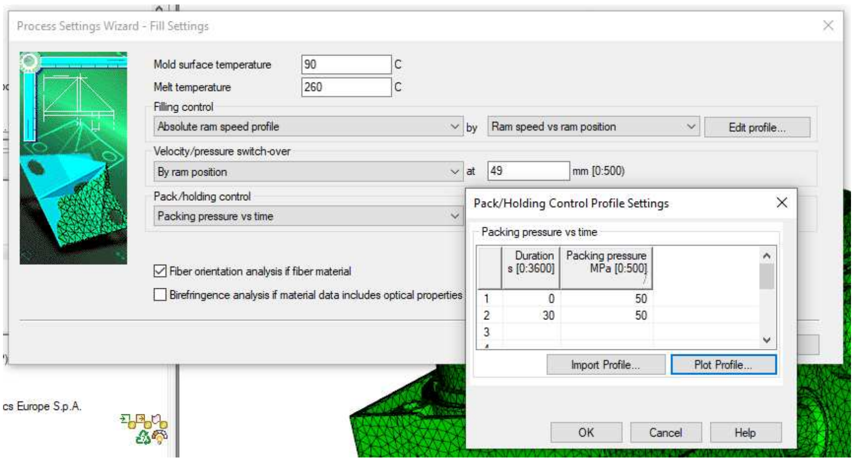



Figure 3.11: Second set of parameters inserted for the fill analysis. Edited by following the path: >Study task panel >Process settings >Process settings wizard: >Pack/holding control >Packing pressure vs time >Edit profile (insert data from RPI)

been followed to see if there is a possibility to solve these errors, but the piece complexity is too high. One solution could have been to refine the mesh further, but the system already puts the software capability under pressure. The first signal of the struggle of the software is detected by the long time necessary to run any analysis on it. Furthermore, the system will have to stand also all the cooling channels, so a simple mesh is preferable over a refined and complicated mesh. One of the worries about this project is that the software cannot stand the amount of information inserted due to the situation's complexity. To try to avoid this condition the choice to be made is to maintain the system as simple as possible with the maximum mesh refinement possible while keeping the number of tetrahedrons as low as possible. These warnings are important, but the analysis will still be run without modifications. If anomalies are detected in the results, then a finer mesh will be attempted, but only for a fill+pack analysis. All the subsequent cooling analyses and the complete analysis will be run over this mesh file.

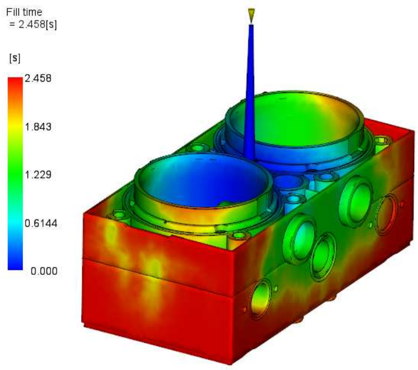
```
Filling Control:
----------------
Filling control type                              = Ram speed profile
Ram speed profile control by                      = Flow rate vs ram position
Starting ram position                             =    280.0000 mm
Cushion size                                      =     20.0000 mm
Ram speed profile:
        Ram position              flow rate
       ----------------------------------
       278.0000 mm            450.0000 cm^3/s
       149.0000 mm            450.0000 cm^3/s
        50.0000 mm            450.0000 cm^3/s
         0.0000 mm            200.0000 cm^3/s

Velocity/pressure switch-over control:
--------------------------------------
Velocity/pressure switch-over control type        = By ram position
    Specified ram position                        =     49.0000 mm

Pack/holding control:
--------------------
Pack/holding control type                         = Packing pressure vs time
Pressure profile:
       duration             pressure
       -----------------------------
           0.00 s            50.0000 MPa
          30.00 s            50.0000 MPa
```

Figure 3.12: Resume from the analysis log of the parameters inserted in the analysis from the RPI of the company. It is important to check the analysis log for possible warnings and errors in the set of parameters.

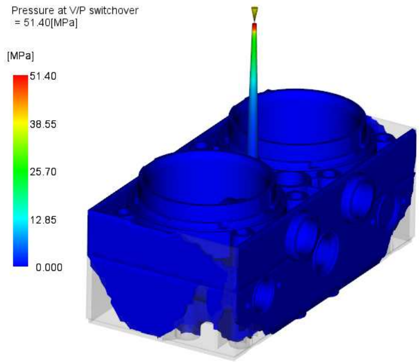
## 3.4 Fill+Pack analysis

After the fill analysis of section 3.3.3 a complete fill+pack analysis is run and analyzed. Being this analysis the most complete for the first stage of the injection molding process, the results are discussed and presented in an extended way. The same settings from the previous fill analysis are used and shown in figures 3.10 and 3.11. The only addition to that is the time of cooling that in a fill+pack analysis can be specified. In the followingly described analysis, the cooling time is set to 145 seconds.

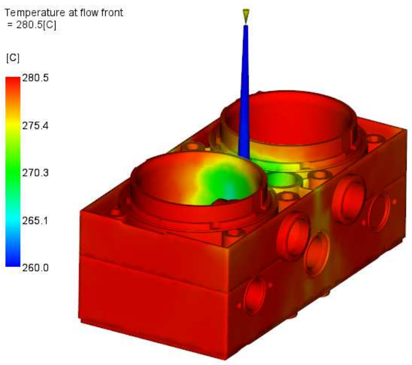
For the theoretical explanation of each of the following results, the Autodesk guide has been of great help. Its consultation is recommended before the analysis of the results. [26], [23], [28], [29]



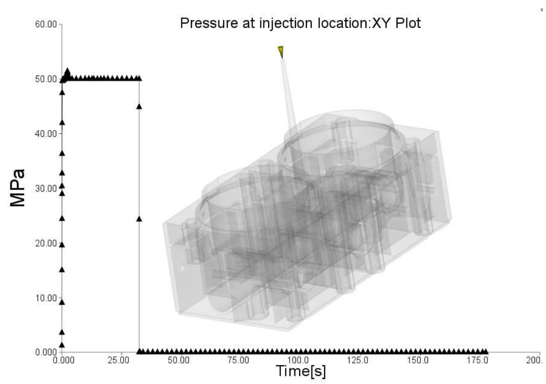

(a) Fill time




(b) Pressure at V/P switch-over




(c) Temperature at flow front




(d) Pressure at injection location: XY plot

Figure 3.13: Fill+Pack result obtained. All these results will be discussed in the relative sections.

### 3.4.1 Fill time

The fill time is represented in figure 3.13(a). The final result for the analysis is indicated as 2.458 seconds, using the parameters from the company. This means that the software can simulate the fill, but it results in a shorter time than the one indicated by the company. A second analysis is run with a fixed fill time equal to 3.14 seconds, as given by the company, without the specification of the ram speed profile. No short-shots are detected in the first case or the second one. To be kept in mind, the ram speed profile is much more accurate than the total filling time reported in the RPI of the company to simulate the process. For this reason, the results presented here are the ones from the initial analysis, and the second one, with a constant flow rate, will be presented simply for comparison. Eventually, showing discrepancies between the two can be helpful for the company to understand which simulates better the real situation.

For the analysis with fixed fill time, the velocity/pressure switch-over will be set to automatic since now the ram position for the switch is not defined anymore. The pack control profile will be maintained. After the run of the analysis, a filling time of 3.196 seconds is obtained, which is much closer to the company values.

### 3.4.2 Temperature at flow front

In 3.13(c) it can be immediately noticed that the increase in temperature for this case is much more than the 5℃ defined as the limit for material degradation and surface defects. This is a serious problem in the analysis. The complexity of the piece and the presence of multiple thin ribs does not help the increase in temperature since the shear stress in these areas is very high. Since one of the suggestions is to increase the fill time, there is the possibility to compare this result with the result from the fixed filling time analysis. It is interesting to see that the change of one second in the filling duration greatly influences the temperature at the flow front. This will be an interesting characteristic of the analysis to compare also with the experimental results from Erofio company.

### 3.4.3 Pressure at injection location: XY plot

The pressure plot in figure 3.13(d) shows the pressure evaluated to inject and then pack the part.

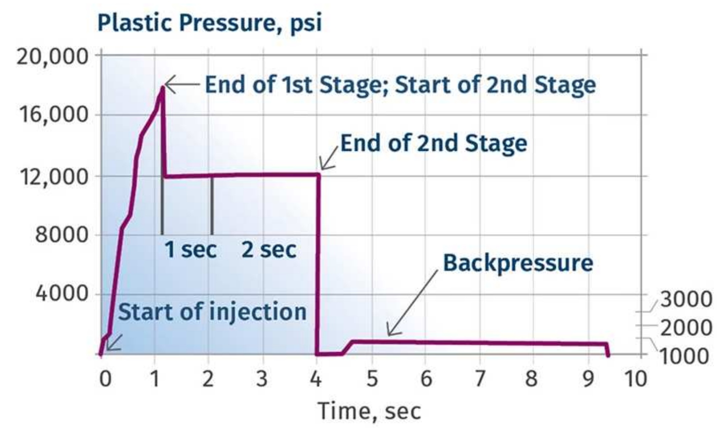
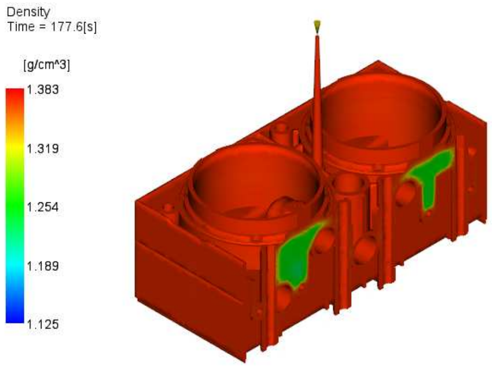



Figure 3.14: How an injection pressure plot should look like in an analysis and how it should also look in a real production run. (unit in psi) [30]

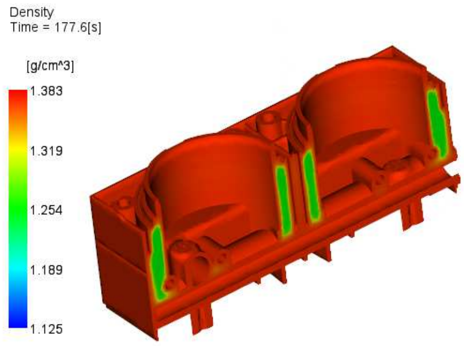
The results obtained are much similar to the ones defined as standard, but being the profile of the injection already set as a parameter of the analysis, it cannot be considered as a result. By observation of the analysis log, it can be noticed that the mass of the part does not vary from the second 8 in the injection process. This means that a pack phase of 30 seconds, as set by the company, is not necessary and it is a waste of resources. A shorter packing time as setup can be set if the packing obtained in this period is considered good by the company, or a higher temperature to be maintained to be able to pack more the polymer inside the cavity are the variations that can be attempted to obtain the required results. The company can evaluate the properties achieved and choose the necessary variations in the setup parameters.

### 3.4.4 Density

The previous paragraph (3.4.3) is spent to explain the pressure at injection result. Once realized that the packing phase ends its efficacy much sooner than planned in the setup, the Density result has to be analyzed in detail to define if the packing reached with the current setup can be considered enough for the final properties of the piece. If the density is found sufficient, then the company can reduce the packing time to the one suggested by the analysis. If not, then the packing has to be prolonged by maintaining the gate and the majority of the piece's volume liquid for a longer time.




(a) Density of the material after the packing and cooling phase. Section view of the thickest point of the piece



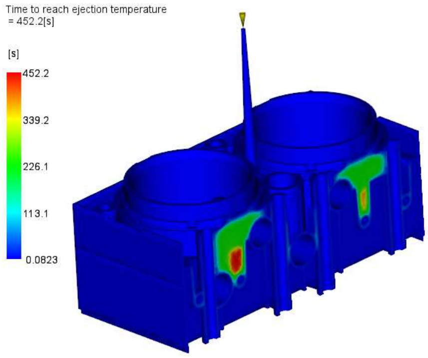

(b) Density of the material after the packing and cooling phase. Section view of the filter's holder main holes.

Figure 3.15: Density after packing.

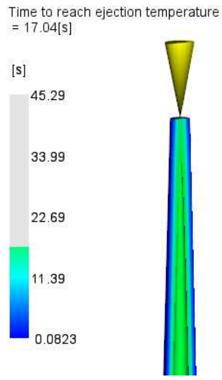
One of the problematic points of the piece is the thick region shown in figure 3.15(a). Since it is one of the thickest points in the piece, it has both heat retention and a lack of packing. All the contours of the main filter holders (figure 3.15(b)) also revealed serious density problems. The walls of the filter holders will for sure resent the effect of poor packing with an extensive sink marks problem when the piece is finished and this may create problems with the proper filter fitting. A longer and higher packing of the piece is the only solution. A solution to this problem will be discussed after observing the frozen fraction result and studying when the gate freezes in these conditions.

### 3.4.5 Time to reach ejection temperature

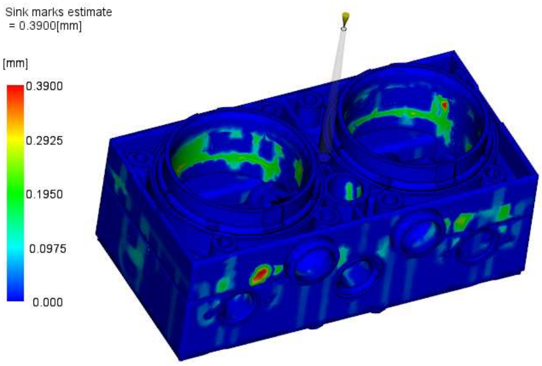
One important thing to analyze through figures 3.16(a) and 3.16(b) is the time at which the feeding system freezes. This output can show at what time the packing stops even if pressure is still applied. Once this instant is determined, it also permits to study in more detail other packing problems that may have been found in other result panels (subsection 3.4.4). The similarity between the density (figure 3.15(a)) and the time to reach ejection temperature (figure 3.16(a)) is easy to see here; higher temperatures are maintained where more material is concentrated, this means more time to reach the



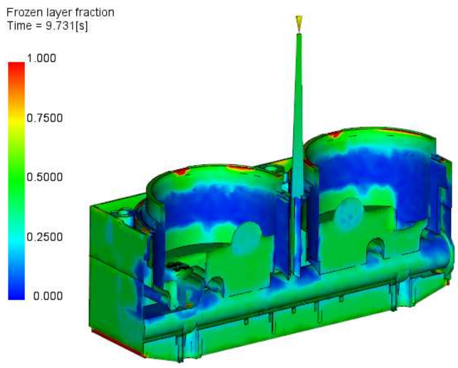

(a) Time to reach the ejection temperature (TRET), critical area in the piece




(b) TRET, instant at which the sprue freezes (time re-scaled)




(c) Sink mark estimate




(d) Frozen layer fraction

Figure 3.16: Fill+Pack result obtained. All these results will be analyzed in the relative sections.

ejection since more material in bulk has to be cooled down. But a higher concentration of material also means a difference in thickness of the piece between the area under observation and the surroundings; these surroundings will cool down much faster and so they won't permit a proper packing of the area, hence a lower density of the same site.

Also in the fill analysis with fixed time, the sprue is indicated as frozen much earlier than the end of the packing phase, as seen in figure 3.16(b). This result indicates that the parameters must be re-balanced to maintain the sprue liquid for at least as long as the packing phase is going. The sprue that is used is at high risk of freezing before the wanted time due to its geometry. The orifice of the sprue is just 3 mm in diameter, and it is a cold runner, so no heating is provided to keep this area of the polymer liquid. The use of a packing phase of 30 seconds is a loss of time and energy since the frozen sprue will not allow any polymer flow during half of the time set for packing.

### 3.4.6 Sink mark estimate

In figure 3.16(c) the depth and position of the sink marks are shown. Thicker regions, ribs roots, and bosses are the main areas that are subject to sink marks, and in this result, they are highlighted. Being the sink marks caused by contractions of the polymer while cooling down, they can be avoided with proper packing of the material. In terms of their severity and position, they can be more or less critical for the final quality and functionality of the piece. In this case, the sink marks around the main filter holder's holes are very critical. The marks around the external walls of the piece can be considered less critical. Other properties that can affect sink marks as material, geometry, and injection location can't be changed in this case; only the filling conditions and the packing parameters can be optimized.

Like the previous results, it can be seen that the packing profile should be changed to avoid sink marks.

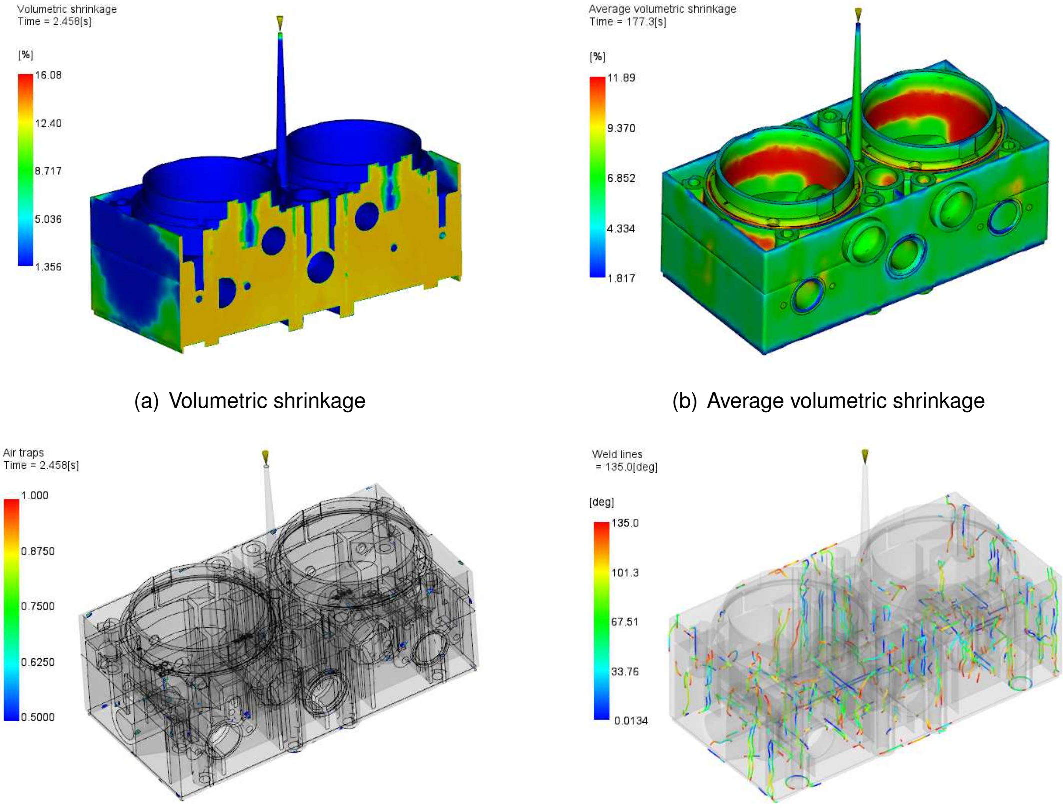
### 3.4.7 Frozen layer franction

The frozen layer result shown in figure 3.16(d) represents how the piece starts to solidify due to the contact of the injected material with the mold cavity walls. The figure shows the percentage of thickness that has solidified at each moment (reaches the ejection temperature of the material). The viscosity is strongly linked to this result since the cooling process decreases the melt viscosity until solidification and the display of these results is usually much similar. It is important to analyze if the material is maintained liquid for enough time to have a proper filling and packing even along the sprue that feeds the cavity. A specific instant in the process is represented in figure 3.16(d): at 9.731 seconds the sprue is already half frozen in thickness, not permitting proper packing from this moment on. The packing phase is set from 3.14 to 30 seconds, but at 9.731 s the sprue is already partially frozen, and by instant 10.5 is completely frozen. So 20 seconds of packing are lost in the process.

This is the first clear indication that the set-up parameters that the company is using are not balanced for the process and need to be revised to optimize the production of this piece. At the end of this comment section, an attempt to optimize the parameters will be described.

### 3.4.8 Volumetric shrinkage and Average volumetric shrinkage

Reference to figure 3.17(a) and figure 3.17(b). The volumetric shrinkage is evaluated point by point in the piece, and the final result is the last value from the last iteration at the end of the cooling system. The highest the volumetric shrinkage the more probable is to have sink marks and voids at that point at the end of the cooling phase in the piece. This result is usually used to foresee the appearance of sink marks and structural voids in the final piece. A good parallel can be seen with the sink mark result obtained and discussed before in section 3.4.6. Also, the warpage will depend strongly on this result, so minimizing the occurrence of volumetric shrinkage will minimize the final warpage of the piece. The averaged result is the point-by-point volumetric shrinkage previously described averaged over the half-gap thickness of the piece and plotted on the surface to show the result. The same problems can be detected with this averaged result, so the data is shown side by side in figure 3.17. A 12% averaged volumetric shrinkage is a very critical result for the piece. The occurrence of sink marks is inevitable when the percentage of shrinkage is high. Once again the absence of a well-optimized packing phase is shown in the results of the analysis.




(a) Volumetric shrinkage

(b) Average volumetric shrinkage

(c) Air traps

(d) Weld lines

Figure 3.17: Fill+Pack result obtained. All these results will be discussed in the relative sections.

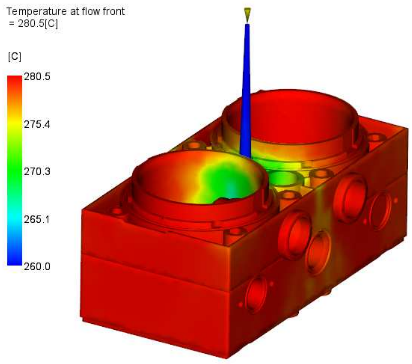
## 3.5 Some suggestions for process optimization

By the end of the fill+pack analysis, some problems are already clear. Errors made in the design phase can affect the quality of the final result of the process.

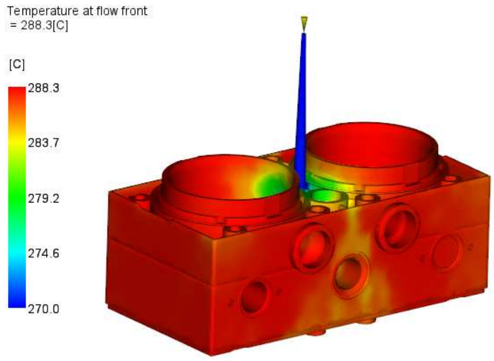
The first critical problem observed in the injection molding process is the increase in temperature at the flow front. It has to be maintained below 5℃ of increase to avoid problems. In the analysis described in section 3.4.2 the increase in temperature is 20.5℃. In areas where the flow front temperature increases by several degrees, material degradation and, surface defects can occur and so this value needs to be decreased. The main reasons for high temperatures are:

- Injection time is too low: the injection time is already below the time indicated by the company so any decrease in its value will distance the current work from what the company is experiencing in its production facility. Since this goes against the purposes of the work, the solutions will be searched elsewhere.
- Areas of hesitation: these are usually thin sections of the piece where the polymer struggles to enter. To do so, it needs to be subjected to high shear stresses, and consequently its temperature increases due to friction. Since the geometry of the piece is fixed, the most logical way to decrease friction for the polymer in these areas is to increase the temperature of the melt, decreasing its viscosity and increasing its ability to enter the narrowest parts of the cavity.

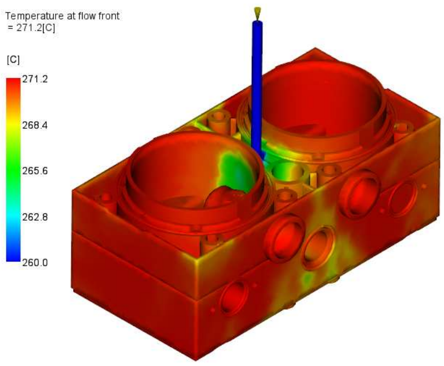
The First attempt to solve the problem is to increase the temperature of the melt from 260℃ to 270℃. This will increase the fluidity of the polymer and will decrease the friction with the side walls of the cavity. The difference in temperature decreases from 20.5℃ (figure 3.18(a)) to 18.3℃ (figure 3.18(b)). To further improve the filling there is the possibility to increase the dimensions of the sprue. 6 mm on top and 8 mm on the bottom are the new dimensions set where a little slope is maintained to permit the extraction. The main idea is to make the top entrance of the sprue as big as possible to delay the freezing of the sprue.



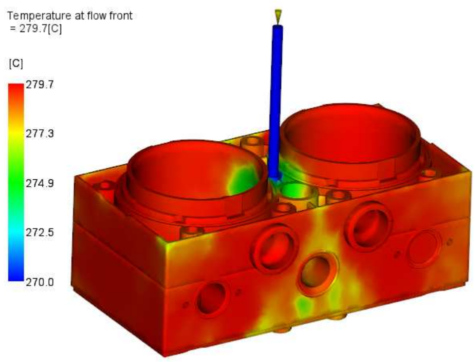

(a) Initial result at 260℃ and original geometry for the sprue




(b) Result with increase of the melt temperature to 270℃ and original geometry for the sprue




(c) Increase the diameter of the sprue, temperature at 260℃




(d) Increase the diameter of the sprue, temperature at 270℃

Figure 3.18: Temperature at flow front, comparison of results between four different setups. a) result at 260℃ and original sprue. b) result at 270℃ and original sprue. c) result at 260℃ and enlarged sprue. d) result at 270℃ and enlarged sprue.

As seen in figure 3.18(d) the difference is only 9.7℃. The temperature has been maintained at 270℃ here; so for completeness, an attempt to increase the diameter of the sprue and keep the temperature to 260℃ is run.

From a comparison between figure 3.18 and figure 3.18(c) can be easily determined how a temperature change of 10℃ in the melt only influences the temperature at flow front for a couple of degrees while the enlargement of the sprue gives in both analysis a decrease of around 10℃. It may be interesting to consider as a future work the study of the dependence on the time of fill and flow rate of fill, and other parameters that can be used to solve this specific problem. Considering that the main aim of this work is to try to simulate the piece production and not to find the optimal set of parameters, this chapter will be left open for future development. Here the correct way to simulate this complex piece in Moldflow is found. From this point on, the work can be continued easily in the direction of parameter optimization.

The next step is to run the cooling analysis. The main aim of this work is to try to find a way to run analyses over a very complicated piece with CC channels for cooling. Due to the CC geometries, the cooling analysis can be considered the main core of this work since the simulation of these features may be extremely complicated. For this reason, the cool analysis simulation will be considered in the following separated chapter.

# Chapter 4

# Feasibility study on the Conformal Cool analysis

The best methodology to incorporate complex conformal cooling and traditional channels in the same system is still unclear. For this reason in the present study it has been necessary to understand first which are the available methods in Moldflow, attempt some of them until one that work is found, and in the end, manage to get some cooling results that are helpful to understand the weak points of the studied case.

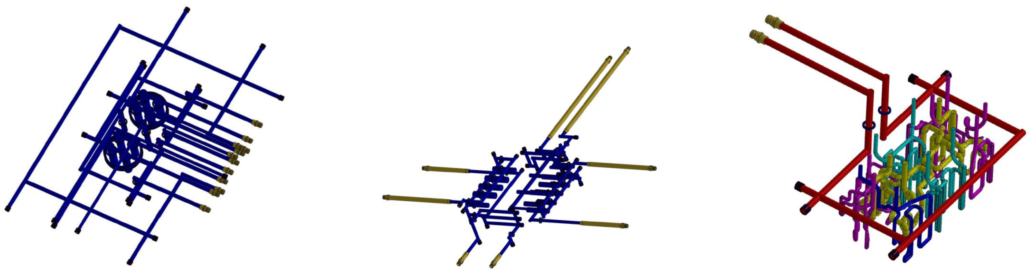
Whenever the cooling system is very complex, the recommended choice for the analyses in Moldflow is to import the channel geometries from technical drawing software. All the cooling system geometries were already designed in Solidworks by the company and the files were shared at the beginning of the study. When this is the case the import, mesh with 3D mesh, and run a Finite Element Method (FEM) analysis is the only available option.

Then, to run a cool analysis in Moldflow it is necessary, depending on the type of analysis to be made, to model the mold and mesh it. For the FEM analysis the mold is necessary, while for Boundary Element Method (BEM) and others it is not strictly needed. Many ways have been attempted, and to ease the work of whoever will continue this study, they are here followingly listed and carefully described.

Only once reached this step different types of cool analysis can be run and the results analyzed.

## 4.1 Introduction on the geometry of the cooling circuits

The complexity and the size of the piece require special attention while creating the cooling system. Special dimensional tolerances have to be achieved. The technical office of the company managed to find a cooling system that has a good chance to be able to cool down the part properly, but the company is not able to run a Moldflow analysis due to the complexity of the system, so they are proceeding by experimentation with a huge expense of time and money. This work is intended to find a way to run these analyses on the Moldflow software, and by doing so to help the company to save time in the production of new pieces.



(a) Cooling system on the fixed side of the mold

(b) Cooling system on the lateral sides of the mold

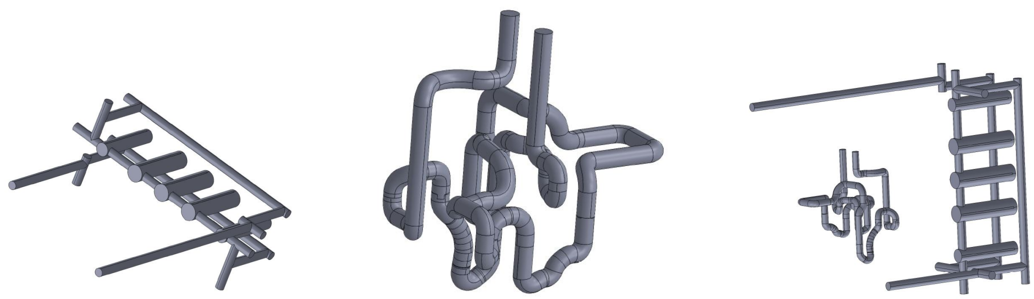
(c) Cooling system on the movable side of the mold, conformal cooling

Figure 4.1: View of the complete cooling system for this piece

The cooling system for this piece is extremely complicated; this can be seen in figure 4.1(c) where the conformal cooling part of this system is represented. To produce these complicated cooling channels the company is using a Additive Manufacturing (AM) metal printing method. The AM insert has different properties than all the other parts of the mold that are being produced traditionally. Special description and attention when setting the analysis properties are required for this reason. Considerations will be eventually discussed at the end about the error introduced in the analysis if the whole mold is considered to have the properties of the AM insert. This simplification will be applied to the system, considering that the error is found to be small enough for the results to still be considered valid.

The cooling system embedded in the fixed part of the mold (figure 4.1(a)), the lateral cooling channels (figure 4.1(b)), and the conformal cooling respectively (figure 4.1(c)), are available as Solidworks files.

In comparison with figure 4.2(a), figure 4.2(b) shows the most complex cooling channel in this case. The difference is verified not only in terms of complexity but also by dimensional comparison in figure 4.2(c) have to be noted; the traditional cooling is much bigger than the conformal, both in diameter and in the volume occupied, but the total length is similar for the two circuits. This means that the heat exchange in the CC case is much more focused on one point of the mold permitting it to quickly cool a specific part of the piece in a very efficient way.



(a) Single traditional cooling channel once separated from the others and cleaned

(b) Single conformal cooling channel

(c) Dimensional comparison between the two previously shown channels

Figure 4.2: Cooling channels

## 4.2 Available procedures to recreate or import the cooling system in Moldflow.

To run a cool analysis in Moldflow, it is necessary to have the cooling circuits incorporated into the study. For that, there are multiple procedures that can be applied. It is possible to import external cooling channel geometries only if a "Cooling FEM" analysis is run and not for traditional cooling. When the geometry of the channels has already been developed in Computer-Aided Design (CAD)/Solidworks software programs, this is the recommended procedure.

The complexity of this system calls for cool FEM analysis, being the most precise among the analysis types available. This requires attempting the import procedure for this case. In case of failure though, Autodesk Moldflow Synergy allows running FEM also in case of the representation of the cooling channels manually. [31] The procedures are listed here in the order they will then be attempted.

IMPORT - It permits to import channel's geometries from different technical drawing software like Solidworks or CAD:

- CAD Model: This option is only available if a conformal cooling analysis is to be simulated. In this case, the whole geometry of the cooling channel is already present in the file and not only the center line of it.
- *.iges Curves: Exporting the curves from the CAD program as *.iges files allows for easy import into Moldflow. Once imported, default cooling properties are assigned to them but can be changed manually, then need to be meshed to create beam elements.
- *.sdy/*.udm file: This option allows for pulling a cooling system from another study or UDM file from Moldflow.
- *.adv file: Save the file as *.sdy or *.udm, to import via "Add".

CREATION - Moldflow allows multiple options to create a cooling circuit directly inside the software:

- Cooling Channel Wizard: This wizard steps through the size, orientation, and occurrence of the cooling circuits. When using this, the cooling channels will be generated in a simple, symmetric pattern on both the cavity and core sides of the mold.
- Manually Draw: This modeling option allows for more complex/custom cooling channels to be created using curves. The curves must then be meshed to create the beam elements.

### 4.2.1 Import multiple cooling channels at one time from CAD

As the company shared the files with the complete cooling system divided into three main areas: front, back, and sides, the first attempt will be to try to import the file as given. If the files can be imported as blocks, this procedure will allow an easy way to start running the analysis without spending much time on the import procedure. The chances of success though are quite low due to the probability of defects in the geometries of the channels.

From the inspection of the files obtained from the company, it is immediately clear that some modifications and simplifications are necessary. Each file has been opened and inspected to understand the geometry of each channel and relative problems if present. Start and end points have been determined, and unnecessary items have been identified for elimination, as observed in figure 4.3.

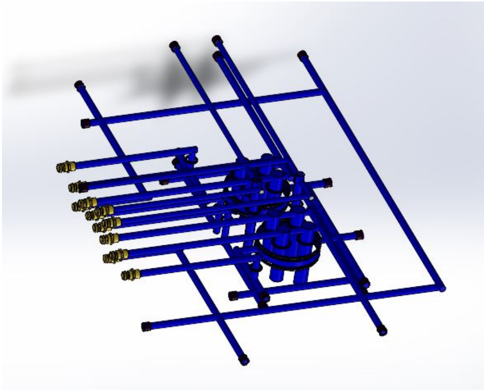


Figure 4.3: Cooling system on the fixed part of the mold. Solidworks file received from the company.

The import procedure of one entire file at once with multiple cooling channels in it is not possible due to defects in the geometrical CAD file. Even if the unnecessary items are canceled, and visible defects are treated there are still defects that cannot be identified by the eye and these defects do not allow the import of one whole side of the cooling system. To try to identify these more complicated defects, the files have to be broken into single cooling channels, and each channel has to be carefully inspected. This procedure will require careful work to prepare and then run the analyses.

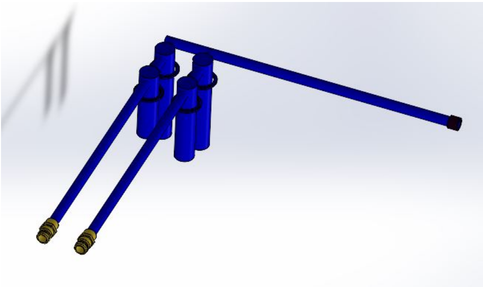
In the next sections, a detailed description of the process used to import the cooling system will be made, as inserting all cooling channels at once proved not to work. It should be noted that not all the procedures tested were able to succeed, due to the complexity of the cooling system and the part itself.

### 4.2.2 Import single cooling channels one by one from CAD

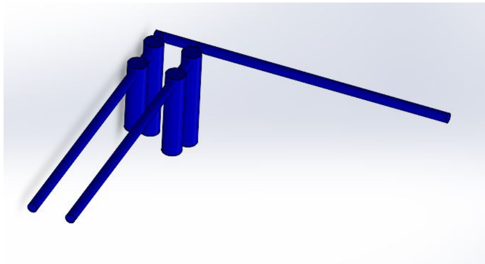
The Autodesk guide for cooling FEM analysis suggests importing the channel one by one until the whole system is imported. This will help to mesh the channels and detect eventual defects in the geometries. To start with, it is necessary to disassemble the Solidworks files. It should be noted that only one channel will be taken into consideration for the description from now on, but the same procedure has been applied to every channel present in this study.

To start with this methodology one channel has to be chosen among all of them. This one has to be isolated, and all the other bodies that pertain to other channels in the file have to be eliminated. Only the wanted ones have to be maintained in the file, without any complementary geometry. Entrance nozzles, seals, and other specific pieces that are not useful in terms of cooling analysis have to be deleted from the file, and only the geometry of the channel has to be maintained. Figure 4.4(b) shows a cleaned channel geometry, ready for import.

Each file has to be checked for visible geometrical defects. Some cooling channels, during this stage of observation, are defective or have collapsed surfaces. Each visible geometry defect has to be solved before proceeding with the import into Moldflow. Having solved the previously identified defects at this stage does not give assurance of the ability to import and mesh the channel into the software correctly,



(a) One single channel isolated from the original files sent from the company. It still shows all the accessory items that need to be deleted



(b) Cleaned channel. Only the geometry is maintained

Figure 4.4: Single cooling channel Solidworks file.

so this described step is just the very beginning of the process.

After all this, the file has to be saved in the permitted formats for import in Modflow. The Autodesk guide lists all the available formats [32]; depending on the original type of the file sent by the company, only some of these will be allowed so one trial of import will be applied to each available encoding.

Formats available for this specific case:

- SOLIDWORKS Part(*.prt,*.sldprt): this permits us to have the file in the original file format but only the cooling channel under consideration. This file format will be the one used if modifications to the geometry are necessary.
- STEP AP203 (*.step, *.stp) or STEP AP214 (*.step, *.stp): this permits to have always a backup file with the original version of the geometry in case there is the need to modify something in the other files, in general, it will be helpful for future consultation of the geometry through Solidworks.
- ProE/Creo Part (*.prt): this is the version of the file that permits the correct import of the geometry in Moldflow. This type of file will be the one searched when importing the geometry of the channels.

Now each channel has to be imported individually over the already meshed piece. It is necessary to prepare a Moldflow file with the piece correctly meshed and the injection point or the whole running system present in it. The analysis sequence has to be set as COOLING FEM and all the process parameters have to be correctly set as wanted. Only now is the software ready for import. On the task list for the cooling FEM analysis there is the possibility to create/import the cooling channels; after a right click on that line and having chosen the import method the file in ProE/Creo Part format can be chosen for import.

Once correctly imported, to be able to mesh the channel correctly, there is the need to first set the properties of the imported geometry as cooling channel if not already imported through the import channel method (figure 4.5). Secondly, the inlet and outlet of this channel have to be set, and only now the mesh of the Three Dimensional (3D) channel can be activated through the top middle command in the mesh panel as seen in figure 4.6.

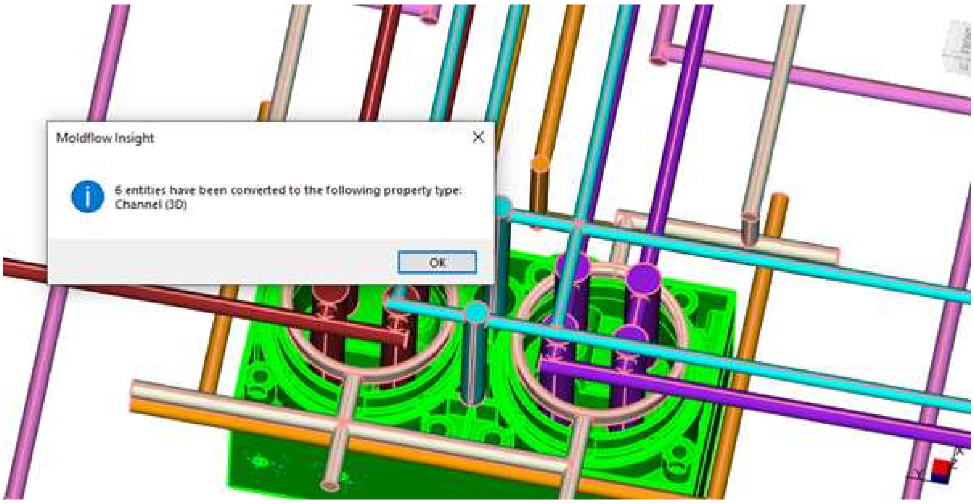



Figure 4.5: Change property for the imported channels before the mesh. This passage can be achieved by >select the complete geometry of one channel >right click on the selected area >change properties >channel or 3D channel.

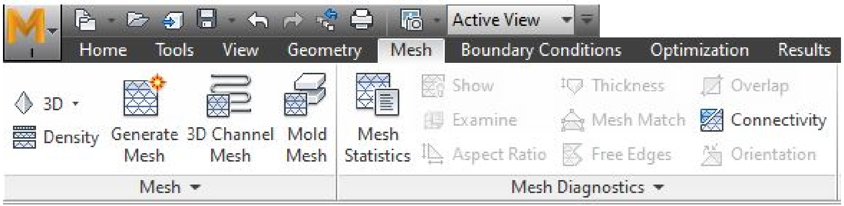



Figure 4.6: Mesh panel that can be found on the top border of Moldflow. Choose 3D mesh to mesh the channels once the inlets and outlets have been set correctly.

#### 4.2.2.1 Mesh of conformal cooling channels

In case of importing from CAD the geometry, the 3D mesh necessary to run a Cooling FEM analysis is specific: due to the Computational Fluid Dynamics (CFD) solution being more complex and resource intensive than an ordinary 1D solution in the cooling channels, it is more efficient to use the 1D solution for drilled hole geometries and only use the CFD solution for complex cooling channels. For this reason, only imported CAD bodies are used for the initial conformal cooling geometries to be analyzed with the CFD solution. [33] Whenever a channel geometry comes from a CAD file, Autodesk Simulation CFD 2014 places enhancement layers close to the boundary wall of the channel, and allows the user the option of specifying the number of enhancement layers used. This will permit the system to analyze better the heat transfer between the mold and the cooling channels.

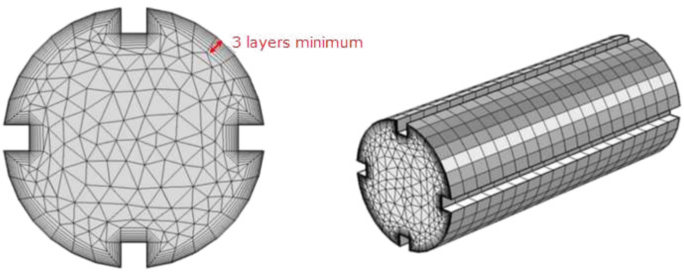



Figure 4.7: Enhancement layers required in any 3D cooling channel mesh. [34]

Four case scenarios have been found:

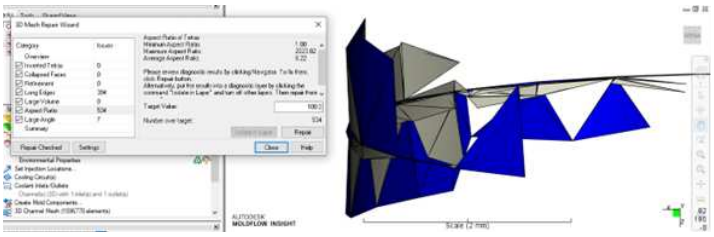
1. CHANNELS with SUITABLE MESH: some channels, once imported and meshed have been found to reach a good mesh in the system automatically. The mesh repair wizard was not showing defects that would have compromised the functioning of the analysis, so these channels had to be saved and stored in the memory for ready use once the complete system had been imported and meshed.

2. CHANNELS with UNSUITABLE MESH: some other channels that Moldflow was able to import showed some geometrical defects once imported and meshed. The mesh repair wizard was able to detect aspect ratio problems, large volumes, angles, and long edges. These problems needed to find solutions before proceeding. In some cases, the wizard was able to detect and repair the problems automatically. On some other occasions, slight variations of the geometry of the channel were necessary. One specific case that has been found multiple times was the junction of straight parts of the channels with particularly shaped curves; the struggle in drawing these complex curves was causing geometrical defects in the structure with consequent high values of aspect ratio. Only in some easy cases, the wizard has been able to solve the problem itself. In many other cases, the geometry had to be modified by hand in Solidworks and then re-attempted the mesh until the problem was solved. Iteration of this procedure was applied until the mesh was suitable for the analysis. The representation of this example can be seen in figure 4.8

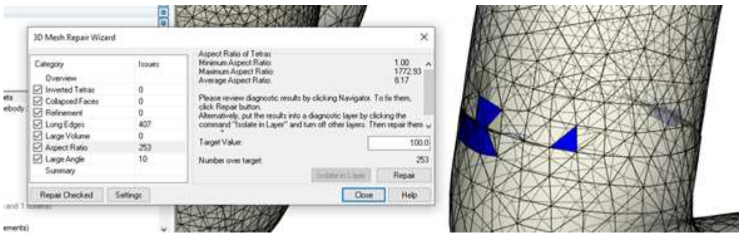
3. CHANNELS that are IMPOSSIBLE TO MESH: in this case, the channel can be imported correctly, but the mesh is not allowed by the software for some problems in the reading of the file or some intrinsic defects in the way the channel is drawn from the beginning. In order to overcome these problems, changes in the channel geometry from the original file were performed, but the problem was not able to be fixed. Autodesk knowledge network suggests using some software for geometrical analysis as Sim Studio 2016.3, Spaceclaim, CAD analysis, SC, Fusion 360, and Inventor and try any combination of import and export procedures from these analysis software types to find if there are small defects in the geometry that can compromise the ability to mesh the channel. Another possible solution is to redraw from the beginning the channel with attention to the way the geometry is built and check in Moldflow, step by step, the feasibility of the mesh of parts of the channel.

   From the Autodesk knowledge network, written by Hanno van Raalte whose contact was used during the development of the project and from whom some very useful clarifications about these technical problems have been found, it is said: "The mesh on the conformal cooling channels has a different structure from the normal Moldflow mesh. Within Moldflow, there is integrated a tuned version of the CFD solver and mesh for the conformal cooling channels. The meshing options are tuned specifically for the interior flow, but they have their sensitivities (that are a bit different from the normal Moldflow mesh). This external mesh is driven through API calls, but it has limits in terms of the ability to extract useful information from the mesh (e.g. where it fails, recommendations of how to resolve it, etc.). To get the mesh from the original format, into Moldflow, and into the tuned conformal cooling mesh, the model goes through a few model conversions (*.step → ASM → *.sat), and each of these steps introduces some risk of conversion errors, which can trip up a mesh. Something that may play a role here too is the different versions of the CAD kernels (in Inventor, Moldflow, SimStudio Tools, and/or SpaceClaim) that may create inconsistencies. The Moldflow team is looking at the possibility of overhauling the conformal cooling workflow in Moldflow to overcome some limitations. Going by recommendations from the CFD team; if the model does NOT mesh in their environment, quite often it is better to go to the CAD system (and check/resolve model errors)." [35]

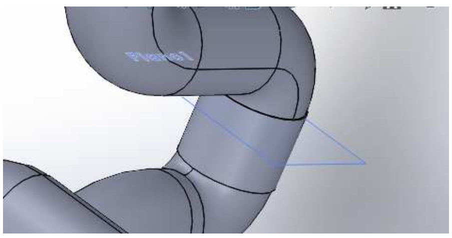
4. CHANNELS that are IMPOSSIBLE TO IMPORT: some channels seemed to have defects in the file that could not be solved by modifying in any way the geometry. Before proceeding with the redraw of these channels, being their number very low, fortunately, it has been decided to proceed with an attempt to run the analysis with the channels that have been able to be correctly imported. This procedure is described below, and further comments on this type of file can be found here followingly at the end of the procedure's explanation.



(a) Initial analysis of the Mesh repair wizard, aspect ratio of 2023.82




(b) Result after the attempt to automatically solve the problem through the wizard, aspect ratio of 1772.93



(c) Geometrical modification of the channel to solve the problem. The modification has to be as small as possible in order not to influence the heat transfer of the channel

Figure 4.8: Example of mesh repair procedure for channels.

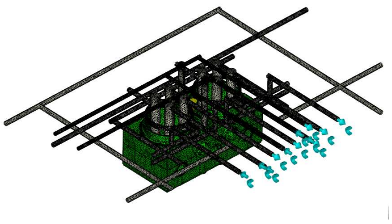
### 4.2.3 First trial of a cooling analysis with only part of the cooling system

Once a good number of suitable channels have been reached a cooling analysis is attempted. However, a limitation related to the number of cooling channels was detected within the software. It is able to support only 8 cooling channels for this case study. For more than this, the software is not able to mesh the mold.

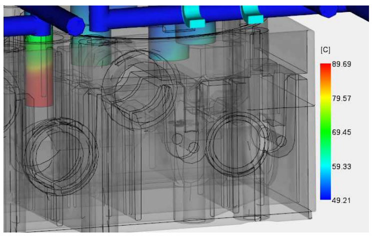
The only attempt with imported channels that have reached the end can be described as follows: the piece mesh was obtained without a runner system, the cooling channels imported are the ones on the side defined as the front of the piece, and the temperatures of the coolant have been set to 50℃. The same situation was run for a coolant temperature of 70℃ as wanted by the company, but the analysis failed to reach a reasonable cooling time, so the analysis stopped halfway.

A careful analysis of the results obtained from this first run has been extremely helpful in pointing out also some defects in the way the software can read and represent the cooling channels. When importing channels, the system was not able to correctly read the baffles as they were represented in Solidworks but treated them as normal empty channels with consequent stagnation of fluid in that spot. It can be seen in figure 4.9(b) how the geometrical structure of the baffles is not correctly read by Moldflow. The stagnation of fluid at the farthest distance from the coolant flux creates a localized increase in average temperature at the extremity of the baffle due to the incorrect flux of cooling fluid.

A correct representation of what a baffle should look like in the result is reported in figure 4.10 on the other hand. The temperature along the baffle should be uniform due to the capacity of the baffle to exchange temperature also between the two fluxes of coolant upward and downward along the geometry. Any local increase in average temperature that does not follow the coolant flow path is to be considered a stagnation point in the cooling channel and has to be avoided.



(a) Channels considered in the first conformal cooling analysis attempt




(b) Detail of the average temperature along the channels in this analysis. Detail of a baffle with a clear view of a wrong representation of this geometry by the software.

Figure 4.9: Analysis of the setup and results of the first attempted cooling analysis.

As referred previously, and considering the computer used in the present work for the Moldflow analysis, the number of channel circuits able to be introduced in the cool FEM was a maximum of 8 for the mold geometry model to mesh correctly. Trials to run the mold's mesh with different combinations of channels, to avoid influence on the problem of eventual defects in the channels added, have been attempted and the result from these attempts can not be mistaken: the complexity of the system is too high for the software to be able to process the information, and the use of a more performing computer

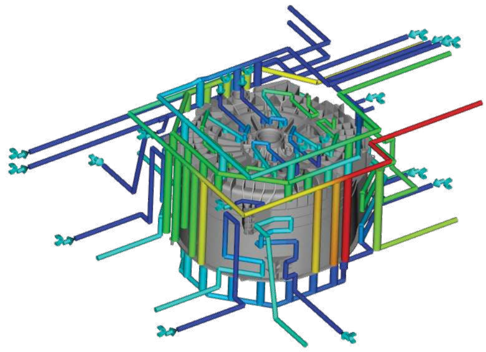


Figure 4.10: Correct representation of the average coolant temperature inside of a baffle. In the picture, multiple baffles can be seen, and the temperature is found to be uniform in the baffles as it is supposed to be. [36]

will probably not solve the problem being it related to the structure of the software more than the computational power of the computer. Also, a more performing computer was not available at this time, so the results for this project have to be obtained with the materials and appliances given.

The only possible solution to knowledge at this moment is the manual drawing of the channels as beams and curves to simplify the geometry and reduce the mesh complexity of the system.

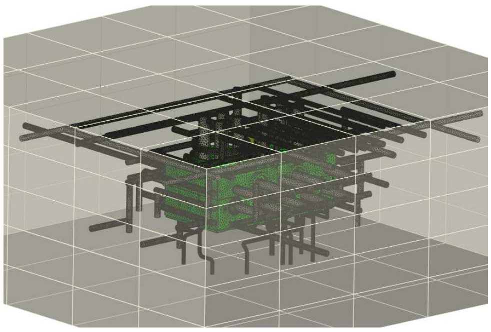


Figure 4.11: View of the mold block defined through the mold block wizard over the system with all the channels that could be imported and meshed up until this moment. The mesh of the mold was never achieved by the software.

### 4.2.4 Manually draw the channels directly in Moldflow

As seen in section 4.2.3, in order to properly model the baffles, it is necessary to draw them in Moldflow through curves and beams manually. At the same time, the same procedure can be used to overcome the limitations and problems indicated in the previous section for the general complexity of the system.

With this solution, it is possible to solve all the problems that have been found in this case. This methodology should only be applied when the problems faced during the import attempt have no other solution than this. This procedure has to be considered the last resource for the company because it takes a lot of time to be implemented, even if it is the easiest of all the procedures available, and it is also the least precise.

By manually drawing the channels, they will be represented with beam elements. The 3D mesh will not be necessary anymore, and the computational complexity of the final result will be much less intensive than in all the previously described cases. Using this procedure, care should be taken in measuring the cc channels, in order to achieve a more accurate representation of all systems. This procedure is considered a valid way to represent a Conformal Cooling (CC) system even by the developers of the software in case the other methods are not available.

It has been decided to attempt it even if it is time-consuming for the company. If used as a last resource it will still help the company to obtain some analysis, and it will still decrease the time and expenses of the company in the project phase of the production of a new piece and mold.

In this case, the steps to be followed are:

1. Open the *.step version of the Solidworks files used for the previous import procedure. The use of the already cleaned and separated files is recommended for this procedure since the need to measure the path distances and geometries of each channel is required.

2. Define one of the extremities as the starting point for the design of the channel and measure the coordinates of the center point of the round surface that defines the start (figure 4.12(a)).

3. Orientate the whole channel along the principal directions and start to measure the distances. Some simplifications will be needed especially when complicated curves are inserted in the geometry.

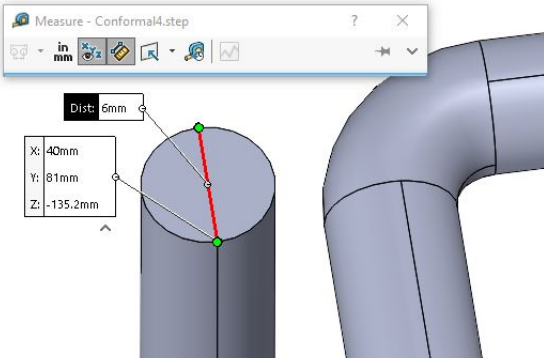
4. Once obtained the geometry dimensions, the coordinates of each major geometrical point of the center line of the channel have to be inserted in the Moldflow panel window for channel drawing to obtain the representation of the channel. The more care is taken while obtaining the dimensions, the more the channel obtained will be similar to the one drawn in Solidworks by the company.

5. Once reached the representation of the whole geometry of one channel. It is important to check for distancing from the piece surface to avoid touch points or excessive vicinity. Also, interference with other channels has to be checked, and eventual intersection points have to be eliminated by slightly modifying the geometry of one of the two channels under observation (figure 4.12(b)).

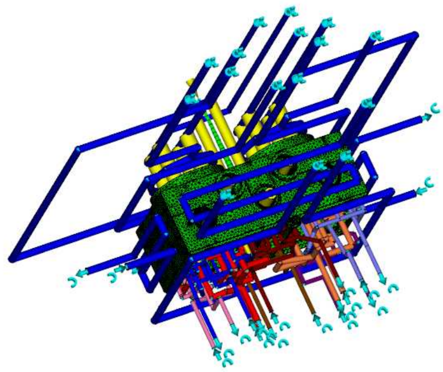
6. If channels with non-circular sections are present, the choice of maintaining that shape or modifying it to round has to be made. Since the complexity of the studied system is already a challenge for the software, it has been decided to always maintain a circular section for this case, but for future developments, Moldflow also allows non-circular sections.

7. Once obtained the whole cooling system. It can be meshed again to obtain a finer beam mesh for the channels. This passage is not necessary for the ability to run the analysis, but it would give better solutions in terms of accuracy.

Once these passages are concluded successfully the analysis can proceed. The only problems that can be found are intersections between the piece and the channels that have not been spotted by the eye, but a simple local modification of the geometry of the channel under consideration will solve the problem and the analysis is ready to be run.




(a) Representation of the measuring procedure for the channels from the Solidworks file. Procedure to acquire the coordinates of the initial point for the channel.



(b) Complete cooling system hand-drawn in Moldflow.

Figure 4.12: Representative figures for the manual drawing procedures of the channels. The figures represent the process of retrieving the coordinates for the drawing from Solidworks and the final result obtained.

For completeness of the study, two other methods of import have been attempted but not used for this study. In this way, all the listed possibilities have been attempted and described along this elaborate, but the description will be presented in appendix B. One of them is the *.iges format, which will be described in section B.1 and the other is the possibility of redrawing from start the defected channels in Solidworks and see if redrawing them will avoid the insurgence of the observed defects. This second way is described in section B.2.

### 4.2.5 Remarks on the import procedure

The import of the cooling system has been challenging in many aspects. One entire chapter was needed to describe the various attempts to insert the cooling system in Moldflow to find the way that is more suitable for this specific case. Any of the previously described procedures can be applied for any future projects, so a resume can be helpful for future reference:

- Import all the cooling at one time - in this case, it was not possible due to defects in the files. It was necessary to deconstruct the files given into singular cooling channels and clean them from additional pieces.
- Import one at a time - First of all it has been necessary to define the right type of file to save from Solidworks to be able to import the geometries correctly in a way the system can read and perceive them as cooling channels. Once reached the knowledge of the available file types then it is possible to proceed with the import. - Proceeding with the import it is necessary to obtain the first mesh to see if the geometry is represented correctly, without major mesh problems like collapsed surfaces. If there are problems, solutions have to be found until a correctly meshed channel is obtained. - One first attempt of analysis has to be done at this point to check the correctness of the procedure until now. The search for any possible error is necessary to see if continuing with this procedure is worth it or not. Any defect found discards this procedure, and many have been found. One, in particular, is the excessive complexity that blocked the ability to run the analysis

and so to continue on this path.

- Manual drawing of the channels into Moldflow - this is the procedure that has been found to work properly for this case.
- IGES format import - the same geometrical defects found during the import are found here, and the correction seems more complicated than the previous mode.
- Manual drawing of the channels in Solidworks for future import - the length of this procedure is not worth it knowing that the complexity of the final system will block the analysis.

Future developments from this point of the project are multiple. Each one of the previously mentioned points is open for future developments but here are the major ones:

- Redraw all the defective channels and attempt to run the analysis with the complete system on a more performing computer if available.
- Attempt to run a mixed analysis with some manually drawn channels and some imported. Moldflow is already able to run these combined analyses, but the level of complexity is even lower than the one-type analysis, so no attempts in this direction have been made.
- Further research on the Solidworks files to discover what are the problems that do not allow the import, and what are the ones that do not allow the mesh to have a list of defects to search for and avoid in the drawing stage of the project.

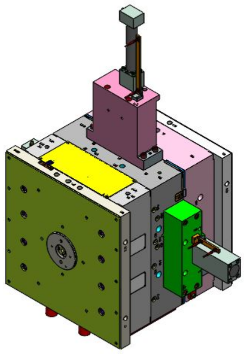
## 4.3 Representation and mesh of the mold in Moldflow

After describing all the cooling import procedures and all the relative challenges of this part of the study, it is important to get into a detailed description of the mold and its characteristics. The mold for this piece is a big challenge for the company under many aspects, some of them already mentioned in the previous chapters. In the present section, an overview of the mold components, materials used as well as traditional and non-traditional techniques to produce them will be presented.

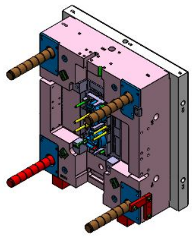
### 4.3.1 Mold components overview

Designing the mold and its various components (referred to as tooling) represents a highly technical and complex process requiring high precision and scientific know-how to produce top-quality parts with tight dimensions. The proper grade of steel must be selected so that components that run together do not wear out prematurely. Steel hardness must also be determined to maintain the proper balance between wear and toughness. Waterlines must be well-placed to maximize cooling and minimize warping. Tooling engineers also need to calculate gate/runner sizing specifications for proper filling and minimal cycle times, as well as determine the best shut-off methods for tooling durability over the life of the program.

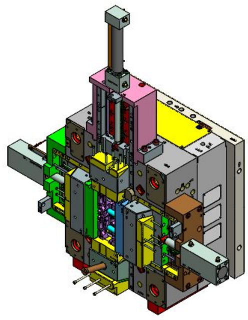
In general, more complex injection-molded products require more complex molds. These often must deal with features such as undercuts or threads, which typically require more mold components. Other components can be added to a mold to form complex geometry; rotating devices, rotational hydraulic motors, hydraulic cylinders, floating plates, and multi-form slides are just some examples.



(a) Whole mold



(b) Fixed side



(c) Movable side (180° rotation from previous view)

Figure 4.13: Exploded view of the mold geometry

Once established that the piece under study is extremely complex and the cooling channel is too consequently, it cannot be expected anything different for the mold. The size of the piece under study (figure 1.5) and the complexity of the cooling system around determine the final dimension of the mold: 125.4 cm of width, 144.4 cm of height, and 70.3 cm of depth.

It is pretty clear in figure 4.13 and it can also be foreseen from the observations on the complexity of the system that this mold is composed of many pieces. From a rough estimation, the number of inserts that compose the complete structure is for sure above 800 (the specific number obtained from the Solidworks file is 834).

### 4.3.2 Mold material for the conformal insert

The mold insert with the conformal cooling channels is particularly complicated to produce. Additive manufacturing is necessary in this case. The material chosen for this insert is a maraging steel 18Ni300 MS1 - approximately 1.2709. It is necessary first to break down and explain the designation in more depth to understand the properties of the material used.

MS1 stands for maraging steel of steel class 1. Maraging steel is a type of ultra-high strength steel, it is based on carbon-free or ultra-low carbon Fe-Ni Martensite as the matrix, making the metal compounds, when the metal is aged, precipitated, and harden. To indicate this particular composition we have the compact AISI denomination 18Ni(300). (300) indicates the specific grade of this steel. Grades have different yield strengths obtained by adding different contents of Co, Mo, and Ti into the Fe-Ni Martensitic alloy through aging hardening (better shown in 4.1). The strength of Maraging steel does not come from the carbon but from the precipitation of inter-metallic compounds. After solid solution, 18Ni steel forms ultra-low carbon Martensite with a hardness of 28 30HRC. After aging treatment, it gets aging hardening due to the dissolution and precipitation of various intermetallic compounds. The hardness can increase to 50HRC. The excellent characteristic of 18Ni steel is that it still has good toughness and high fracture toughness under the condition of ultra-high strength and high hardness. 18Ni maraging steel is a perfect combination of high strength and hardness, good toughness, and plasticity. It has been widely used in aviation, aerospace, precision mold, and other industrial fields, such as rocket engine shells, missile shells, uranium isotope centrifuge high-speed rotating cylinders, and other high-precision load-bearing parts of the material. [37], [38]

Table 4.1: Composition of AISI 18Ni, comparison between grades

| GRADE | C | Si/Mn | P/S | Ni | Co | Mo | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| 200 | $\leq 0.03$ | $\leq 0.10$ | $\leq 0.01$ | $17.0 \sim 19.0$ | $8.0 \sim 9.0$ | $3.0 \sim 3.5$ | $0.15 \sim 0.25$ | $\leq 0.01$ |
| 250 | | | | | $7.0 \sim 8.5$ | $4.6 \sim 5.2$ | $0.3 \sim 0.5$ | |
| 300 | | | | $18.0 \sim 19.0$ | $8.5 \sim 9.5$ | | $0.5 \sim 0.8$ | |
| 350 | | | | | $11.5 \sim 12.5$ | | $1.3 \sim 1.6$ | |

Table 4.2: Useful data from the mold material datasheet. [39]

| Data sheet properties | Value | Unit | Moldflow data | |
|---|---|---|---|---|
| DESCRIPTION | | | | |
| Trade name | | | 18Ni300 MS1 | |
| Manufacturer | | | Unknown | |
| Data source | | | Osprey | |
| Data last modified | | | November 2019 | |
| Data status | | | Confidential | |
| THERMAL | | | | |
| Mold density | 8.1 | $g/cm^3$ | 8.1 | $g/cm^3$ |
| Mold specific heat (20℃) [40] | 430 | $J/kgC$ | | |
| Mold specific heat (500℃) [40] | 460 | $J/kgC$ | | |
| Mold specific heat (90℃) | | | 434.375 | $J/kgC$ |
| Mold thermal conductivity (20℃) | 14.2 | $W/mC$ | | |
| Mold thermal conductivity (600℃) | 21.0 | $W/C$ | | |
| Mold thermal conductivity (1300℃) | 28.6 | $W/mC$ | | |
| Mold thermal conductivity (90℃) | | | 15.06 | $W/mC$ |
| Coefficient of thermal expansion | $10.3x10^{-6}$ | $1/K$ | $10.3x10^-6$ | $1/C$ |
| MECHANICAL | | | | |
| Elastic modulus | 185 | $GPa$ | 185000 | $MPa$ |
| Poisson ratio [41] | 0.27 | | 0.27 | |
| ELECTRICAL | | | | |
| Electrical resistivity | 0 | $\Omega m$ | 0 | $\Omega m$ |
| Relative magnetic permeability | 0 | | 0 | |

To be even more precise with the categorization, the company also specified the equivalent Werkstoff number for this steel. The number is approximately 1.2709.

Werkstoffnummern: 1.2709

Main group: 1 - steels

Sorting 2709(xx): 27 - tool steel - 09 - number - (xx) - no additional number

The DIN – Deutsches Institut für Normung - defines West German steel specifications. These specifications are usually preceded by the letters DIN followed by an alphanumeric or, more commonly, a simple numeric code. The numeric code is the well-known Werkstoff number. [42]

Other designations for this steel are UNS K93120, ASTM A538 (C), or ASTM A579 grade 73. [43]

In most cases, the specific heat data is not present in most of the material datasheets, so an external source needs to be found. Usually, it is recommended to search for this type of data in scientific articles or manuals. In this case, the data has been found in a specific article published by Elsevier from the AIAS 2019 International Conference on Stress Analysis [40]. Whenever the data found are referred to specific temperatures it is best practice to interpolate.

### 4.3.3 Mesh of the mold

For obtaining good quality results from complex Moldflow analysis, the import and mesh of the mold are of fundamental importance. The definition and then description of the correct material for the mold will influence all the temperature evaluations; but also the mesh size and the mesh accuracy will influence the way the temperature results are obtained and so the quality of the final results.

Getting ready to generate a 3D mold mesh requires several steps, depending upon the starting point. In all cases, it is important to generate a mesh that is sufficiently fine on the internal surfaces next to the part, feed system, and cooling channels, yet sufficiently coarse on the outside edges to minimize the element count to decrease the computational time necessary. [44]

The mold's internal edge lengths, that is, the parts of the mold in contact with the part, the feed system, and the cooling channels, should be sufficiently small that they define the shapes of the elements with which they are in contact. The way contact between them will be represented is one of the main points that will influence the evaluation of heat exchange.

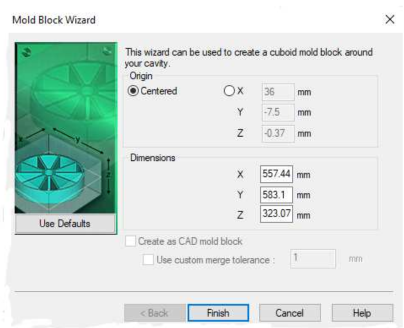
Important to remember is that the mold is strictly necessary only to run a Cool FEM analysis, but it will give more precise results in any of the cool analyses. But it will also increase the computational time needed, so a quick balance of gains and losses has to be considered each time.

Two options are possible to obtain the mold block at this point:

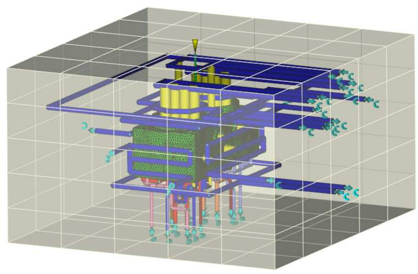
- Mold model: There is the possibility to import a model exactly in the same way the piece model has been imported. The import and mesh procedure for this case follows the procedure already described for the piece so that no more time will be spent on this method. This approach is not taken into consideration due to the lack of a simplified mold structure from the company, and any attempt to import the mold file geometry that the company provided will surely fail within the Moldflow software due to its extreme complicacy.
- Mold Block Wizard: The Mold Block Wizard enables either to generate a mold block as a region or to create a CAD mold. In either case, the cooling channels and feed system must be represented by underlying curves to be included in mold generation.
  - Mold region model: Mold block as a region is the default setting. When the Mold Block Wizard button is clicked, a message appears indicating that the software will generate the mold block as a region. The right dimensions should be set and adjusted if necessary, until all the cooling channels and runners are inside the outer contour of the block shown (figure 4.14(b)).
  - Mold CAD model: This option is available for CAD formats only. Generating a CAD mold using Mold Block Wizard simplifies the next step of meshing the mold: it enables the use of the Auto-sizing option in the CAD tab of the Mold Mesh tool, a merge tolerance option is available in the Mold Block Wizard dialog, to avoid the use of manual stitch contact interface

later on and the internal components like inserts, parts, runner system, and cooling system, are subtracted and a simplified cuboid mold is created. It is also possible to create a CAD block after having created and checked the block obtained as a mold region.

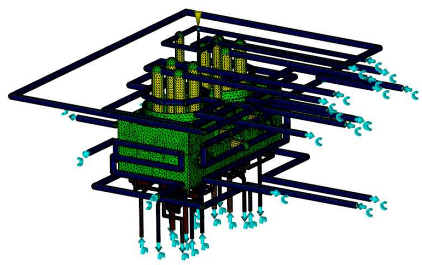
The mold block in this case has been created as a region through the wizard, with the procedures described just above. The final dimensions can be seen in figure 4.14(a). The file containing the mold geometry is extremely complex and could not be modified to reach just the main block and simplify the structure to a point that permitted the import. However, there are studies that point out the insignificant difference in results between the two methods for creating the mold block. Specifically, a study from Kaushikbhai C. Parmar and Dr. H. Kaiser points out with evidence that the difference in all the main results of the cool analysis for their case is negligible. The only difference is the computational time needed to run the analysis, which is higher for the case where the import procedure has been used. In terms of efficiency then, the use of the wizard is recommended. [45]



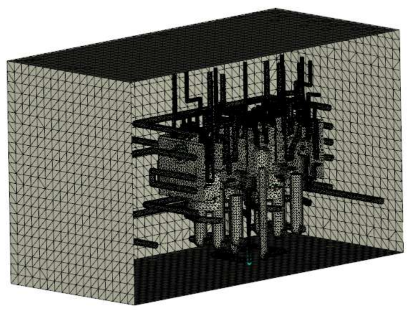

(a) Mold block wizard - dimensions



(b) Mold block region boundaries



(c) Mold block internal triangles when meshing the mold in the first step - DD mesh obtained



(d) Mold block section view when meshing the mold in second step - 3D mesh obtained

Figure 4.14: Construction of the mold through the mold block wizard - Mold block region procedure

When meshing the mold, it is important to read the mesh logs carefully in search of any warning message or error message. In this case, one initial error was found due to the contact between one of the designed cooling channels and the piece, then solved with a slight variation in the geometry of the channel itself. Also, some warnings have been showing off about the contact between consequent curves that have been drawn to reach the final shapes of the channels. No necessity to change the geometry in this case. The warning can be overseen and left there since the following 3D meshing of the mold will solve any of these problems with a proper 3D structural mesh.

Another problem that was found, in this case already in the second stage of the mesh, was the overlap of the runner system beam structure with the 3D mesh of the mold. Also, this problem can be omitted, as specifically said by Shoudong Xu from the Autodesk Moldflow Meshing in an Autodesk Forum discussion dated back to November 2016 [46].

After the solution of any found problem and inspection of the final mesh results to assure its geometrical integrity and correct meshing, the cooling analysis can be attempted. The setup and results of this analysis will be described in the next chapter (section 4.4).

### 4.3.4 Summary of the procedure to mesh the mold

The design of the mold is extremely important in the manufacturing process of injection molded parts. The mold is the most expensive component of the whole process. The mold needs to be designed with the parting line, runners, and gates in mind. If these are not designed properly, the part will not come out correctly, and the mold will need to be scrapped. [47]

The importance of the correct development of the mold in real life is perfectly mirrored in Moldflow where the representation of the mold and its inside components is fundamental for the quality of the final results. Usually, obtaining the molded mesh in Moldflow is a straightforward procedure once most of the time is spent importing the piece and the cooling channels. But this is not the case here. In this system, the mold itself has been a complicated step to overcome. Multiple ways needed to be attempted and all the study about the material was necessary to achieve the best possible representation. All this is necessary whenever the mold presents particular features that are not automatic for the software.

Even more here, where the mold has traditionally machined parts, and parts that are 3D printed, the consequent different behaviors of the materials must be taken into consideration. In this study, no time was spent defining how to manage this difference, how to apply simplifications when possible, and how to reach a good representation of the mold. But further study development can be important in this direction.

## 4.4 Study of different types of cool analysis

As already seen in chapter 3 for the fill and pack analysis, the description of the results of the analysis that have been run is of fundamental importance to understand the quality of representation of the real case scenario through Moldflow simulation. After the fill+pack analysis, the following step in the development of a Moldflow project is the cooling analysis, and the same importance should be given to the description of the final results of this type of analysis.

Independently from what is needed for this project, Moldflow has a wide set of possible cool analyses to run, and every one of them has its specific characteristics that make them more or less suitable for the case under study. It is then important to understand all the possible alternatives before starting to run the analysis.

In section 3.1 it has been fully described how to obtain a 3D mesh for the piece involved in the study and why the 3D mesh is fundamental for this type of project. Since the piece is 3D meshed, the type of cool analysis to be involved in the study is the 3D Cool solver that performs Cool analyses on three-dimensional (tetrahedral) part meshes. [48] Moreover, the FEM cool analysis is required for the presence of the CC system, since that is the only procedure that can incorporate the complex geometry of a CC channel when imported from external files and 3D meshed in Moldflow.

The cool FEM would then be the only option whenever this project is applied to a system for which the cooling system can be imported completely, or partially. But as seen in section 4.1 this is not the case for this system. Since the cooling system for this case has had to be fully described with beams, this opens the possibility to study the difference in terms of results between a Cool boundary element method (BEM) analysis and a Cool finite element method (FEM) analysis.

The in-depth description of the results obtained will represent the main core of these paragraphs, but for clarity of results, a first paragraph with the description of the parameters that have been set for these analyses is necessary. As already done for the fill analysis, the main intention for this project is to represent through computer analysis what happens in real life at the production site of the company during the production cycle of the piece. So, to maintain consistency, the parameters that have been used for the fill analysis will also be used here, in addition to the ones specifically related to the cool analysis, which also have been obtained from the company.

### 4.4.1 Process set-up parameters for the cool analysis

Multiple analyses have been run with different set-up parameters to see the variation of results among the different possibilities that Moldflow gives. Both automatic and specified times have been set for the averaged-within-cycle analysis and will be described here. Run for the transient analyses have not been attempted both for uselessness about the aim of the project and for the computational time that would have been needed. The main focus will be maintained on the comparison between the results of a Traditional Cool BEM analysis and a Cool FEM analysis.

For a first attempt to run the cool FEM analysis the set of parameters used are listed in 4.3. The automatic total time for the analysis is maintained to see what the best time evaluated by the software is. After this first attempt, once checked that everything works correctly and since the company provided the total cycle time that is wished to be achieved, an attempt to set the wanted time will be described. (In this project the time referred as target time has to be considered as the time obtained by the company during their experimental attempts. In the project, this time becomes the target time since the aim of the research is to represent through computer analysis what the company is experiencing.)

The set of parameters is maintained the same that is described in table 4.3 except for the Inj+pack+cool (IPC) time that is set with equation 4.1.

$$t_{tot} = 3.14_{fill} + 30_{pack} + 145_{cool} = 178.14s \simeq 180s \tag{4.1}$$

One important comment to insert here is that the cool analysis takes around two hours and a half with the beam-designed cooling channels; before, when attempting to run the analysis with the imported channels the analysis would take more than two days to run completely and then still fail most of the times. This once more proves that the complexity of the system is too high for the software to handle, at least for the present moment and for the current version of the software.

Table 4.3: Set of parameters used for both the Cool (FEM) analysis and the cool (BEM) analysis.

| SETTINGS | | Value | Units |
|---|---|---|---|
| COOL (BEM) | | | |
| Melt temperature | | 260 | ℃ |
| Mold open time | | 5 | s |
| 1. Inj+pack+cool time | | automatic | |
| | Mold surface T | 90 | ℃ |
| | Ejection T | 179 | ℃ |
| | Minimum frozen % at ejection | 100 | % |
| 2. Inj+pack+cool time | | specified | |
| Additions for COOL (FEM) valid for both specified and automatic time | | | |
| Mold close time | | 0 | s |
| I. Mold temperature options | | Averaged within cycle | |
| II. Mold temperature options | | Transient within cycle | |
| III. Mold temperature options | | Transient from production startup | |

After the attempt to run some FEM analyses, it has been decided to run also some BEM analyses to then be able to compare the results. The preparation of the FEM analysis was already fully described in section 4.1 since it has given major problems in development. The preparation of the BEM analysis was also rich in obstacles but their solution was much less problematic and so the description of the procedure is reported in the next couple of sections.

### 4.4.2 Cool BEM analysis with 3D mesh for the piece

To run this analysis, at first, the mold has to be recreated and re-meshed; it can be seen in figure 4.15. While for the mesh of the cool FEM mold a whole paragraph (4.3.3) has been spent to understand the whole procedure here it can be seen that it is much easier to obtain. It is not even considered necessary to have the mold block in this type of analysis. The whole analysis can be run without the mold if wanted. Another thing to notice from figure 4.15, in comparison with figure 4.14(d) in section 4.3, is the simplicity of the mesh used in this case.

Once started, the analysis failed through the end due to ** ERROR 701010 ** Cool analysis has not converged. This error message was found in the analysis logs that Moldflow makes available. Logs are important instruments to understand the reasons for the failure if analyzed with care. The Autodesk guide suggests that there may be issues in either the part and beam mesh or the process parameters.

The beam mesh is the first problem that will be addressed. For a beam cooling circuit, it is suggested to check that the modeling of the circuit is correct by: [49]

- Reduce overlapped beams and check for centroids that are too close.
- Check for small beams at the base of baffles. Replace with a longer beam that joins at the base.

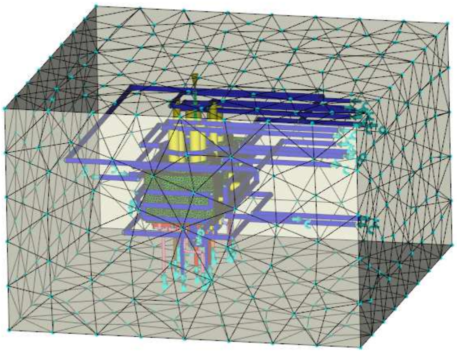
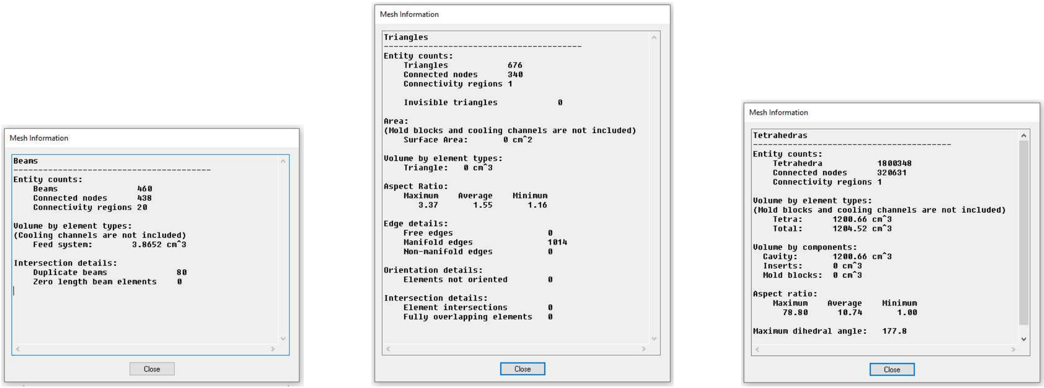


Figure 4.15: Mold mesh for Cool (BEM) analysis.




(a) Beams from the cooling channels

(b) Triangles from the mold box

(c) Tetrahedra from the piece

Figure 4.16: Mesh statistics windows for the different types of meshes that are present in the cool BEM analysis file for this case.

All the previous have been checked through visual inspection and the mesh statistics wizard. It has been found that there are 80 duplicated beams in the model. This didn't cause any problem for the FEM analysis but can influence the BEM analysis. This error has to be addressed and solved since it is found that it can also be the cause of the failure of the analysis.

As found in the Autodesk guide, duplicate beam elements can cause analysis problems and convergence errors in Cool analyses (for example, "** WARNING ** Solution iteration limit reached before convergence"). Duplicate beams can be present in cooling channels, runners, or connector elements.

In most cases, the Auto-Repair mesh tool can be used to remove duplicate beams automatically, as happened for this case [50]. In the eventual need to repair this problem manually, Autodesk offers a procedure scheme on the same online page where this information has been found (Reference to bibliography [50]).

No other problems can be found from the inspection of the cooling beam elements, so the repair procedure can continue with the piece body. The part mesh has to be inspected to ensure there are none of the following issues:

- Invisible triangles.
- Free edges.

- Non-manifold edges.
- Elements not oriented.
- Element intersections/overlaps.

All these things can be checked in figure 4.16(c) and none of them are found to be present. Some warnings can still be found in the logs of the analysis that are assigned to the piece 3D mesh. The warnings are the following: ** WARNING 701350 ** The aspect ratio of element ... is very high and ** WARNING 700955 ** Two elements are too close. First Element: id = ..., location = Part_model. Second Element: id =..., location = Part_model.

For the high-ratio elements, there is not much that can be done because the obtained mesh for this piece is the best that could have been achieved due to its complexity. This problem is effectively a problem for the cool BEM analysis due to the low refinement of the mold surface mesh while the refinement of the piece is much higher. Since these problems are indicated as WARNINGS and not ERRORS the analysis will be able to run properly even if they are present. The only concern is now to reach convergence. After the solution of the duplicated beams problem, a second attempt in running the analysis is done and here followingly there are reported the results.

The convergence problems continued also after the solution of that problem. The decision at this point is to try to put the limit of accepted convergence a little higher. It has been put to the highest limit of 0.5 from 0.1 and still, it was not enough. The following message showed: ** WARNING 700990 ** Solution iteration limit reached before convergence. Solution error = 0.6004 C.

As convergence was not possible to be achieved, the last choice is to try to run this analysis on a Dual Domain mesh file with the same cooling channels used for the 3D mesh case. This attempt is described in the next section, section 4.4.3.

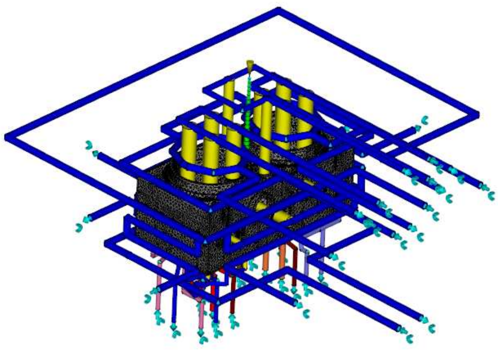
### 4.4.3 Cool BEM analysis with DD mesh for the piece

The old Dual Domain (DD) file for the piece has been retrieved from the very first stages of the study. This file has been merged with the files containing the cooling system and the final structure has been checked for errors and problems. Since no errors have been found and the mesh statistics gave permission to run the analysis, all the parameters have been set as previously. Before proceeding to run the analysis, to already solve partially the mentioned mesh refinement warning, a coarser DD mesh is set for the piece. Not much difference between the two dimensions of the mesh can be achieved, because of the complicacy of the piece (the mesh statistics can be seen in figure 4.17(b)).

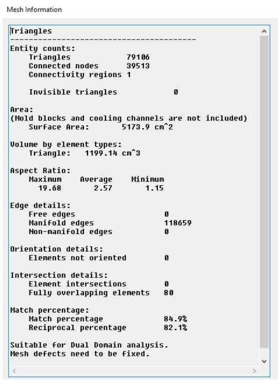
Also important to point out, this analysis has been run without the presence of a mold block, as seen in figure 4.17(a). This was applied to avoid further complications to the analysis file in an attempt to avoid problems in the convergence.

It has been seen after the analysis was completed that this variation was enough to achieve convergence. Since this file has reached convergence it has been used for both the run of a fixed time analysis and an automatic time analysis. Both results will be described here followingly.

By analyzing the logs it can be noticed that there are still some warnings shown that have already



(a) View of the structure used for the cool BEM analysis. No mold is used in this case.




(b) DD mesh statistics, they assure that the analysis can be run properly.

Figure 4.17: General characteristics of the file used for the run of the cool BEM analysis.

been described, for example, the ** WARNING 700955 **. Considering the presence of these warnings and paying attention to any possible effects that they may have, the results obtained are described.

A brief description of the two analyses will be presented in separate subsections here followingly, and then the chapter will proceed with the comparison between their main results. Whenever referring to them, the following codes will be used to simplify the references:

- SA = specified time analysis
- AA = automatic time analysis

#### 4.4.3.1 Cool BEM with DD mesh results with specified time (SA)

As was expected from the time to reach ejection temperature results, after the IPC time of 180 seconds the part is not yet 100% solidified. Many elements are individuated as not frozen by the end of this time and the list of all of them is indicated in the logs with the following warning: ** WARNING 701500 ** Cannot freeze element 13527.

This partially invalidates the results from this analysis, but one point that can still be helpful is to try to realize what percentage of the piece is not frozen by the $180^{th}$ second. This will give an idea of how far the system is from the optimal freezing situation and an idea of how much time will be needed to reach complete freezing. The easiest way to visualize this property is to show the Time to reach ejection temperature and scale it down to 180 seconds or any time around this limit. We can see in figure 4.18 that the majority of the piece is still not frozen here and the final time estimation for this piece with this type of analysis is 974.3 seconds in total. Important to remember is that even at this time the system still detects parts that will not freeze in the piece, so effectively the time is even higher than this. (Just for reference 974.3 seconds = 16 minutes and 14 seconds = more than a quarter of an hour to produce one piece).

The main problem in cooling is found to be on the rib near the gate location. That part being particularly thin should not be a problem to cool down but the way the piece is built does not give space for any cooling channel to reach this area. This region presents some critical characteristics that are important

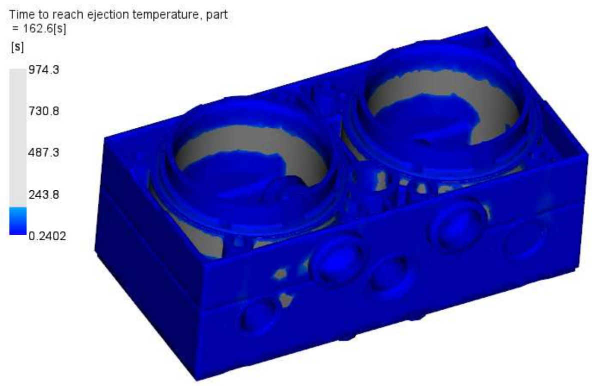



Figure 4.18: View of the part of the piece that is not frozen by the time set by the company, shown in grey. Most of the piece is not already frozen.

to point out at this time of the study:

- It is a thin rib in the middle of the piece → it should not be difficult to cool down if any cooling channel can reach the area → the area cannot be reached by any cooling → very low cooling efficiency in that part of the mold → hot spot of the geometry.
- It is at the very entrance of the melted polymer → it is positioned at the gate location for the piece → it receives the hottest melt polymer of any other location and almost all the polymer flows through it.

These two characteristics united, create a very huge problem for the system. The only solution for this problem will be a change in the geometry of the piece and some options are listed here followingly:

1. Change the gate location to another point of the piece → a whole study and eventual necessary geometrical variations of the piece are necessary here before being able to point out the pros and cons of this solution.

2. Change the rib geometry, enlarge the rib to permit better flow → most probably it will make the problem even worse due to the increase in local polymer melt quantity.

3. Elimination of the rib completely → structural assessment is necessary here to see if the geometrical change influences the structural performance of the piece itself.

Which one of the previous is the best solution will have to be determined by further analysis after the respective changes in the geometry of the piece files. This is a good prosecution branch for the study for whoever will want to continue it.

It is important to remember the main reason for the use of the cool BEM analysis: the boundary element method (BEM) determines the temperature on all surfaces of the mold, that is the outer surface, the part, and the cooling channel surfaces, then uses the boundary element integrals to calculate the internal temperatures of the mold. This provides an accurate representation of the temperature and enables the researcher to optimize the placement, quantity, and operating conditions of cooling channels in the mold. [51]

#### 4.4.3.2 Cool BEM with DD mesh results with automatic time (AA)

The same file from the previous analysis has then been used to run this one. Only the time evaluation has been changed to automatic in the process settings and the analysis has been run. One of the main things to mention among the results of this analysis is the difference in time between this and the previous, to see what is the time that Moldflow evaluates as the more suitable and how distant this is from what the company is forcing to the system. The difference in time then will have effects on all the defects that have been found on the final result of the previous analysis, described in section 4.4.3.1.

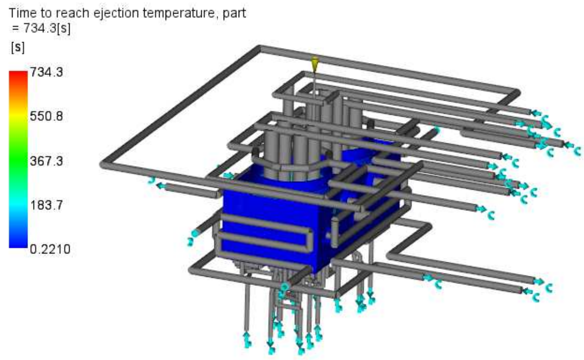



Figure 4.19: Time to reach ejection temperature for the cool BEM analysis with automatic cycle time.

The time evaluated by the system in the automatic analysis is lower than the one found for the fixed time one. In this case, the time necessary is 734.3 seconds and there is no indication of any unfrozen element in the analysis logs.

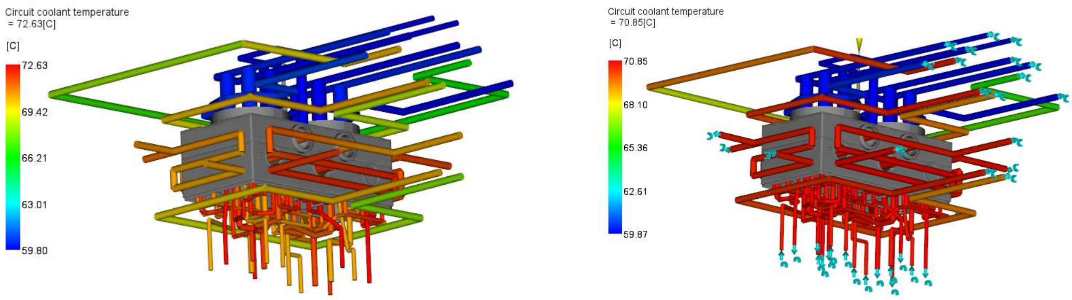
#### 4.4.3.3 Comparison of the results of cool BEM analyses with DD mesh - SA versus AA

As already said, BEM determines the temperature on all surfaces of the mold, so these main temperature results are observed and compared in this chapter.

First, by looking at the circuit coolant temperature results, it can be noticed that the heat removal attempted in the SA (figure 4.20(a)) is much more severe than in the AA (figure 4.20(b)). This can be deduced from the higher temperature difference between the inlet and the outlet reached by the cooling channel of the SA in comparison with the AA. This is the result of the time restriction for the cooling that has been fixed in the first case, while the second case is free to cool down over a much higher time.

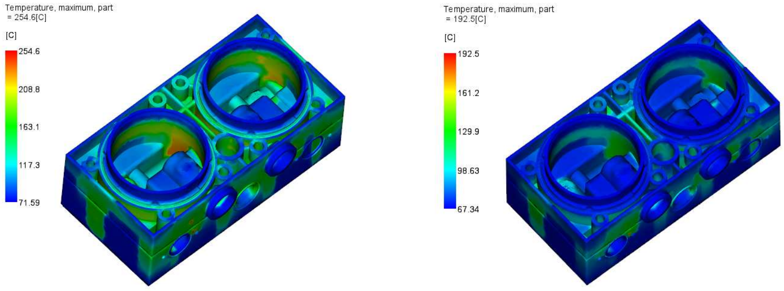
The attempted higher heat exchange showed in SA was supposed to cool down the piece much faster, but the time given was not enough to reach good results and the piece had no time to completely cool down. The result of the maximum part temperature of the SA (figure 4.21(a)) shows quite clearly how in this restricted time window the general temperature of the piece remains higher than the one that is given enough time to cool (AA, figure 4.21(b)). Also, the absolute maximum for the SA is 254.6 ℃ versus 192.5 ℃ for the AA. The same can be observed for the averaged temperature of the part.

The next result that can be used to comment on the part problems, and that is directly linked with the maximum temperature result just analyzed, is the Maximum Temperature Position of the part. This result shows the position of the reached maximum temperature along the thickness at that point. For uniform




(a) Circuit coolant temperature SA (b) Circuit coolant temperature AA

Figure 4.20: Set of results to be compared in this section from the Cool BEM analysis.




(a) Maximum temperature of the part SA (b) Maximum temperature of the part AA

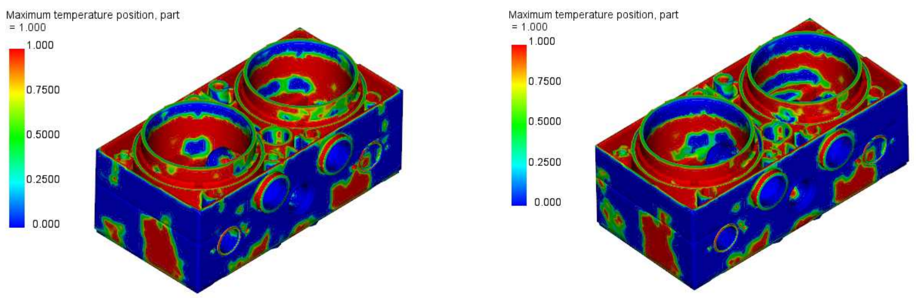
Figure 4.21: Set of results to be compared in this section from the Cool BEM analysis.

cooling, the relative position of the peak temperature should equal 0.5, since the maximum temperature on a homogeneous wall is placed at the central point. But for very complex structures such as this one, the position is not visible. Important is to notice where the value of the position is 1.0 because in this case the position of the maximum temperature is reached at the surface and in this location appropriate cooling has to be placed to avoid surface hot spots.

The piece under study has huge variations in the position of the maximum temperature, and these variations can be quite immediate along one surface, as seen both in figure 4.22(a) and figure 4.22(b). This is a problem due to the difficult positioning of the necessary cooling system and also due to bending and differential shrinkage of the material from point to point. There are differences also between the SA and AA results, but these have to be caused by the different times of cooling.

Another temperature result that is important to describe at this point and then will be compared with the FEM results is the general ”Temperature, part” result. This result represents a general view of the average temperatures of each point of the piece and can give an idea of where the heat will concentrate in the piece. Figure 4.23 shows the result for the SA analysis, and once more the gate area for the piece is the one that maintains the highest temperatures up to the very end of the cycle. One more indication that this area will be critical for the good result of this production.

All this has to be analyzed while keeping in mind that it is valid only for the initial stages of the project since the BEM analysis gives results that can’t be considered particularly accurate in terms of representation of reality. The results lose importance when wanting to understand what truly the real




(a) Maximum temperature position of the part SA

(b) Maximum temperature position of the part AA

Figure 4.22: Set of results to be compared in this section from the Cool BEM analysis.

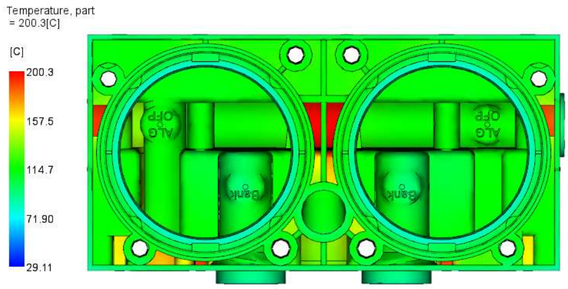



Figure 4.23: ”Temperature, part” result from the fixed time, cool BEM analysis.

case scenario will be, but they are extremely important for the project phase. This kind of analysis should be always run when still developing the cooling system and the mold structure, but once the system is fully developed and a good situation seems to have been found, then a proper cool FEM analysis should be run. Or better, a cool FEM analysis becomes necessary to understand more deeply what the real case scenario will give as a result.

### 4.4.4 Cool FEM - Averaged within cycle with automatic time

The work will focus on the cooling analysis with fixed time since the company wants to represent the experimental attempts that they are currently running. Reference to the automatic time results will be mentioned in this next section only for comparison with the other results whenever it is considered important.

For this case, it is reported just a summary of the analysis log with the major information about the cooling channels and their evaluated characteristics. Important points to notice in figure 4.24:

- Channel 4 does not reach the proper turbulent flow, the Reynolds number for this channel does not reach 10000. Still, the number is kept above 4000 which is the absolute minimum requirement, so the results can still be considered valid. The channel under observation is the one with the split of the main flow in two branches to go around the baffles in the front side of the piece; this division in two is the main reason for the decrease of the Reynolds number since the flow decreases to half when the two branches are created (the channel can be seen in figure 4.25). With this observation, the circuit flow rate and Reynolds number results can be considered as analyzed.

- Channel 5, 6, and 8 have a negative heat removal value and consequently a decrease in coolant temperature along them. Since all cooling channels are created to remove heat from the system, these channels have to be modified to be efficient for the system's purpose. Suggestions are to switch inlets and outlets and see if this solves the problem, or eventually decrease the temperature of the coolant for these channels. Particular care should be taken if the second solution is applied to avoid unbalanced cooling of the piece.

| Channel number | Inlet node | Flowrate in/out (lit/min) | Reynolds No. range | Press. drop over circuit (MPa) | Pumping power over circuit (kW) | Coolant temp. range | Coolant temp. rise over circuit | Heat removal over circuit |
|---|---|---|---|---|---|---|---|---|
| 1 | 539611 | 2.52 | 10000.0 - 14310.8 | 0.0051 | 2.132e-04 | 60.0 - 61.4 | 1.4 C | 0.234 kW |
| 2 | 539558 | 3.60 | 10000.0 - 16355.2 | 0.0045 | 2.687e-04 | 60.0 - 61.7 | 1.7 C | 0.413 kW |
| 3 | 539601 | 3.60 | 10000.0 - 16355.2 | 0.0045 | 2.687e-04 | 60.0 - 61.8 | 1.8 C | 0.442 kW |
| 4 | 539690 | 2.20 | 5000.0 - 10000.0 | 0.0014 | 5.067e-05 | 60.0 - 61.7 | 1.7 C | 0.257 kW |
| 5 | 539612 | 1.91 | 10000.0 - 10000.0 | 0.0011 | 3.594e-05 | 67.9 - 70.0 | -2.1 C | -0.279 kW |
| 6 | 539550 | 1.91 | 10000.0 - 10000.0 | 0.0010 | 3.106e-05 | 69.8 - 70.0 | -0.2 C | -0.032 kW |
| 7 | 539635 | 2.49 | 10000.0 - 20000.0 | 0.0133 | 5.518e-04 | 69.9 - 71.6 | 1.6 C | 0.267 kW |
| 8 | 539691 | 1.91 | 10000.0 - 10000.0 | 0.0010 | 3.179e-05 | 69.6 - 70.0 | -0.4 C | -0.058 kW |
| 9 | 2698231 | 1.14 | 10000.0 - 15000.0 | 0.0352 | 6.718e-04 | 70.0 - 72.4 | 2.3 C | 0.178 kW |
| 10 | 2698194 | 1.14 | 10000.0 - 10000.0 | 0.0080 | 1.524e-04 | 70.0 - 71.2 | 1.2 C | 0.092 kW |
| 11 | 1618904 | 1.25 | 10000.0 - 13333.3 | 0.0309 | 6.429e-04 | 70.0 - 73.8 | 3.7 C | 0.320 kW |
| 12 | 2158512 | 1.52 | 10000.0 - 10000.0 | 0.0053 | 1.346e-04 | 70.0 - 71.2 | 1.1 C | 0.117 kW |
| 13 | 2698171 | 1.25 | 10000.0 - 13333.3 | 0.0374 | 7.770e-04 | 70.0 - 73.2 | 3.1 C | 0.266 kW |
| 14 | 2698143 | 1.14 | 10000.0 - 12228.5 | 0.0233 | 4.442e-04 | 70.0 - 71.8 | 1.7 C | 0.132 kW |
| 15 | 1079267 | 1.52 | 10000.0 - 12228.5 | 0.0073 | 1.860e-04 | 70.0 - 71.2 | 1.2 C | 0.122 kW |
| 16 | 2158517 | 1.14 | 10000.0 - 12228.5 | 0.0304 | 5.799e-04 | 70.0 - 73.0 | 2.9 C | 0.230 kW |
| 17 | 539644 | 1.91 | 10000.0 - 10000.0 | 0.0008 | 2.697e-05 | 70.0 - 70.5 | 0.4 C | 0.056 kW |
| 18 | 539661 | 1.91 | 10000.0 - 10190.4 | 0.0019 | 6.037e-05 | 70.0 - 71.6 | 1.6 C | 0.204 kW |
| 19 | 539636 | 1.91 | 10000.0 - 10000.0 | 0.0008 | 2.415e-05 | 70.0 - 70.2 | 0.2 C | 0.024 kW |

Figure 4.24: Summary table of the cool analysis with averaged temperatures and automatic time

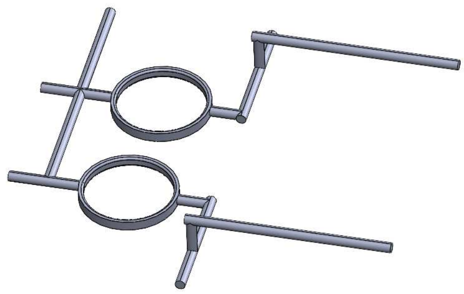
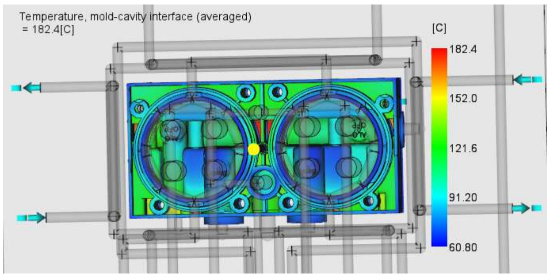


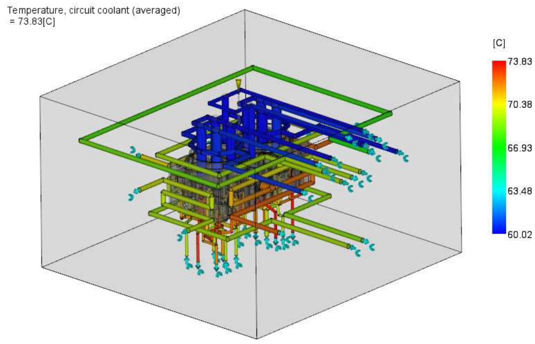
Figure 4.25: View of the channel that has Reynolds number below 10000. The split of the channel into two branches can be noticed where the red arrows point.

For the remaining results not much has to be added to this commentary. The time to reach ejection temperature for the part is estimated around 250 seconds in total and the runner is found to be frozen much earlier than the wanted packing time as already noticed in the filling analysis described in chapter 3. Here it is possible to notice how the results between fill and cool analysis are coherent.

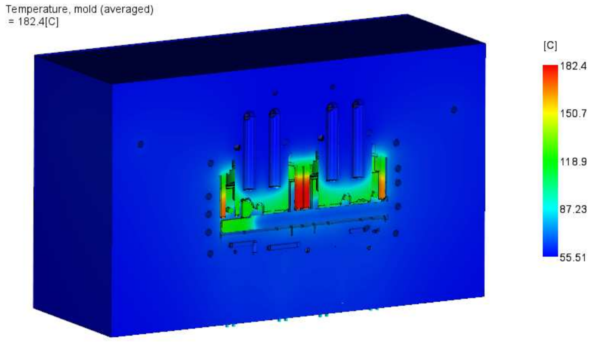
Both the major circuit pressure and the greatest heat removal efficiency are assigned to the CC channels. The length of these channels and the small diameter, with numerous turns and complicated shapes, determine an elevated pressure drop along their path, with the consequent necessity to pump fluid at high pressure to win the pressure drop. For heat removal efficiency, on the contrary, it is the vicinity to the cavity surface that has the major influence on the result; the nearest the cooling fluid flows to the cavity the highest the heat that the coolant can remove. Also, the high Reynolds number that characterizes the CC channels due to their complex shapes helps increase the heat removal efficiency.




(a) Temperature, mold-cavity interface (averaged) result for Averaged within cycle with automatic time analysis




(b) Temperature of the coolant, averaged along the cooling channel path




(c) Temperature of the mold, averaged. Section view of the point of maximum temperature

Figure 4.26: Important results from the first cooling analysis.

The minimum and maximum mold temperature should be within 10℃ of the target temperature for amorphous materials but this guideline is usually difficult to achieve for most molds. It is obvious that the narrower the temperature variation over the mold face, the less likely the mold temperature variation will contribute to warpage and an extended cycle time, but for this case, the range is 60℃ - 182℃ with an incredible difference of 122℃ as seen in figure 4.26(a). On the other hand, the circuit temperature difference is kept inside the 3℃ allowed (figure 4.26(b)) and the mold average temperature for most of the mold is kept under or around the 90℃ desired (figure 4.26(c)).

### 4.4.5 Cool FEM - Averaged within cycle with fixed time

Considering that this analysis is supposedly the one that describes more accurately what the company is obtaining with its experimental trials, all the results will be explained in depth. The same structure of chapter 3 is used.

#### 4.4.5.1 Circuit flow rate and Reynolds number

Important to notice is that the flow rate and Reynolds numbers used for this case are the same already seen in the previous case of FEM analysis. So it can also be said that the same observations listed in section 4.4.4 are applicable here. It is just from the separation line in figure 4.27 that the data are different from the previous analysis.

| Channel number | Inlet node | Flowrate in/out (lit/min) | Reynolds No. range | Press. drop over circuit (MPa) | Pumping power over circuit (kW) | Coolant temp. range | Coolant temp. rise. over circuit (C) | Heat removal over circuit (kW) |
|---|---|---|---|---|---|---|---|---|
| 1 | 539611 | 2.52 | 10000.0 - 14310.8 | 0.0051 | 2.132e-04 | 60.0 - 61.7 | 1.6 | 0.283 |
| 2 | 539558 | 3.60 | 10000.0 - 16355.2 | 0.0045 | 2.687e-04 | 60.0 - 62.0 | 2.0 | 0.495 |
| 3 | 539601 | 3.60 | 10000.0 - 16355.2 | 0.0045 | 2.687e-04 | 60.0 - 62.1 | 2.1 | 0.527 |
| 4 | 539690 | 2.20 | 5000.0 - 10000.0 | 0.0014 | 5.067e-05 | 60.0 - 61.9 | 1.9 | 0.285 |
| 5 | 539612 | 1.91 | 10000.0 - 10000.0 | 0.0011 | 3.594e-05 | 67.9 - 70.0 | -2.1 | -0.273 |
| 6 | 539550 | 1.91 | 10000.0 - 10000.0 | 0.0010 | 3.106e-05 | 69.9 - 70.1 | 0.0 | 0.002 |
| 7 | 539635 | 2.49 | 10000.0 - 20000.0 | 0.0133 | 5.518e-04 | 70.0 - 72.2 | 2.1 | 0.359 |
| 8 | 539691 | 1.91 | 10000.0 - 10000.0 | 0.0010 | 3.179e-05 | 69.7 - 70.0 | -0.3 | -0.045 |
| 9 | 2698231 | 1.14 | 10000.0 - 15000.0 | 0.0352 | 6.718e-04 | 70.0 - 73.1 | 2.9 | 0.232 |
| 10 | 2698194 | 1.14 | 10000.0 - 10000.0 | 0.0080 | 1.524e-04 | 70.0 - 71.6 | 1.6 | 0.123 |
| 11 | 1618904 | 1.25 | 10000.0 - 13333.3 | 0.0309 | 6.429e-04 | 70.0 - 75.0 | 4.8 | 0.415 |
| 12 | 2158512 | 1.52 | 10000.0 - 10000.0 | 0.0053 | 1.346e-04 | 70.0 - 71.5 | 1.5 | 0.154 |
| 13 | 2698171 | 1.25 | 10000.0 - 13333.3 | 0.0374 | 7.770e-04 | 70.0 - 74.1 | 4.0 | 0.343 |
| 14 | 2698143 | 1.14 | 10000.0 - 12228.5 | 0.0233 | 4.442e-04 | 70.0 - 72.3 | 2.2 | 0.176 |
| 15 | 1079267 | 1.52 | 10000.0 - 12228.5 | 0.0073 | 1.860e-04 | 70.0 - 71.6 | 1.5 | 0.161 |
| 16 | 2158517 | 1.14 | 10000.0 - 12228.5 | 0.0304 | 5.799e-04 | 70.0 - 73.9 | 3.8 | 0.298 |
| 17 | 539644 | 1.91 | 10000.0 - 10000.0 | 0.0008 | 2.697e-05 | 70.0 - 70.7 | 0.7 | 0.085 |
| 18 | 539661 | 1.91 | 10000.0 - 10190.4 | 0.0019 | 6.037e-05 | 70.0 - 72.2 | 2.1 | 0.275 |
| 19 | 539636 | 1.91 | 10000.0 - 10000.0 | 0.0008 | 2.415e-05 | 70.0 - 70.3 | 0.3 | 0.040 |

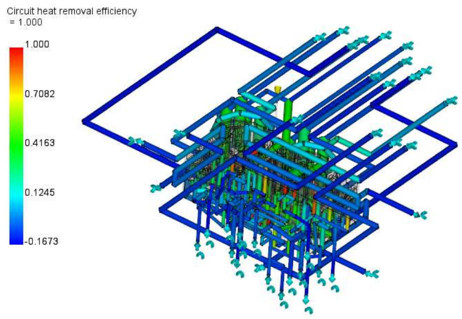
Figure 4.27: Summary table of the cool FEM analysis with averaged temperatures and fixed time

To better understand the references of the channels, it has to be considered the following:

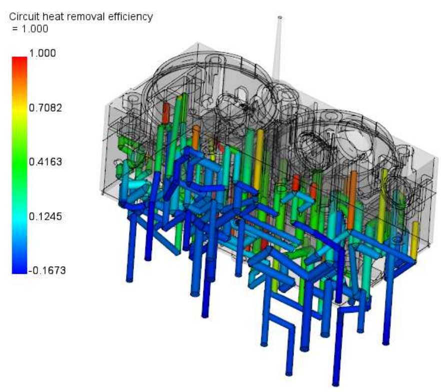
- Channels from 1 to 6 are the ones on the top side of the piece
- Channels from 7,8,9,10 are the ones on the lateral sides
- Channels from 11 to 19 are the conformal cooling side

#### 4.4.5.2 Circuit heat removal efficiency

One of the main characteristics of CC channels is the ability to remove a lot of heat from the system even with low usage of coolant due to their efficiency. This main feature is visible in these results: here the CC channels are the ones that have the lowest flows in terms of coolant as described in the previous section and showed in figure 4.27, but still, they have the highest heat removal efficiency as seen in figure 4.28.




(a) Circuit heat removal efficiency

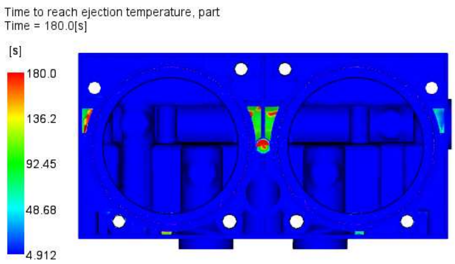



(b) Circuit heat removal efficiency, detail of the conformal cooling channel

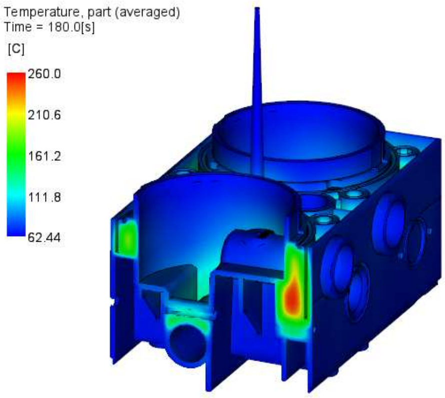
Figure 4.28: Circuit heat removal efficiency results for the FEM analysis with fixed time assigned

#### 4.4.5.3 Time to reach ejection temperature

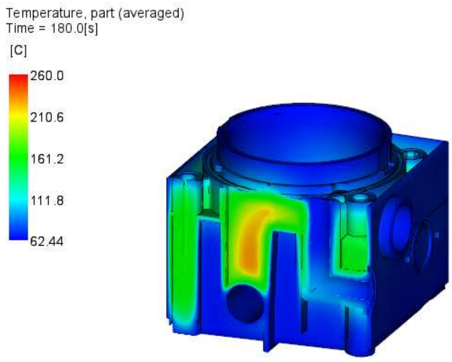
This result is extremely important because here it is possible to see which ones are areas that will freeze last in the 180 seconds given to the software to complete the analysis. This result, shown in figure 4.29(a), when compared with the generic temperature result for the part obtained in the cool BEM analysis (described in figure 4.23), clearly shows that there is a strong connection between the BEM and FEM analysis and that the results obtained in the first mentioned can be used to predict problems that the second will point out at the end. One careful observation of the first type of analysis, even when the times will not agree with the ones wanted by the end of the study, can indicate where to act to optimize the system from the very beginning of the development.




(a) Time to reach ejection temperature




(b) Temperature, part (averaged): section 1, highest averaged temperature area




(c) Temperature, part (averaged): section 2, gate rib location

Figure 4.29: Results from the cool FEM analysis with fixed time

#### 4.4.5.4 Temperature, part (averaged) result

Once more the results about the temperatures are the ones that will give the major indications on how to proceed with the development and optimization of the piece and mold structure. The average temperature should be about halfway between the target mold temperature (90℃) and the ejection temperature (179℃), for an optimized mold. So here we can immediately say that the developed system up to now is still very far from the optimal condition. Furthermore, there should be only a small variation in average temperature in the part. Areas of high average temperature are usually thick regions of the part or areas that are poorly cooled, and this is exactly what is happening in this case. In figure 4.29(b) a thick region with the consequent increase in average temperature is shown, while in figure 4.29(c) the area near the gate is shown. As already pointed out, this area is poorly cooled due to difficulties in reaching it with a cooling channel.

#### 4.4.5.5 Temperature, mold (averaged) result

At last, one more representation of the problems that persist in the system. The narrower the temperature variation over the mold face, the less likely the mold temperature variation will contribute to warpage and an extended cycle time. But in the studied case the variation has a range of 142.6℃, from 55.6℃ to 198.2℃. For some points in the mold, the average temperature is above the transition temperature of the polymer used; this is a very serious problem in terms of cooling since in these areas the polymer will not reach proper freezing before ejection.

### 4.4.6 Comparison among all the analyses previously described

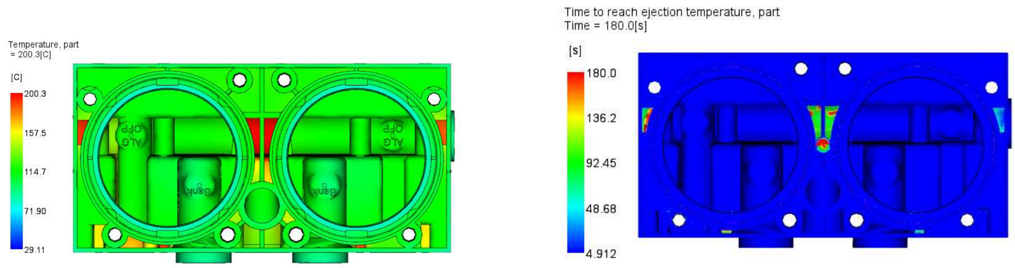
Table 4.4: Summary table for the comparison of some BEM and FEM results.

| Results | BEM automatic time | BEM fixed time | FEM automatic time | FEM fixed time |
|---|---|---|---|---|
| Mesh for the piece | (3D failed) DD | DD | 3D | 3D |
| Mold mesh | without | without | with | with |
| Complete freezing in 180s | Ejection time 734.3 s | Ejection time 974.3 s | Ejection time 250 s | Ejection time 180 s |
| Maximum coolant temperature reached | 70.66 C | 72.63 C - higher heat exchange attempted from prev. | 73.83 C | |
| Maximum temperature on the part at the ej. time | 192.5 C | 254.6 C | | 260 C |
| Maximum T mold-cavity interface | | | 182.4 C | |
| Maximum mold T | 140.6 C | 198.7 C | 182.4 | 198.2 C |
| Sprue tip frozen | Much earlier than 30 s | Much earlier than 30 s | Much earlier than 30 s | Much earlier than 30 s |
| Renymolds number (turbulent flow) | | | One channel only 5000 Re | One channel only 5000 Re |

First to be remembered is that the BEM analyses are much less precise with their results than the FEM analyses, but they are still comparable since they can be considered as two consecutive steps in the study of a piece. The BEM has to always be considered and run in the first steps of the project development, and then FEM has to be run to effectively check if all the problems supposed while developing have been solved. FEM analysis results are the ones that describe the reality of the production process in detail and so these are the ones to be considered as the description of what will be observed in real life.

The first important thing to compare is the time to reach ejection. The low precision of the BEM gives respectively 734 s and 974 s for the automatic and fixed time analyses. The FEM gives 250 s and 180 s. The decrease in time evaluated is massive, but the reason might be due to the precision of the analysis. In literature, numerous articles present projects for which the BEM analysis has much higher ejection times than the FEM. The real case scenario has to be somewhat a little higher than the FEM due to simplifications that are necessary for the software evaluations but not as high as the BEM.

The ejection time of the FEM can also be compared with the temperature part of the BEM. In this case




(a) Temperature, part form the BEM cool analysis. The picture is orientated to show the areas at the highest temperatures in the part.

(b) Time to reach ejection temperature from the FEM analysis. The same orientation of the previous is used.

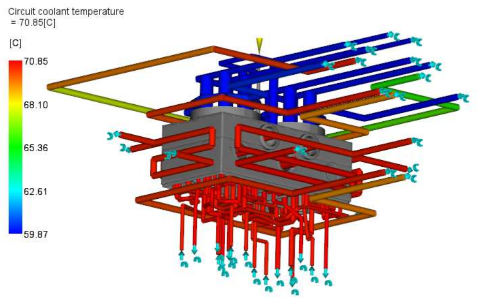
Figure 4.30: Comparison of results from BEM and FEM analysis, both of them with time fixed. It can be seen that the BEM prevision of the highest temperatures areas then becomes a problematic area to reach ejection temperature in the FEM. This result can seem obvious, but this is proof that the two analyses can be used in sequence to point out and solve problems during the development of the project.

The time to reach ejection temperature, shown in figure 4.30(b), when compared with the generic temperature result for the part obtained in the cool BEM analysis (described in figure 4.30(a)), clearly shows that there is a strong connection between the BEM and FEM analysis and that the results obtained in the first mentioned can be used to predict problems that the second will point out at the end. Careful observation of the first type of analysis, even when the times will not agree with the ones wanted by the end of the study, can indicate where to act to optimize the system from the very beginning of the development.

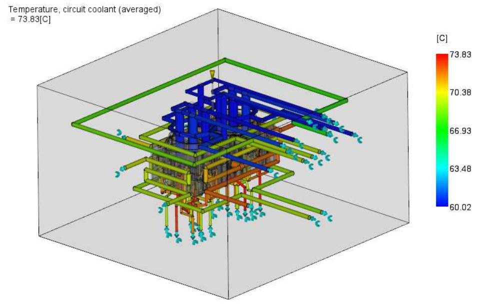
One thing that is kept particularly similar between the two types of analysis is the temperature variation of the coolant between the entrance and the exit of the channels. The system has almost the same temperature variation for each channel and this means that the heat that each channel has to absorb from the system in every run analysis is considered to be the same. Also, the channels that had problems with the decrease of temperature along their length are the same among the analyses.

It was observed that besides the FEM and BEM being different there are some results that are similar. The BEM has lower precision results than the FEM but it can still be considered a perfectly valid analysis to start a new injection molding project even for very complex parts. The higher the complexity the lower the precision in the BEM results, but still the defects that the BEM can point out are valid critical points for the system and have to be addressed.

As a final comment for this paragraph, while describing all the results obtained, numerous problems have been pointed out. All these problems need to be addressed in further optimization studies of this




(a) Circuit coolant temperature for the BEM with automatic time.




(b) Temperature of the coolant, averaged along the cooling channel path for the FEM analysis with automatic time

Figure 4.31: Comparison of results from BEM and FEM analysis for the circuit coolant temperature. Both results refer to automatic time but the same can be said for the fixed time. The FEM temperature results tend to be slightly higher than the BEM due to the higher precision in the heat exchange evaluation but each channel is treated in the same way in terms of heat exchange efficiency.

system. For sure it can be said that the software, with the parameters given, is not able to simulate the correct production of the piece. Not only the software simulates a piece with incorrect tolerances and mechanical properties, but the piece is still not able to be ejected correctly with the set of parameters currently considered. Some areas are for sure not frozen by the end of the cycle time wanted. It has in fact to be considered that a production time of around 10 minutes or above may be not competitive in terms of the final cost of the product for the company.

Much more can be said about the results of these analyses, many more analyses can be run, and proper parameter optimization seems necessary for the study. Of course, the completion of all these developments necessitates its own time and work and can be considered a good branch for the further development of this study.

# Chapter 5

# Conclusions and Future developments

After the long development of this study, it is necessary to resume the work done and comment on the conclusions that have resulted from it. The main goal for the project, in the beginning, was set to run the analysis in Moldflow to obtain results that would then be compared with the results obtained by the company while this project was carried out. The project deviated from this main branch due to the complexity in setting analyses of such complexity in Moldflow software that is still under development for this new type of cooling system. The procedure to correctly set this kind of analysis has taken much more time, and much more research than expected and so this project may be considered the initial step of a longer study.

A general conclusion is that it is indeed possible to simulate the injection molding production process for complex pieces that require conformal cooling circuits in Moldflow. However, with the geometries and set of parameters given at the company at the beginning of the project, Moldflow analysis results suggest that it is not possible to produce the piece in these conditions.

## 5.1 Conclusions on the Moldflow procedure

To begin any Modlflow analysis, a base file should be created containing information regarding the piece, the material for the piece, the cooling system, the mold, the mold material, and the process parameters of the study. To help the creation of this file, preliminary analyses have to be run and their output should be manually verified since Moldflow can misinterpret the base file without throwing any error messages or warnings. If inconsistencies are found, the base file should be reviewed.

The Autodesk community already makes available some guidelines for the general procedure for the creation of this file, even when this comprehends CC systems, but the information available is not detailed enough to provide a systematic description that can be valid also for very complex cases.

This study went into much more detail on this procedure. The majority of the available proceedings have been attempted, and a final functioning file has been obtained.

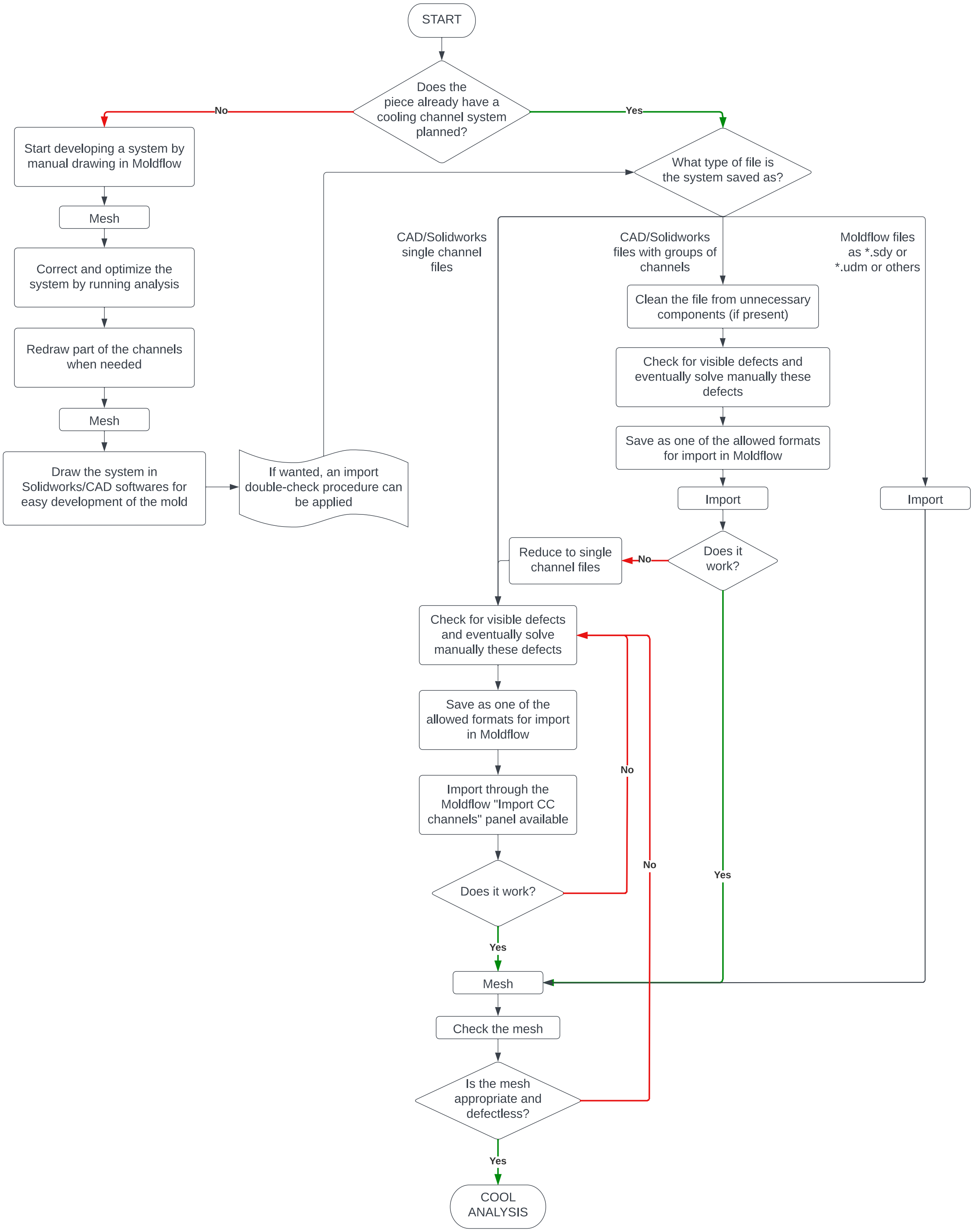



Figure 5.1: Flowchart scheme for the available import procedures for the cooling system.

While the mesh of the piece has followed the general guidelines, it is the import and mesh procedure of the cooling system that has taken the longest time to be achieved. The import of the CC systems is recommended by the Autodesk guide, but the difficulties found while obtaining the correct import show that the software is still under development. The procedure that can be followed, with the majority of the available options in case of problems, is represented in a flowchart that can also be used for future implementations (figure 5.1). This flowchart has to be considered one of the most important results of this thesis.

Another problem that might be related to the software is the limit that has been found in the quantity of data that Moldflow can organize and analyze. While importing the few channels that didn't present problems, it was noticed that up to a number of 8 the analysis was still able to run, but more than this number the analysis was impossible to run. This is not assured to be a software problem, but it might be, and only further research with better-performing computers can be proven or not.

It has been important to not only import and obtain the mesh but also to run partial analysis on the channels because the import and mesh can work properly, but then the perceived geometry is not the correct one. This happened with the baffles of the traditional cooling channels that were perceived by the system only as simple blind tubes without the middle partition that characterizes the baffle geometry.

The next step that has been treated in the development of this thesis is the mold block. The importance of the creation of the correct mold representation comes from the heat exchange evaluations that Moldflow will perform while running the analysis. If the correct mold is represented, then the right heat exchange will be evaluated. If not, the results will not be correct. The mold has been found to be mandatory only for the Finite Element Method (FEM) cool analysis and the complete analysis. For the Boundary Element Method (BEM) analysis the mold is not considered necessary to be modeled, but a boundary limit of the mold block is set automatically still. So in both cases, more or less precisely, the mold presence is considered.

Both FEM and BEM cool analyses have been run. FEM is for detailed/high-resolution results, and BEM is for initial steps in the project and cooling position optimization. They are both valid, and they both point out problems in the system. Also, they can be quite similar in the results over certain aspects. But if the need is data comparison with the real case scenario, then the FEM has to be considered only. The higher precision in the result evaluation makes it more appropriate for this. The errors made in BEM are directly proportional to the increase of the difficulty of the system under study, and so in particular for this case.

## 5.2 Conclusions for the assigned system

The whole process has not only been developed with a focus on the Moldflow base analysis file to be obtained but each and every step has been analyzed to point out, at the same time, defects in the studied system.

To obtain the correct mesh of the piece the file has not only been visually inspected but also iteratively imported and meshed. By the simple visual inspection, no major problems were visible, but from the first piece mesh the aspect ratio analysis pointed out little geometrical defects. One confirmation of the importance of this process was that the same defects were observed by the company and geometrical alteration of the piece was necessary.

The following gate location analysis detected a major filling problem due to the positioning of the gate. The company effectively defined the gate location in concordance with the gate locator analysis of Moldflow, and this is a second confirmation of the utility of these analyses, but the position was not optimal. Another geometrical variation that has been applied unknowingly in parallel has been to enlarge the gate area for the piece in order to permit good polymer flow to the piece.

The variation of the gate location solved the problems identified in the fill analysis for the piece. But problems were then identified in the subsequent packing phase too. The company suggested packing phase parameters that are not possible to be reached in the studied geometry. The sprue that has been considered for this thesis has dimensions that are very far from the traditional recommendation for the dimensioning of the runner system. Common knowledge usually recommends having a sprue that has more or the same dimensions of the highest thickness in the piece. This is not applied to this case, so problems with the packing phase were expected and the results were confirmed.

The representation of the cooling system has been the most complex part of the study, but once a functioning file has been obtained the results of it have been carefully analyzed for two main reasons: to find eventual geometrical defects in the Moldflow representation of the system and to spot problems that are related to the production of the piece itself and that can be useful suggestions for the company.

The cooling system, even if probably not optimal, is considered sufficient by the software for the homogeneous cooling of the system. Once the way to represent it in Moldflow has been found, the results from the cool analysis showed a cooling that, as far as possible for this system, was fairly homogeneous. Still some hot spots persist in the piece, and their solution is not as easy to find as for other areas.

Some hot spots, especially the one created by the geometrical variation of the piece to permit correct filling, are found to be in areas where reach is not possible, even with conformal cooling. Also, it can be observed that the premature solidification of the sprue, which leads to packing problems, is confirmed during the cooling analysis.

The mold block for this case has suffered a drastic simplification from the real case scenario. This introduces errors in the representation of what it is the real situation that the company may have faced in the meantime. Still, from the way Moldflow is built, simplification has been necessary. Also to reduce the computational time, not many details have been possible to be inserted. The decision to simplify the mold to a single material block with the properties of the conformal cooling insert was thought for future data comparison with the company. If this simplification is valid or not has to be proven by data analysis with experimental results from the company.

## 5.3 Future Developments

Numerous future developments are possible and in some cases necessary for this study. A resume of them in schematic form can be found in appendix B.

Most of the study has been organized over a fixed geometry for the piece. Since it is supposed that the structure of the piece is non-modifiable the only way to improve the study further is to optimize the mesh representation of the piece. A good mesh has already been obtained and can be used for future analysis, but optimization is always possible. If, on the other hand, the company is open to the possibility of changing the geometry of the piece (always taking into consideration the compatibility with the filter machine it will be inserted into) then there is the possibility of studying a better gate location that will not give hot spot problems during the production process, and also a general simplification of the piece structure is always a development that can be applied.

It has been previously mentioned the problem related to the feeding system of the piece. The sprue has been found to be too small for the system causing premature freezing and incomplete packing while the enlargement of the gate location to permit better flow then resulted in a hot area that was not easy to cool down. Both problems need solutions, and the solutions have to work in parallel since they refer to two opposite types of problems. For premature freezing, an enlargement of the sprue may be suggested as a first-step solution for the problem. A hot runner system can then be considered as a second solution in case the first is not effective. In case the geometry has to be maintained fixed as defined in this project, then an increase in packing pressure, with the decrease in the packing time, may be considered as a last resource to try to solve the problem. Particular care needs to be taken in the last method since the increase in pressure may not be sufficient to obtain correct packing due to the intricate geometry of the piece and the little time given before the freezing of the sprue.

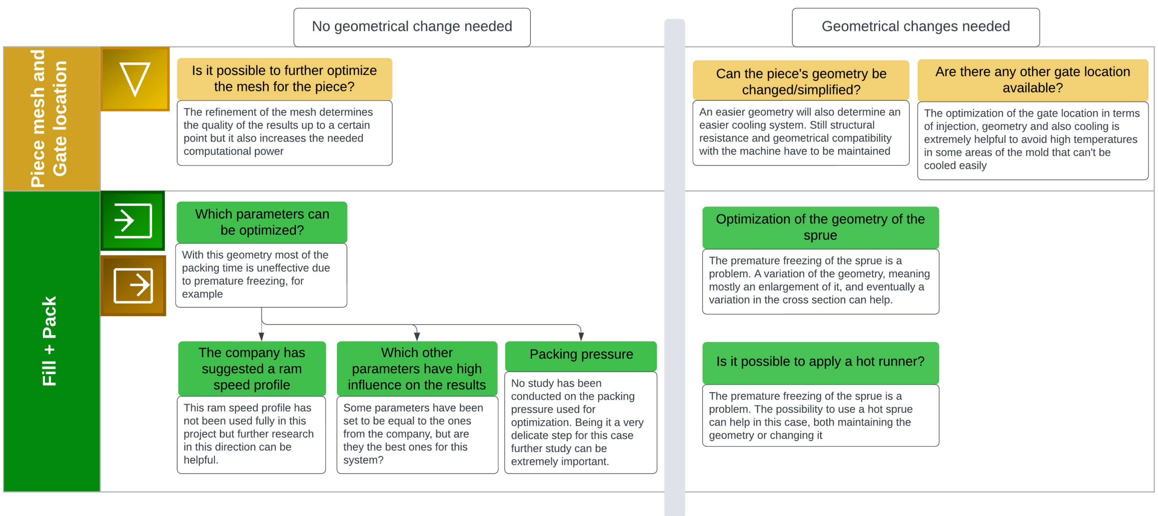



Figure 5.2: Possible future developments for the piece: piece mesh, gate location, runner system, fill, and pack.

Also, the mold block representation is subjected to some problems still. The simplifications applied have not been tested for this specific application, so further study is considered necessary. Moreover, the representation of the mold in the analyses described in this thesis has always been obtained through the wizard, while there are other possibilities in Modlflow. The possibilities to represent the mold more in detail are listed here followingly:

- Computer-Aided Design (CAD) IMPORT: A simplification of the mold file made available from the company is necessary here, and then it is possible to import directly the mold geometry from CAD/Solidworks. After this, the mesh has to be obtained and corrected.

- MODEL MULTIPLE BLOCKS: The mold block wizard in Moldflow also permits to model molds divided into different blocks. Each one of them can have different properties, and multiple materials can be simulated. This tool is probably the easiest to use to try to model the mold correctly, and it can also be applied in the attempt to prove that the initial material simplification is good to be applied without sensible change in the results.

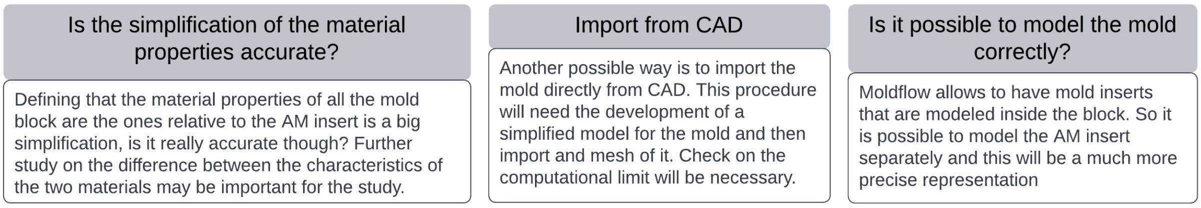



Figure 5.3: Possible future developments for the mold representation.

Furthermore, even for the cooling analysis, there are numerous further developments. The attempted ways to import the cooling cover almost the totality of the available ways but not exactly all of them. Mixed analysis in which part of the cooling channels are imported and part of them are manually drawn, the use of other drawing software for the external files, other combinations of file types for the import, and better beam representation are just a few possible future scenarios. It is probably the part of this project that has the widest development horizon and by causality also the part for which the lowest amount of literature has been found available.

The final characteristics that the piece should have due to its use have never been shared by the company. Some final properties have been deduced from what is known of the use of the piece, but no real data has been made available. In case this information is known, also a complete structural analysis of the final piece can be done to understand if the characteristics wanted are achieved.

Up until now, no mention has been made of the comparison with the results of the company. While this project was being developed, the company continued its efforts to obtain experimentally a set of parameters that would be good for the production of the piece. No comparison of these results was possible for time limits, but it will be necessary, The main suggestion for future development is presented here at the very end of the work: before starting any other development branch mentioned, the comparison of the results might be considered the first and most important future development of this project. Now that the files are set and correctly working, and after an update on the used parameters from the company, the comparison of results can start. This will permit the assessment of the quality of the representation that Moldflow can give and can also decide the implementation of this software in the company if the results are considered useful in terms of project development.

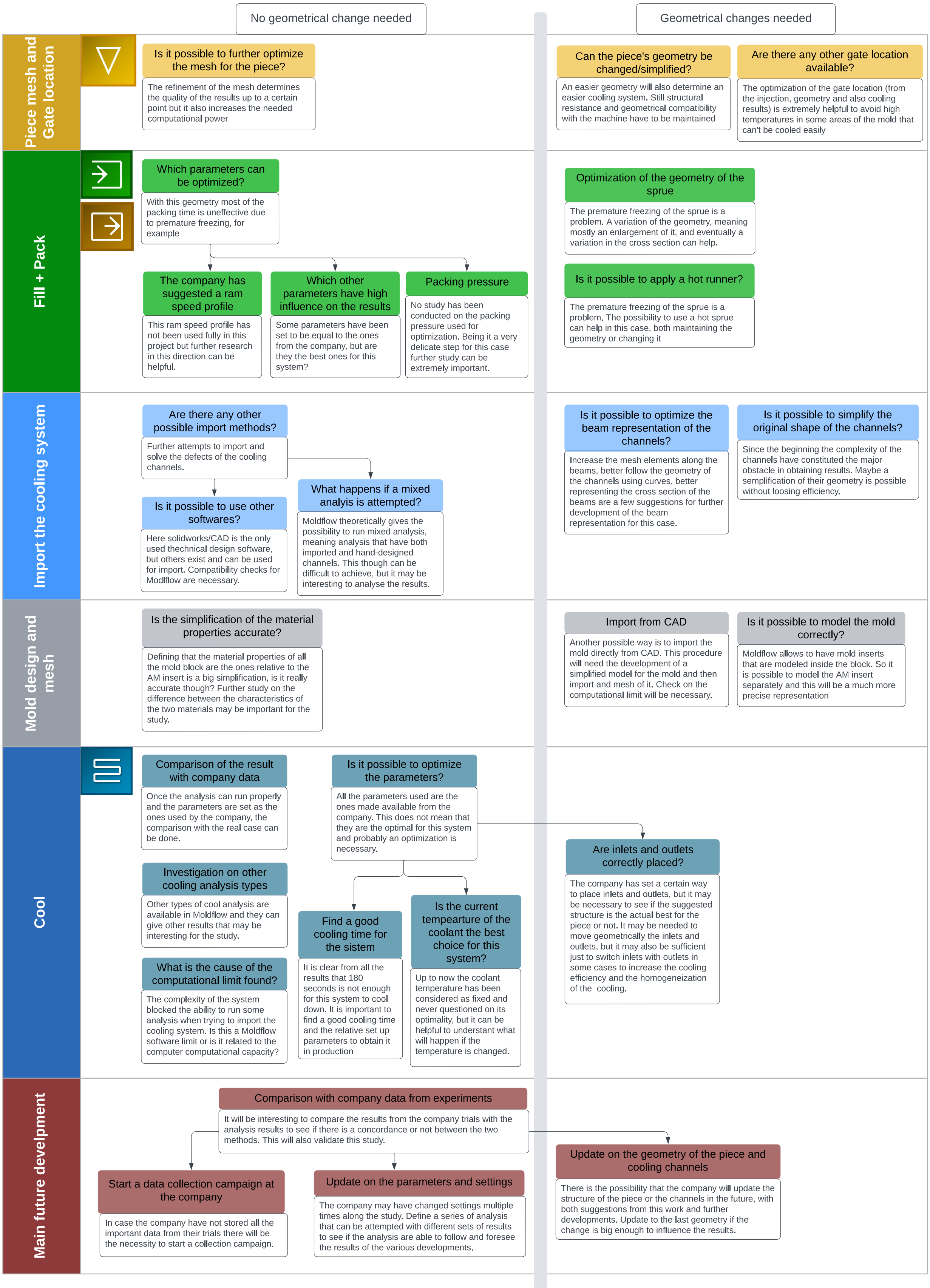



Figure 5.4: Schematic resume of the possible future developments for this project.

To conclude this project, not much information are available in the literature. The research in this field is still open and running fast due to the high interest in the development of this technology. The assigned piece has been a challenge in many aspects, and it will still be a challenge for whoever will continue it.

The hope is that the project can be a guide through the whole analysis process in a comprehensive and understandable way. It is well known that this is just the tip of a much bigger iceberg, but it is a starting point that can help future researchers that want to enter this field to quickly set the characteristics of the base files for the studies and then proceed with data analysis and comparison.

# Bibliography


[1] Keyence Corporation. What is Injection Molding?, 2022. URL https://www.keyence.com/ss/products/measure-sys/machining/injection-molding/about.jsp.

[2] Yangzhou DingYue Plastic Electronics Co. What is a plastic injection mold?, July 2019. URL http://ko.dy-plastics-sp.com/info/what-is-plastic-injection-mold-37602767.html.

[3] Topworks Plastic Mold. Injection Molding Machine Components And Its Function, September 2012. URL https://www.myplasticmold.com/injection-machine.html.

[4] Autodesk. Product design & Manufacturing, Plastic Injection Molding, July 2017. URL https://www.autodesk.com/solutions/plastic-injection-molding.

[5] Redshift - Autodesk by Shveta Berry. How the Injection-Molding Process Helps Create Pretty Much Everything, May 2019. URL https://redshift.autodesk.com/articles/injection-molding-process.

[6] S. Feng, A. M. Kamat, and Y. Pei. Design and fabrication of conformal cooling channels in molds: Review and progress updates. *International Journal of Heat and Mass Transfer*, February 2021.

[7] Star Rapid by Chris Williams. Conformal Cooling for Plastic Injection Molding, 2020. URL https://www.starrapid.com/blog/conformal-cooling-for-plastic-injection-molding/.

[8] W. Guilong, Z. Guoqun, L. Huiping, and G. Yanjin. Analysis of thermal cycling efficiency and optimal design of heating/cooling systems for rapid heat cycle injection molding process. *Materials and Design - Elsevier*, January 2010.

[9] Hsu, Wang, Huang, and Chang. Investigation on conformal cooling system design in injection molding. *Advances in Production Engineering& Management vol.8*, June 2013.

[10] M. Hall and M. Krystofikk. Conformal cooling. *RIT Rochester Institute of Technology - Centre of excellence in sustainable manufacturing*, November 2015.

[11] Pat Zaffino and Conformal Cooling Solutions. What is conformal cooling?, 2022. URL https://www.conformalsolutions.com/test.

[12] K. M. Au and K. M. Yu. A scaffolding architecture for conformal cooling design in rapid plastic injection moulding. *International Journal of Advanced Manufacturing Technologies*, June 2006.

[13] Y. Wang, K.-M. Yu, C. C. Wang, and Y. Zhang. Automatic design of conformal cooling circuits for rapid tooling. *Computer-Aided Design*, April 2011.

[14] O. A. Mohamed, S. Masood, and A. Saifullah. A simulation study of conformal cooling channels in plastic injection molding. *International Journal of Engineering Research, VOLUME 2*, September 2017.

[15] S. Marques, A. Souza, J. Miranda, and R. Santos. Evaluating the conformal cooling system in moulds for plastic injection by cae simulation. *ICIT and MPT 2014*, May 2014.

[16] S. A. Jahan, T. Wu, Y. Zhang, H. El-Mounayri, A. Tovar, J. Zhang, D. Acheson, R. Nalim, X. Guo, and W. H. Lee. Implementation of conformal cooling and topology optimization in 3d printed stainless steel porous structure injection molds. *Procedia Manufacturing ,VOLUME 5*, January 2016.

[17] L. Shu, Z. Zhang, Z. Ren, and T. Zhang. Design and simulation of conformal cooling for a die-casting mold insert. *Journal of Physics, MEMAT 2021*, 2021.

[18] I. Yadroitsev, I. Yadroitsava, A. D. Plessis, and E. MacDonald. *Fundamentals of Laser Powder Bed Fusion of Metals*. Additive Manufacturing Materials and Technologies - Elsevier, Copyright ©2022 Elsevier B.V., 2021. URL https://www.sciencedirect.com/book/9780128240908/fundamentals-of-laser-powder-bed-fusion-of-metals#book-info.

[19] S. Mayer. Optimized mould temperature control procedure using dmls. *EOS GmbH*, 2005.

[20] Protolabs Inc. Direct Metal Laser Sintering Capabilities, 2022. URL https://www.meddeviceonline.com/doc/direct-metal-laser-sintering-capabilities-0001.

[21] Siegfried Mayer and Augustin Niavas. Conformal cooling: Why use it now?, 08 December 2009. URL https://www.plasticstoday.com/injection-molding/conformal-cooling-why-use-it-now.

[22] Krauss Maffei GmbH. *Technical Data: Injection Moulding Machines Series CX*. Krauss Maffei GmbH, Krauss-Maffei-Strasse 2, D-80997 Munich, Germany, September 2007. URL www.kraussmaffei.com.

[23] Autodesk Knowledge Network. Performing a Gate Location analysis, March 2017. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/MoldflowInsight/files/GUID-E0C02AE2-0491-434A-862C-9BF2AC2E63C5-htm.html.

[24] Autodesk Help. Part thickness (Concept), February 2014. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2014/ENU/MoldflowInsight/files/GUID-06D98333-2213-44BA-8478-0DA71DD9533E-htm.html.

[25] Autodesk Knowledge Network. Fill analysis: Concept, November 2018. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2019/

ENU/MoldflowInsight-Analyses/files/GUID-50917B39-2B67-4145-880C-BD2A28DD6EC9-htm.html.

[26] Autodesk Inventor. Fill analysis, October 2021. URL https://knowledge.autodesk.com/support/inventor/learn-explore/caas/CloudHelp/cloudhelp/2020/ENU/Inventor-Help/files/GUID-91A41E88-A83A-4631-A08F-FF2863E698D4-htm.html#:~:text=Part%20fill%20analysis%20prerequisites%3A%201%20Select%20a%20plastic,least%20one%20gate%20location.%204%20Define%20process%20settings.

[27] Autodesk. Warnings 302113, 304920 and 304930 for insufficient mesh refinement shown in Moldflow log file, May 2021. URL https://knowledge.autodesk.com/support/moldflow-insight/troubleshooting/caas/sfdcarticles/sfdcarticles/Receiving-warnings-302113-302114-304920-and-304930-in-Simulation-Moldflow.html.

[28] Autodesk Moldflow Insight. Conformal cooling analysis, 2018. URL https://help.autodesk.com/view/MFIA/2018/ENU/?guid=GUID-09B6241A-63B4-4B64-8755-10DE44FD1CB8.

[29] Autodesk Moldflow Insight. Cool analysis results, 2019. URL https://help.autodesk.com/view/MFIA/2019/ENU/?guid=GUID-077521D7-6F22-4445-8EA7-E010A182E094.

[30] Plastic Technology - Injection Molding - John Bozzelli. Graphing Injection Pressure: What Should Pack & Hold Curves Show?, January 2019. URL https://www.ptonline.com/articles/graphing-injection-pressure-what-should-pack-hold-curves-show.

[31] Autodesk support. Modeling a Cooling circuit in Synergy, October 2015. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/sfdcarticles/sfdcarticles/Modelling-a-Cooling-circuit-in-Synergy.html?us_oa=akn-us&us_si=be48cf1e-028d-4a35-a377-af6bde61de48&us_st=conformal%20cooling%20analysis.

[32] Autodesk Guide. Supported model import formats, June 2022. URL https://knowledge.autodesk.com/support/moldflow-adviser/learn-explore/caas/CloudHelp/cloudhelp/2021/ENU/MoldflowAdviser-CLC-NewUser/files/Import-and-Export/GUID-D63BA077-3570-42B4-8464-A8C1E91D66FE-html.html.

[33] A. simulation. Transient cool: conformal cooling. *Autodesk site*, 2014.

[34] Autodesk help. Create 3D channel mesh, March 2017. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/MoldflowInsight/files/GUID-F38F7EBB-D7D5-4323-9C3F-567C9FE93910-htm.html.

[35] Autodesk Knowledge Network. Can't create 3D Channel mesh, 2017. URL https://forums.autodesk.com/t5/moldflow-insight-forum/can-t-create-3d-channel-mesh/td-p/7083860.

[36] CAE SERVICES — Moldflow Analysis Consulting, Software& Learning. Consulting levels, 2022. URL https://caeservices.com/moldflow-analysis-consulting/consulting-levels/.

[37] WorldIron & Steel. What's 18Ni Maraging steel?, 2018. URL https://wldstainless.com/whats-18ni-maraging-steel/.

[38] HLPowder. What exactly does 18NI300 die steel mean? What is the main purpose? What about the composition and performance?, October 2021. URL https://www.hlpowder.com/news/what-exactly-does-18ni300-die-steel-mean-what-50798913.html.

[39] Sandvik. *Datasheet: OSPREY 18NI300-AM Maraging steel for additive manufacturing*. Sandvik, Box 510, SE-101 30 Stockholm, Sweden, November 2019. URL https://www.metalpowder.sandvik/siteassets/metal-powder/datasheets/osprey-18ni300-am-maraging-steel.pdf.

[40] F. Fiorentinia, P. Curcio, E. Armentani, C. Rosso, and P. Baldissera. Study of two alternative cooling systems of a mold insert used in die casting process of light alloy components. *AIAS 2019 International Conference on Stress Analysis - ScienceDirect - Elsevier*, 2019.

[41] J. Piekło and A. Garbacz-Klempka. Use of maraging steel 1.2709 for implementing parts of pressure mold devices with conformal cooling system. *Materials 2020*, December 2020.

[42] SteelExpress. German DIN/Werkstoff Steel Standards, 2022. URL https://www.steelexpress.co.uk/werkstoff-DIN.html.

[43] Matweb. AISI Grade 18Ni (300) Maraging Steel, Aged, 2022. URL https://www.matweb.com/search/datasheetText.aspx?bassnum=M1820A.

[44] Autodesk Help. Preparing the mold mesh (Concept), January 2017. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2017/ENU/MoldflowInsight/files/GUID-569013B6-9383-41B1-B2F0-BBE708058BA6-htm.html.

[45] K. C. Parmar and D. H. Kaiser. Comparison of simulation results when using two different methods for mold creation in moldflow simulation. *International journal of scientific& technology research, VOLUME 6*, April 2017.

[46] Shoudong Xu from the Autodesk Moldflow Meshing. Mold meshing, November 2016. URL https://forums.autodesk.com/t5/moldflow-insight-forum/mold-meshing/td-p/6690780.

[47] Gavin Leo - Aria manufacturing. How to Make Injection Molds: The Complete Process from Start to Finish, February 2022. URL https://www.madearia.com/blog/how-to-make-injection-molds-the-complete-process-from-start-to-finish/#:~:text=Injection%20molding%20is%20a%20complex%20process%2C%20and%20the,design%20of%20the%20mold%20right%20the%20first%20time.

[48] Autodesk Help. 3D Cool analysis (Concept), May 2015. URL https://knowledge.autodesk.com/search-result/caas/CloudHelp/cloudhelp/2016/ENU/MoldflowInsight360/files/GUID-D4DFA0BA-889E-42D2-B81C-A4B6BBBFEE0E-htm.html.

[49] Autodesk Support. "Error 701010 - Cool analysis has not converged" in analysis log in Moldflow, April 2022. URL https://knowledge.autodesk.com/support/moldflow-insight/troubleshooting/caas/sfdcarticles/sfdcarticles/Moldflow-Error-70101-Cool-analysis-has-not-converged.html.

[50] Autodesk Help. Beam elements, deleting duplicates manually (Procedure), March 2017. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/MoldflowInsight/files/GUID-278AC2A1-7555-4DCA-9916-236D7324C85D-htm.html.

[51] Autodesk Help. Cool analysis for part optimization (Concept), January 2017. URL https://knowledge.autodesk.com/support/moldflow-insight/learn-explore/caas/CloudHelp/cloudhelp/2017/ENU/MoldflowInsight/files/GUID-52F639F0-2938-4723-AF2A-74C60BF9C0DE-htm.html.

[52] FileInfo.com - ICAM. .IGES File Extension, May 2022. URL https://fileinfo.com/extension/iges.

[53] Autodesk Knowledge Network. Guidelines for preparing IGES files for import(Procedure), November 2018. URL https://knowledge.autodesk.com/support/moldflow-adviser/getting-started/caas/CloudHelp/cloudhelp/2019/ENU/MoldflowAdviser-NewUser/files/GUID-7F2D55E0-457F-4775-B1B5-97830C8A20AC-htm.html.

# Appendix A

# Fill+Pack+Cool+Warp analysis

This chapter presents the description of the complete analysis for this piece. As previous chapters have been organized, also in this one there will be the set-up parameters paragraph, and a brief description of the preparation of the analysis to then continue with the in-depth description of the results obtained.

## A.1 Set-up parameters of the complete analysis

Moldflow allows for the complete analysis to be run starting already from the previously obtained cool analysis, and this will be done here. The files obtained during the cool FEM analysis described in section 4.4 will be the starting point for the following complete analysis.

For this reason, the set-up parameters related to the cool part of the analysis will be maintained, and also the same ones used for the fill and pack analysis will be added. All these parameters are reported in table A.1.

In the complete analysis, Moldflow will use the already evaluated cool results as boundary conditions for the evaluation of the fill and pack stages of the analysis. Only at this point, with both results from cool, fill, and pack analysis the warp analysis will be conducted.

Effectively, at this point, the only results that are left to be discussed are the warp results. But, being the results for the fill+pack analysis in this case much more precise than the ones obtained at the beginning, also a quick comparison among them will be mentioned for completeness of the research.

These final results, obtained from a complete analysis after a cool (FEM), are the most precise results that Moldflow can achieve. This is the best achievable representation of reality through this analysis software.

## A.2 Fill+Pack+Cool+Warp analysis with fixed time

In this instance, only one analysis will be run and discussed. Getting more into detail in the study of the complete analysis has not been possible both to the unavailability of time and lack of interest in

Table A.1: Set of parameters for the complete Fill+Pack+Cool+Warp analysis. * = the mesh aggregation and the cause of warpage have been switched on and off in different runs to understand which settings are the best for this piece and which combination gives the most complete set of results.

| SETTINGS | Value | Units |
|---|---|---|
| COOL (FEM) | | |
| Melt temperature | 260 | ℃ |
| Mold open time | 5 | s |
| Mold close time | 0 | s |
| Inj+pack+cool time | 180 | s |
| Mold temperture options | Averaged within cycle | |
| FILL+PACK | | |
| Injection time | 4.2 | s |
| Velocity/pressure switch-over | By injection time = 4.2 | s |
| Pack/holding control | Packing pressure vs time | |
| Packing time | 30 | s |
| Packing pressure | 50 | MPa |
| WARPAGE | | |
| Warpage analysis type | Small deflections | |
| Use mesh aggregation* | ON/OFF | |
| Isolate cause of warpage* | ON/OFF | |

terms of the project. For sure running more of these analyses will be an interesting prosecution of this work in the future.

All the results reported for the cool analysis are exactly the ones that have already been discussed. These results are the information that is used to run then the simulation of the other parts of the complete analysis properly.

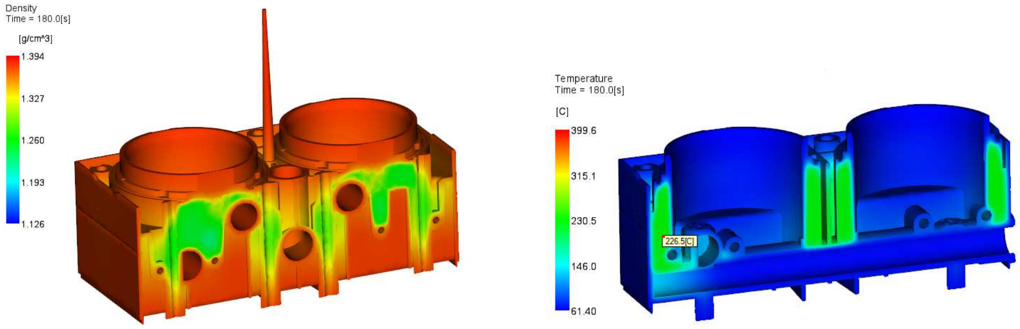
All these results have already been explained in section 4.4, which can be consulted for information needed. No more time than this will be spent on this subsection, to avoid useless repetitions.

### A.2.1 Important Fill+Pack analysis results that changed from the previous analyses

For this case, as seen in the previous section A.1, the fill time has been set at 3.2 seconds. Due to adjustments along the analysis, the fill time has been increased a little by the software, up to 3.268 seconds. This time is quite higher than the one indicated by the company, but considering all the problems discussed in chapter 3, it will be left as it is. The other results will be analyzed before discarding this analysis as not suitable to represent what the company is facing.

Also, the range of increase of the temperature at the flow front continues to be a problem for this piece. As already discussed the complex geometry creates high friction in the injection stage of the cycle with the consequent increase in temperature from 260 C to 283.2 C. With a 13.2 C increase, the possible polymer degradation and surface burn marks have to be kept under careful observation.

One important aspect to notice is the general decrease in the value of the density if compared with the previously obtained result (figure A.1(a)). While in the previous fill+pack analysis the cavity surface is considered to be at an average temperature of 90 C decided by the researcher, here the cavity temperatures and their variations are obtained from the cool (FEM) analysis run before. So here, the more complex and complete representation of the temperatures has some clearly visible effects on the other results.




(a) Density result from the complete analysis.

(b) Detail of the Temperature result of the complete analysis. The result is shown at 180 seconds of the cycle, in sectioned view, and one detailed point is chosen to be shown. For the point in the picture, the temperature is 226.5 C, clearly still above the transition temperature.

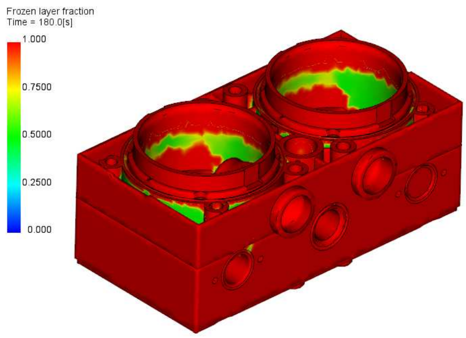
Figure A.1: Results of the first stages of the complete analysis that changed from the ones already described in the previous chapters. a) density result b) temperature result.

The better representation of the temperatures shows not only a prolonged time for the cool but also permits to evaluate correctly the packing phase that is the main responsible for the final density of the piece. In this complete analysis, the more detailed representation of the temperatures is able to spot the premature freezing of the sprue during packing, and consequently, the low amount of polymer inside the cavity results in a low-density polymer at the end of the complete process. This is a major problem for this piece, and it needs resolution since the structural mechanical properties of the piece, and its deformations depend strongly on the correct or not packing of the polymer that constitutes it.

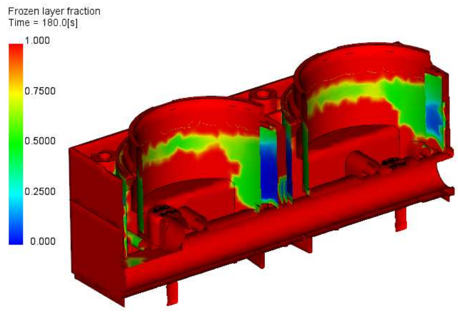
Another difference that seems quite concerning about the results of the final complete analysis is the temperature of the piece at the time of ejection. There are parts that still seem above the transition temperature, and in case this is true then the solidification is not complete, and at the ejection, the piece will collapse. In figure A.1(b) we can see that some points are clearly still above the 179 C that is indicated as transition temperature.

This is confirmed by the observation of the frozen layer fraction results. In this result, it is clearly shown that in this analysis the piece at ejection time is not properly frozen (figure A.2). This is a very important result to keep in the records to then discuss with the company if the same problem has been faced in production; if that is so then the representation of the situation through the computer analysis at Moldflow can be considered already quite good. In fact, this means that the company, having had Moldflow at their disposal by the beginning of this project would have been able to point out this important problem even before starting to produce the physical mold for this piece, with the relative procedure to solve this problem and consequent money and time-saving.

Another confirmation of this problem can be found in the logs where the following warning message appears: ** WARNING 98737 ** All temperature entries in the local mold temperature profile (controller




(a) Frozen layer fraction result. A complete view of the piece.




(b) Section view of the piece that shows how the injection area of the piece is still completely liquid by the end of the cycle time. This is the most critical point of the piece for this result.

Figure A.2: Analysis of the setup and results of the first attempted cooling analysis.

sequential ID = 4375) are greater than the transition temperature value in the rheological properties of the selected material. Please check the temperature entries and material data and, if necessary, re-run analysis.

To double-check the problem pointed out in this analysis, it is necessary to run a complete analysis with automatic total time of the cycle. In this case, it will be possible to see if the results are the same as obtained for this case or if the evaluated cycle time for this case will be higher. The results of this analysis will be reported in section A.3.

In the meantime, all the other results will still be described in detail. In fact, this analysis is what the company is trying to run on its production site. The results of this analysis will be directly comparable with what the company will be able to achieve as results of the real case scenario, so it is of great importance to report them in the project.

For example, the same premature freezing problem for the sprue that was already present in the initial fill+pack analysis is identified here. The company has confirmed that they are using a cold runner system for this piece and this can be considered with certainty one of their main problems. It can be seen in figure A.3 that the sprue is mainly frozen by the tenth second of the cycle, 20 seconds earlier than the established packing time applied by the company. This means once more that the company is losing energy and power trying to pack correctly the piece that will never reach the requirements because the entrance canal is already obstructed.

One last result that seems important to mention here is the average volumetric shrinkage which is found to be even higher than the one described in chapter 3 in figure 3.17. The difference is just slightly higher, one percentage point, but any increase in a piece that has to maintain extremely rigorous tolerances has to be considered with extreme care and analyzed in depth to see how that worsens the situation.

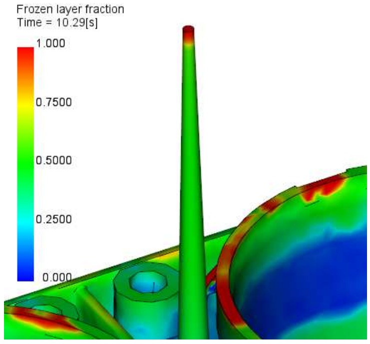



Figure A.3: Frozen layer fraction. Sprue detail at time 10.29 s of the cycle. The sprue is still only 50% frozen along its length, and the gate is still open for filling, but the injection nozzle at the machine-mold interface has already frozen.

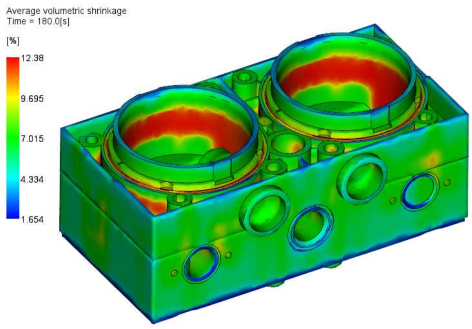



Figure A.4: Average volumetric shrinkage of the piece. Here the maximum shrinkage found is 12.38% while in the prior analysis it was 11.89%.

### A.2.2 Warp analysis results from the complete analysis

At the end of the whole analysis, the warp results are evaluated. These results are extremely important because they give an idea of the final deformations of the product. Not only do they give an idea of how the piece will bend and deform but also they evaluate the severity of these deformations.

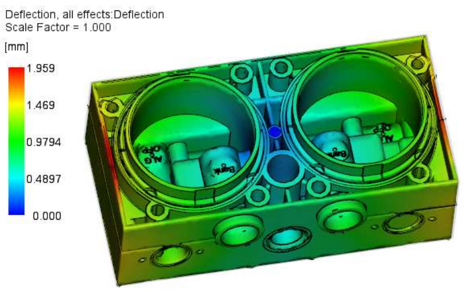
Before starting with the analysis of the results, it is important to analyze the content of the log files to spot any errors or warnings. Depending on the setup defined, as shown in A.1, the following warnings are shown:

1. ** WARNING 201412 ** - The mesh aggregation option is used in the analysis. This option is recommended for typical thin-walled parts, but should not be used for chunky parts.
2. ** WARNING 201410 ** - You have selected the option of analyzing isolated causes of warpage. This option is recommended for typical thin-walled parts, but not recommended for chunky parts.
3. ** WARNING 201434 ** - There are huge gaps in the node or element numbering in the model. It may cause memory allocation failure in warp analysis.

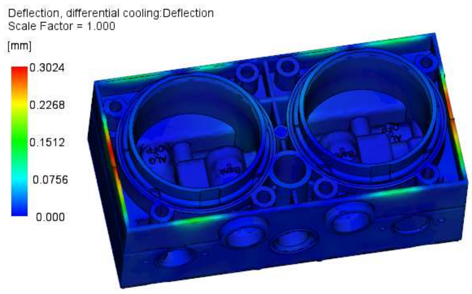
None of these warnings stopped the analysis from reaching the end, so fortunately these warnings did not influence the convergence.

For the first two warnings, there is no real solution in this case. The part can be considered both thin-walled in some areas and chunky in other areas. For the third on the other hand, one attempt at a solution has been made. Autodesk forum suggests the following: do a global merge with a very low tolerance value, that should renumber the nodes and elements. This solution has been attempted, but the warning continued to show. Since the completion of the analysis was achieved nonetheless, the warning is left as it is and the results are considered valid and here followingly presented.

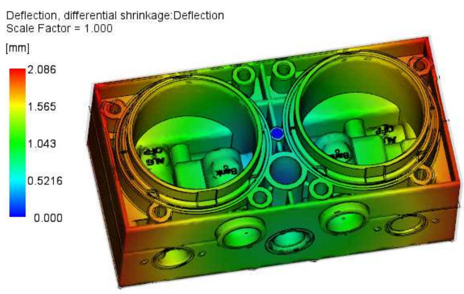
Here starts the description and comment on the warp results for the complete analysis. The results that are presented here come from the analysis with setup parameters described in the previous section, with isolation of the cause of warpage and without mesh aggregation. Eventual comparisons will be described with other types of analysis only if they are important for the development of the study. In other cases, they will not be mentioned.



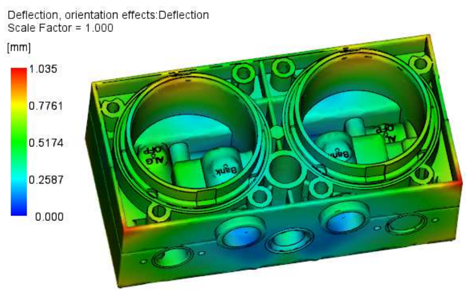

(a) Warpage due to all effects




(b) Warpage due to differential cooling




(c) Warpage due to differential shrinkage




(d) Warpage due to orientation effects

Figure A.5: Warpage results: the all effect result is used as reference to then compare the other three images. The result with the highest warpage effect has to be considered the main reason for the deformation.

The expectations for these results were focused on the differential cooling being this system particularly complicated. It turns out that this effect is the least influential among the results obtained (figure A.5(b)). It seems that the cooling of the piece is quite homogeneous and does not give particular problems. The real problem is caused by the differential shrinkage of the material (figure A.5(c)), meaning that most of the deformation is caused more by the bad packing of the material than the way the piece is being cooled down. Especially, the more difficult areas to pack, so the farthest from the gate location, are the ones that are more subject to this effect. The scale factor for this defect, out of 1.0, is indicated as more than 2. In figure A.6 it is clearly visible how big these deformations are: in the area of maximum effect the deformations that can be measured are over 2 millimeters. Specifically in the figure, we can see one of the screw seats of the piece. The deformation in this area will completely move the seat from its original place, and this can create huge problems when fixing the piece to the machine.

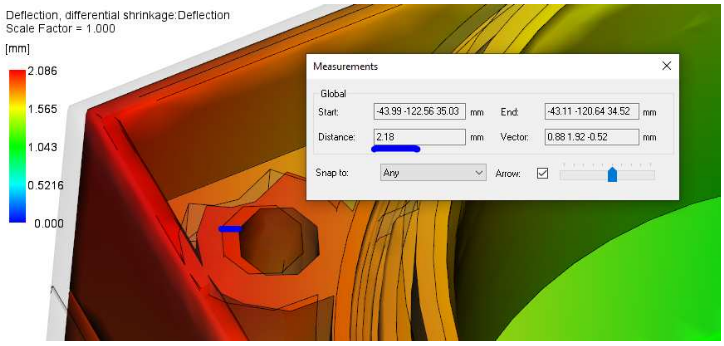
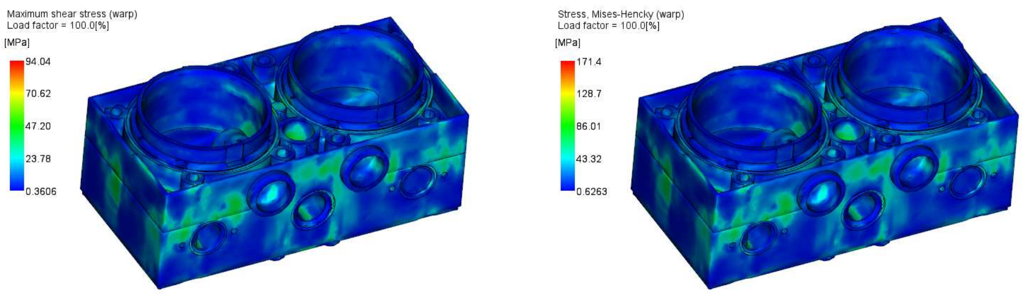



Figure A.6: Detail of the deflection for differential shrinkage.

The orientation effect (figure A.5(d)) reaches a factor 1, so it also contributes to the deflection, while the only effect that can basically be discarded to be considered is the cooling deflection (only a 0.3 factor).

Interesting to point out is also the difference between the evaluated maximum shear stress and the Mises-Hencky stress (maximum normal stress) evaluated for the piece. The pattern evaluated is exactly the same, as seen in figure A.7, and what really changes is the magnitude of the stress scale. The maximum shear stress evaluated is up to 94 MPa while the Mises-Hencky is 171.4 MPa. These two stresses are equivalent in terms of observed results. The first one should be considered when the material is brittle, and the second one when the material is ductile. In the case of Domamid 6 LV G35 H2 BK, being it a PA6/nylon matrix material, it can be considered ductile. PA6 has a brittle/ductile transition around -100℃ and the content in glass fibers is 35% so the composite can still be considered fully ductile. Said so, the result to be considered is the one in figure A.7(b).




(a) Maximum shear stress, for brittle materials

(b) Mises-Hencky stress, for ductile materials

Figure A.7: Warpage results: stresses results evaluated in the warp analysis.

## A.3 Complete analysis with automatic time

This analysis has been run quickly just to check if the evaluated time for ejection, in this case, is higher than the one set for the analysis and if this happens how much higher it is, and possibly why.

The suggested time is 847.2 seconds. This is almost five times the time set by the company. The time that the software is evaluating may be somehow an overestimation of the real-time needed due to the complex structure of this system, but Moldflow suggests the company will not be able to do this piece in just 180 seconds.

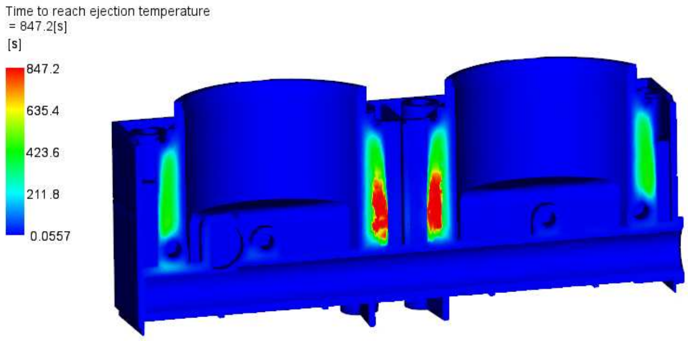



Figure A.8: Time to reach ejection temperature for the piece when the software is set for automatic time.

In figure A.8 is clear how the injection point is the area that will freeze last and there is no way to insert any cooling channel there. No real solution can be found for this problem at the current state of the project. There will be the need to continue further the study with geometrical variations of the piece or eventual modification of the injection location to a place where cooling channels can reach.

## A.4 Observations on the analyses results

It is already clearly shown how this piece still has many problems that have to be faced. The main aim of the project was to see if an analysis of this project could be run and find a way to import into Moldflow as much external information as possible from what the company has made available. In the end, the analysis was able to be run, and it is clear that the optimal production condition for this piece is still quite far from being reached. One interesting thing that has been pointed out by this analysis is that the main deformations are not given by the way the system is cooled down, meaning that the development of the cooling system is quite good even if not optimal still, but by the way the system is packed. It has already been noticed that the packing phase is particularly problematic in this case, but the effects that this has on the system were not thought to be this important up until this moment.

It would have been interesting to have a comparison between the data obtained from the company and the data obtained from the analysis here. If the results obtained by the company are similar to the ones obtained here, it may be sufficient to fix the packing phase of the system to obtain a proper production for this piece and solve most of the problems that the system is having. Of course, this has to be confirmed by the proper continuation of this study, but it seems that the main concern over the cooling system was not the real focal point for the problems of the production of this piece. The time has not been enough to reach this point of the study. This will be one of the possible next steps for this project.

Available developments for this research:

- Comparison between the obtained results and the real case scenario results. If these data have been correctly collected by the company directly compare them, or start a proper collection campaign to achieve a good data set to manage a good comparison.

- Update the actual situation of the piece and cooling channels if there has been any change from the company and do the same procedure. This is important. Always maintaining updated geometries and the parameters used is fundamental for obtaining a good comparison of results.
- Continue the research in any of the previously mentioned possible branches that can start from this initial work.

# Appendix B

# Further information

## B.1 Import the channels through *.iges format from CAD

One quickly attempted way of importing the cooling channel was the *.iges format. It has not been studied in detail for this case since an already functioning way was found. But it may be a future development of the study.

An IGES file is a data file used to exchange 2D or 3D design information between CAD programs, such as Autodesk AutoCAD and ACD Systems Canvas. It typically contains surface information for a model but may also store wireframe, solid model, and circuit diagram information. IGES files are saved in ASCII text format and are based on the Initial Graphics Exchange Specification (IGES) standard. [52]

To successfully translate an IGES model into an Autodesk Moldflow model suitable for analysis, the model must have been correctly prepared in the CAD system. [53]

- The entire model must be described by IGES surfaces, not just lines, and curves.
- Lines and curves can be used to import the cooling channels of a mold and can be used as the basis for cooling channel construction. It may be possible to export the center line geometry of the cooling lines from the CAD package.
- If possible, simplify the model to remove unnecessary detail, such as reference planes and very small features that have no effect on a Fill+Pack or a Stress analysis.
- Before exporting a model to be used by Dual Domain analysis technology, check in the CAD system that the part is fully closed, i.e. no gaps between surfaces.
- Export as surfaces, not shells.

This procedure fails exactly as the import from Solidworks directly whenever there are geometrical defects in the initial file. In this case, it seems that any attempt to solve the defects is not effective for this type of file format. Just a couple of attempts have been made, and not much research has been conducted on this case. Maybe further in-depth research will find a solution to this problem, but it is left for future development.

## B.2 Redraw the corrupted cooling files in Solidworks CAD and then import

Another attempted way of importing the cooling channel was to use the normal import procedure but redraw by hand the channels whose defects were blocking the ability to import. It has not been studied in detail due to the lengthiness of the process of redrawing by hand the channels that needed it.

In 4.2.2 the geometrical import procedure for CAD files has been described. Some files have been found defective and can't be imported into Moldflow due to these defects. In many of these cases, the defect is collapsed surfaces, meaning non-perfectly stitched surfaces in the CAD model. Sometimes this defect can be solved by overlapping to this point an extruded surface created directly in CAD, but in some other cases the defect was related to the way the channel has been drawn; this case is much more difficult to detect and correct. Specifically for the conformal cooling channel identified by the company as n°3, this defect was impossible to be found both by eye and by geometric analysis in Solidworks. No solution has been possible to be found for this specific channel, and the whole procedure has been discarded.

One possible solution to this not-to-be-found defect is to redraw by hand the whole geometry of the channel paying particular attention to the drawing process in order to avoid geometrical defects. One attempt has been made with channel n°3, but still, the complexity of the system would not allow the whole system to be imported so also this solution has been discarded. The time needed to redraw the channels is quite long and knowing that still, the complexity of the final system will block the ability to run the analysis, this procedure has been discarded from the beginning, and no attempts to run the analysis have been made with the redrawn channel.