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LIFE CYCLE ASSESSMENT FOR A PLASTIC PART FABRICATION

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Contents

Abstract

This work conducted a cradle-to-gate LCA focused on the climate change impact category to evaluate the indirectly released GHG emissions associated to the CNC machining of an injection mold and the injection molding of a plastic part. The manufacturing was addressed from a sustainable standpoint by proposing to perform Design of Experiments (DOE) to develop a process window helpful to determine the machining conditions to reduce the energy consumption and to mitigate the GHG emissions.

The improvements on the energy consumption also allowed the processes to achieve the defined quality criteria of the mold and the plastic part. The hypothesis testing is done supported by statistical analysis using multiple linear regression and Analysis of Variance (ANOVA) in order to evaluate the effect of independent variables over the variability of a response variable, and to verify the consistency of the measurements.

1. Introduction

During the last decades, the international concern has focused on global warming caused by the Greenhouse Gas (GHG) emissions and its negative impacts which represent a menace to the earth planet and the future of the humankind. Several human activities are the main responsible, where the manufacturing sector stands out due to its high consumption of electrical energy and other surrounding factors [1]. Climate change mitigation must occur now, but it is not clear which strategies, infrastructures, and practices must be chosen in order to obtain the greatest potential reductions in terms of GHG emissions, which has caused great interest from the scientific community [2].

In the global market, around 75% of the metal molds for plastic injection are CNC machined [3] and the manufacture of injected plastic parts represent approximately 35% of the global consumption of thermoplastics [4]. Regarding energy consumption, in the U.S.A the industrial sector represents 33% of total energy consumption nationwide and the manufacturing sector demands approximately the 77% of this energy [5].

The potential to improve energy efficiency and decrease carbon footprint in both CNC milling and plastic injection molding processes has been already estimated, Pavanaskar demonstrated that by selecting an appropriate toolpath in a milling machine, it is possible to reach up to 20% electricity savings [6]. On the other hand, according to Godec et al. the energy efficiency of injection molding machines still offers potential energy savings from 10 to 80 % [7]. Consequently, if a reduction in energy demand of the manufacturing sector is achieved then there will be a reduction in the amount of generated electricity causing a decrease of indirect GHG emissions, and thus counteract global warming.

As a response to evaluate and achieve a reduction of the indirect GHG emissions involved in the manufacture of an injection mold and a plastic part, this work proposes to use Design of Experiments (DOE) to obtain the best CNC cutting parameters in terms of energy consumption, and a cradle-to-gate Life Cycle Assessment (LCA) particularly focused on the climate change impact category addressing two batch manufacturing processes.

At this point it is possible to realize that manufacturing, electrical energy, GHG emissions and Life Cycle Assessment do have a narrow relationship that must be deeply understood as a way to undertake in low carbon manufacturing affairs. In the end only the time will reveal us if global warming can stop before it is too late.

2. Method

The proposed method for this research spans several activities and it begins with the selection of the research domain followed by the literature review as illustrated in the figure 1. This method seeks to identify process parameters in CNC milling and plastic injection molding in order to know how these parameters influences the indirect release of CO_2 emissions in manufacturing, afterwards the approach of the research project is stated to indicate the objectives, hypothesis, but also justify the value of the present research work. The following steps of the method develop the research approach by addressing some manufacturing experiments from a sustainable standpoint and conducting as case study a cradle-to-gate LCA, later the thesis´s results and discussion are presented, the hypothesis testing is done supported by statistical analysis, and lastly some conclusions are drawn over the whole thesis research work.

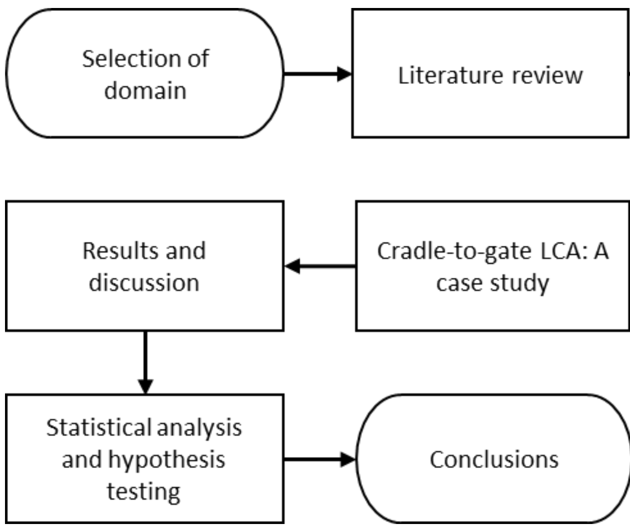

Figure 1. Research method pathway

The background is established in the literature review where different subject matters will be object of study by consulting recent articles and books, the collected information is essential to formulate the bases of this research work, with the eagerness to obtain general, deep, and specialized knowledge that includes methodologies, and approaches used by other researchers into the different fields related to electrical energy, indirect GHG emissions, CNC milling process, plastic injection molding, and LCA. This will be the foundations to undertake into the manufacturing research field, particularly focusing on topics that are around of the environmental implications associated to a plastic part fabrication.

The literature review will show the current progress of the selected domains which will allow to discern which is the relationship between electricity consumption and GHG emissions, which are the most widely used CO_2 emission indicators and how these allocate certain degree of released pollutant associated to a specific activity or process developed in a particular geographical region, how does the equivalent Carbon Emission Factor work, and better understanding about how clean energy influences the released GHG emissions.

Moreover, it will be identified and understood the different approaches of LCA and its features, characteristics of a Life Cycle Inventory Analysis (LCI), the environmental impact categories, and the interpretation of an LCA. As this present work only contemplates the raw material and the manufacturing phase for assessing the life cycle of a product, LCA approaches will be reviewed in the literature in order to choose a specific and suitable approach to conduct the LCA, consequently it will allow to realize about the produced environmental impacts and consequently interpret them.

In the field of CNC milling and plastic injection molding processes, it will be important to pay special attention on the relevant process parameters capable to alter not only energy consumption but also the expected quality, the environmental implications of the required energy and materials during manufacturing are also relevant. Another one important aspect when studying literature focused on manufacturing is how could energy savings be achieved through proper handling and control over the manufacturing process parameters, then this information can be used to propose low carbon processing alternatives that can contradict or support previous work.

The approach of the research project is proposed based on the expectations of the present work, the approach establishes as the major objective of the work to carry out a cradle-to-gate LCA focused on the manufacturing of a plastic part and its corresponding injection mold, the particular objectives will consider that the manufacture need to be addressed from a sustainable approach.

The hypothesis will be formulated, and the statistical analysis of the experiments will say if it is true or not, the hypothesis will disclose the belief that a good selection of parameters for CNC machining will reduce the generated GHG emissions during the mold manufacturing process. With the purpose of justifying the research, it will be argued from a particular perspective that exists tools and techniques just as Design of Experiments (DOE) and Life Cycle Assessment (LCA) that are capable to counteract the environmental impacts produced by manufacturing sector, the justification is important as it will highlight why does this work is meaningful and representative.

An approach to address the manufacturing experiments surrounding the CNC mold machining is presented in section 5, this will allow to observe different possible machining routes and several possible cutting parameters around the mold machining, a mindful selection among the machining alternatives would considerably reduce the machining time, the energy consumption, the released GHG emissions, and consequently that also would reduce the environmental impacts.

The proposed method presents a case study which is also the major objective of this research, here it is conducted a cradle-to-gate LCA focused on the manufacturing of a plastic part for a thermometer´s case. The framework, requirements, and guidelines contained in ISO 14040 and 14044 standards will be used and adapted to conduct an LCA for the specific case study [8] [9]. LCA will be important for this work, as it will be used to know the actual environmental impacts caused by the product that will be manufactured, LCA is also important since in other circumstances this study could be useful supporting decision-making for sustainable development purposes.

The LCA will account energy consumption during the CNC mold machining, then a brief parenthesis must be made to explain that the cutting forces only exerts influence over the spindle drive unit consumption and the feed motion drive unit consumption. Additionally, as a matter of fact the CNC milling machine consumes electricity from several sources as it is the control system, the lubrication system, the lighting system, the spindle drive unit, the feed motion drive unit, the coolant pump drive, among others.

Regarding the electrical measurements of the present LCA study, in the CNC process will be preserved an approach focused on recording the entire process power consumption including all the systems and units, not only on the cutting power consumption say not only on the power consumption caused by the cutting forces. Therefore, the CNC machining process will be considered as a black box where elements such as the operations energy usage distribution or Power Usage Profile (PUP) will be unknown and ignored.

Subsequently, this method contemplates a section to present the relevant results extracted from the manufacturing experiments and a brief recap from the cradle-to-gate LCA results, additionally will include a discussion to interpretate, evaluate, and make suggestions over the results.

Later, the hypothesis testing will be done supported by statistical analysis using multiple linear regression and Analysis of Variance (ANOVA). This will allow to evaluate the effect of independent variables over the variability of a response variable, and to demonstrate the consistency of the measurements, respectively. Thus, it will be verified if it is possible to reduce the generated GHG emissions by an appropriate selection of parameters involved in CNC milling or not.

The last section of this method specifically focuses on obtaining the conclusions relative to the major objective of the research stated in the approach of the research, conclusions will clearly state which has been the main findings, and what is left for future work on the addressed research field.

3. Literature review

The vast field of manufacturing will be ever closely related to energy consumption and all the potential environmental impacts it involves, the review done by Taofeeq Durojaye et al. [10] provides insightful perspective about the threat that climate change represent as a consequence of the manufacturing at a global scale, where the unrestrained economic development is listed as one of the biggest risks to the environment, some corporations argue that environmental policies entails a raising of the production costs, but on the other hand, another standpoint holds that well planned environmental standards would avoid the additional expenses of a cleaner production.

This literature review focuses on the investigative work that has been developed in the domains of interest, where it is essential a deep understanding of environmental performance indicators and LCA approaches, moreover it is also important to understand the relationship between the indirectly released emissions and electricity production and consumption during the addressed manufacturing processes. From this review will emerge the guidelines of this thesis in order to contribute to the development of a more sustainable manufacturing for the posterity. The main subject matters to be reviewed are well illustrated in the figure 2.

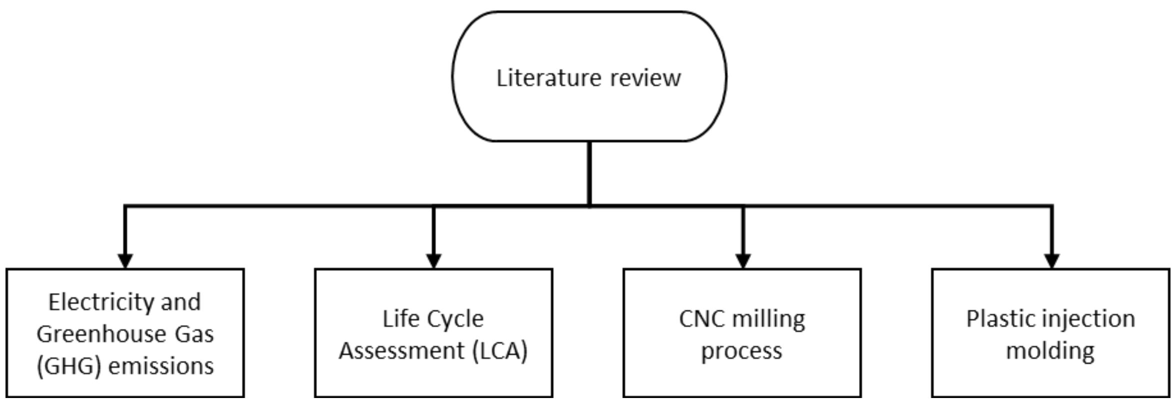

Figure 2. Different subject matters reviewed in the literature

3.1 Electricity and Greenhouse Gas (GHG) emissions

Regarding the impact of electricity on GHG emissions, substantial research has been carried out, e.g., Annika & Garvin showed how to measure GHG emissions from electricity generation, they first identified expected changes in electricity generation sources resulting from modernization of the power grid, subsequently they estimated the potential influence of modernized electricity generation sources on CO_2 emissions. Their analysis is outstanding since the U.S.A. is the world's second largest GHG emitter and electricity generation embodies the biggest portion of the emissions, then this accounting represents an important part of the global GHG emissions [11].

Asumadu-Sarkodie and Owusu examined the nexus between carbon dioxide emission, electricity consumption, industrialization, and economic growth during the period from 1980 to 2012. The study uses time series data obtained from the World Bank (2014) and Energy Information Administration (EIA) (2015) to evaluate from 1980 to 2012. They proposed a linear model, it includes

CO_2 emissions; Total Electricity Consumption (TCE), Gross Domestic Product (GDP) per capita, and Industry value added (IND), they found that the most relevant factors affecting CO_2 emissions resulted to be TCE and IND. [12].

Similarly, Saint Akadiri et al. investigated the relation among the electricity consumption, carbon emissions, economic growth and globalization in Turkey, they used several econometric techniques and statistical analyses and their findings indicate that the electricity consumption and economic growth are relevant variables in the reduction of pollution [13]. Astonishingly, the study estimated that 41% of the total global carbon emissions come from electricity generation.

Rodrigues et al. showed that the main three drivers of the decrease in carbon emissions from electricity generation in the EU between 2007-2015 were: (1) the expansion of renewable electricity, (2) improvements in the efficiency of fossil electricity production, and (3) improvements in the efficiency of electricity use [14].

Mufutau et. al. investigated the impacts of electricity consumption on four different parameters to assess environmental degradation including carbon footprint, water footprint, CO_2 emission and ecological footprint. The results showed that renewable sources of electricity are a feasible alternative to reduce air pollution, especially carbon footprint [15].

Wei et. al. provides an approach to measure electricity-related carbon emissions for a region simultaneously under three different scopes. They use the Intergovernmental Panel on Climate Change (IPCC) emissions accounting method, a network approach, a multi-regional input-output model, a decomposition analysis, and data sources, in order to obtain the resulting emissions into the desired region. Their research helps to understand regional electricity-related carbon emissions and to support carbon mitigation strategies [16].

Li et al. remark that the released emission attributed to the electricity generation could have significant variations among different power grids due to the differences in the regional climate, the source of energy and the power generation capacity [17]. It is important to note that each power grid around the world release different volumes of GHG and these emissions correspond to a different amount of produced electricity.

In order to quantify the emissions and looking for having reliable measurements of the gases released as a result of human activities, several environmental performance indicators as the Carbon Emission Factor (CEF) have been implemented, the Environmental Protection Agency (EPA) defines an emission factor as follows: “An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors usually are expressed as the weight of pollutant divided by the unit weight, volume, distance, or duration of the activity that emits the pollutant” [18].

When it comes to electricity consuming manufacturing processes the associated activity to the release of a pollutant is the electricity generation, indirect carbon emissions related to electricity are notable contributors to global warming [16]. For this reason, it is important to remember that exists a specific emission factor that is related to electricity generation, which is called Electricity Carbon Emission Factor (CEF_{elec}). A similar environmental performance indicator found in the literature is the Aggregate Carbon Intensity (ACI), which Ang & Su defines as the energy-related CO_2 emissions in electricity production divided by the electricity produced, and for a country as the ratio of the total CO_2 emissions from fossil fuels in electricity production to the total electricity produced in the country [19].

Ang & Su studied changes in the Aggregate Carbon Intensity (ACI) for the electricity at the global and country levels. Their main focus was to analyze changes in ACI that took place between 1990 and 2013 globally and in major electricity producing countries by using data collected from the International Energy Agency. Particularly, for Mexico it has been observed that ACI shows a decrease of 8.24 %, while countries such as Romania present a decrease of 53.61%, which means that Mexico's ACI has improved almost marginally [19].

Some environmental performance indicators as the Carbon Emission Factor (CEF) and the Aggregate Carbon Intensity (ACI) do not contemplate more than carbon emissions, and GHG emissions are composed from different gas emissions (Carbon dioxide, methane, nitrous oxide, fluorinated gases). A feasible alternative is an indicator such as the equivalent Carbon Emission Factor (CEF_{eq}) that achieves to embody the total emissions composed by the different gases, which seems to be more accurate for practical purposes and more attached to the nature of actual emissions scenario.

The equivalent Carbon Emission Factor (CEF_{eq}) relates the released GHG emissions to the amount of produced electricity and it is based on the equivalent CO_2, according to Ayala et al. the equivalent CO_2 is a measure to represent in terms of CO_2 the caused level of global warming due to other greenhouse gases, where mainly 80% correspond to CO_2, 7% methane, 6% nitrous oxide and certain refrigerant gases are present in a lesser magnitude [20].

It should be highlighted that according to the Energy Regulatory Commission (CRE) of Mexico the equivalent Carbon Emission Factor in Mexico during 2021 was 0.423 t CO_2e / MWh [21]. According to the Energy Information Administration in the United States of America 0.85 pounds (0.385 Kg) of CO_2 was released per every generated kWh in 2020 [22]. This way in Mexico, a consumption of 1 kWh results in the release of 0.423 Kg CO_2e to the environment, such alarming indicators should make us to appropriately use the energy in manufacturing activities and even make us to hesitate if turn-on the light or not in the household.

E. Marrasso et al. highlighted the time-variability nature of the carbon dioxide emission factor (CEF) and the electric efficiency, the authors suggest that an accurate estimation of these indicators must consider the seasons and hour by hour variability. They analyzed over 2016 and 2017 the Italian electricity production mix with an hourly time resolution, considering fossil and renewable sources of energy. Their measurements indicate that on the summer and surrounding days the renewable-based production is higher than the fossil one from 9 am to 3 pm, never occurring in the winter days, then the variability of the CEF could be present daily and seasonally [23].

Naohiro et al. claim that if there is a reduction in the resource consumption along the manufacturing processes and the same level of production is maintained, then the environmental impacts per produced part is also being reduced. Which means that a reduction in energy consumption means a direct decrement of the CO_2 emissions per produced part [24].

For practical purposes during the assessment of the manufacturing experiments addressed in the present study, it is adopted the equivalent Carbon Emission Factor ($\mathrm{CEF_{eq}}$) provided by the Energy Regulatory Commission (CRE) in Mexico, this electricity Carbon Emission Factor applies over the whole Mexican territory as this is an average value obtained from all the National Electrical System.

3.2 Life Cycle Assessment (LCA)

The literature related to electricity and carbon emissions has already been reviewed, it is required at this point to address Life Cycle Assessment (LCA) since the nature of the present manufacture analyses evidently demand a counting methodology to measure the indirect GHG emissions linked to the different materials and the electricity consumption embodied in manufacturing processes, as well as their implicated environmental consequences.

LCA has been defined in the introductory section of the international standard ISO 14040 as follows: "LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences" [8].

Some characteristics of LCA depend upon the given approach, for instance the cradle-to-grave approach can contain the cradle-to-gate and the gate-to-gate approaches but not inversely. The cradle-to-gate approach can contain the gate-to-gate but not inversely. Finally, the gate-to-gate approach can only contain itself.

Almeida et al. refer to the cradle-to-grave LCA approach as the one which evaluates a product from raw material production until product disposal; the very significance of their analysis lies in that material selection is strategic in terms of environmental impacts from the design stage [25]. It is important to remark that the cradle-to-grave approach begins with raw material production, passing through production of intermediate products, production of an end product, use phase, and it finishes with disposal and/or recycling [26].

Thomitzek et al. refer to the cradle-to-gate approach as the one which considers the complete value chain of a product to count the overall embodied energy and materials until the product goes out of the production chain [27]. The cradle-to-gate approach include raw material production, production of intermediate products, and the production of an end product [26].

The gate-to-gate approach can be observed as a partial LCA, this is the case when operational input-output analyses are carried out, gate-to-gate modules may be linked to form a complete LCA evaluation; two of the major characteristics of a gate-to-gate analysis are: (1) The production of pre-products is not considered. (2) The disposal of end products is not considered. However, gate-to-gate analyses are useful for many applications such as databases for environmental management systems [26]. This type of studies demand significant efforts and resources to accordingly address the required methodologies, measurements, and calculations to obtain reliable outcomes.

In addition, the gate-to-gate approach of LCA is referred to as the one which focuses on the required energy in processes to transform from raw material to a refined material, namely, the embodied energy along manufacturing processes inside a factory [27]. The gate-to-gate approach only contemplates the production of an end product to count used energy.

According to the Society of Environmental Toxicology and Chemistry (SETAC) and standard ISO 14040, the Life Cycle Inventory (LCI) analysis is the second phase of LCA and it goes after goal and scope definition phase but before life cycle impact assessment phase in the LCA framework. The LCI has been defined in the international standard ISO 14040 as follows: "LCI is a phase of Life Cycle

Assessment involving the compilation and quantification of inputs and outputs for a product throughout its entire life cycle" [8]. In other words, LCI is an energy and a materials analysis.

Electricity consumption is an essential part of any Life Cycle Inventory (LCI) as it constitutes an input for any product, the GHG emissions into LCI are represented as an output for any manufacturing process. Those are reasons for LCI to be considered as the backbone for any LCA as mentioned by Jiménez-González et al. [28].

Jiménez-González et al. presented an option to generate gate-to-gate Life Cycle Inventory (LCI) of chemical substances, first a selection of the process was chosen and a clear definition was made, crucial stages are the mass balance and the energy measurement; the methodology proposed by Jimenez-González et al. is useful for LCA practitioners to get a reliable and transparent estimation of LCI even though not all information is available from literature or industry. When a manufacturing process needs to be improved, the LCI information of the proposed methodology can be used [28].

Naohiro et al. identified several tools to assess material and energy balance in terms of efficiency, where the ones that mainly appear are Material and Energy Flow Analysis (MEFA) and Life Cycle Assessment (LCA). The authors define MEFA as "a systematic assessment of the flows and stocks of materials and energy within a system defined in space and time which connects the sources, the pathways, and the intermediate and final sinks of a material". The authors also emphasize that data and results of MEFA can be used to build an LCA study [24].

Thomitzek et al. proposed a method supported by a Material and Energy Flow Analysis (MEFA) to quantify the embodied energy in Li-Ion battery production where the evaluation focused on the value chain, the material flow, and the energy flow. A cradle-to-gate study was conducted under the argument that it is possible to improve environmental footprint by measuring and assessing the overall energy demand in battery manufacturing to be compared to alternative energy systems and make better decisions [27].

Ciacci & Passarini argues that in a world where the environment and the energy are interconnected, it is expected to counteract the climate change through the use of green technologies for energy generation, storage and use. Then the authors highlight that Life Cycle Assessment is crucial but also capable to analyze from a sustainable standpoint the advantages and disadvantages in complex product systems [29]. The study remarks that LCAs can have positive effects oriented to the decarbonization of energy sources and the improvement of efficiency in processes.

Bigarelli Ferreira et al. reviewed the literature related to design tools based on the streamlined LCA of plastic injected parts, the authors pointed out that several studies suggest the injection molding process to be highly impacting on the environment due to the high consumption of electricity and the high use of raw material. Their study become important when looking for tools to analyze plastic injected products in the environmental perspective but in a streamlined way, allowing quick decision making in product development to reduce costs and assist designers to implement Eco-design [30].

J.E. Galve et al. conducted a cradle-to-grave LCA focused on three plastic parts injected with virgin Polyamide 6, virgin Polypropylene and 100% recycled Polypropylene respectively, their results showed that the recycled PP reduces the environmental impacts in 29.8% and the Carbon Footprint in 42.8% compared to virgin PP. Even though the impacts of the energy consumption during the injection molding process remains similar, the evidence is outstanding and beneficial for the environment as long as the recycled material fulfill the desired mechanical properties [31].

3.3 CNC Milling Process

Different authors have worked on the energy efficiency of CNC milling processes, paying special attention to choose the best parameters to achieve the least energy consumption while the required quality of the manufactured parts is obtained. In the meantime, other ones have focused on LCA of CNC-manufactured parts because they wanted to study in depth the environmental behavior of the processes, for other cases the purpose to obtain a comparison among processes, materials or consumed energy is a good reason to undertake LCA studies over CNC milling process.

Sihag and Sangwan highlighted that nowadays the manufacturing industries have as a key priority sustainable manufacturing to reduce GHG emissions and environmental impacts, the reason of this scenario are the rising environmental preoccupations, stringent government regulations, public awareness and ever rising energy costs. They studied that the characterization and modeling of the energy consumption during a machining process implies a challenge since a machine tool is integrated by a large number of energy-consuming components and it is difficult to calculate energy consumption and carbon emissions produced by each one activity [32].

Li et al. investigated how the cutting parameters in milling processes influences on the consumed power and the efficiency. They proposed models to predict the cutting power and power efficiency, the p-values < 0.05 mean that the models are highly significant, then the models can be used to choose the suitable parameters before the machining process begins. Their results indicate that the depth of cut, the spindle speed and the rake angle, had significant effects on the power consumption, the authors highlighted that a higher MRR increases the cutting energy but conversely, it improves the power efficiency [33].

Jiang et al. investigated the energy consumption of the main cutting force that occurs in a milling cutter under vibration, then they proposed a model to predict the energy consumption and the results were compared to the experimentally acquired data, the accuracy resulted to be approximately 80 %. The results showed that the milling vibration alter the cutter trajectory and the inclination angle, the vibrations are translated into a cutter tooth error which changes the instantaneous main cutting force and power consumption. This outstanding work leaves open the way to improve the accuracy of such energy models in machining processes [34].

Kurukulasuriya et al. made the Life Cycle Assessment of a CNC milling machined part, paying special attention to the influence caused by the depth of cut, the feed rate and the cutting speed (rpm). The authors designed a balanced experiment by using a Taguchi orthogonal array, where only the most representative 9 parameter combinations were evaluated from 27 possible experiments, then it was measured the electricity consumption along every experiment with the help of a power logger. Their study was done using ISO 14044 standard as guideline with the belief that good parameter combinations improve environmental performance, which was consistent with the obtained results, moreover, they discovered that the environmental impacts were caused mainly by the electrical energy and the workpiece material [35].

Bergs et al. compared through an LCI and LCA the milling process to produce an aero engine component with two different alloys focusing on the alternative options for material selection and the environmental impacts caused by manufacturing. Specialized software was used for LCA, and an estimation was done to obtain the amount of used coolant, raw material and chips, tool wear, and consumed electricity, this last had a great contribution to the environmental impacts. They clearly demonstrated that to reduce environmental impacts the material can be substituted for another less harmful, also they argue that it is possible to use less material with a novel process such as additive manufacturing [36].

Ayala et al. proposed an equivalent CO_2 accounting model to obtain the Greenhouse Gas emissions produced by the electricity consumption in CNC machining. A first case study was presented, where 9 experiments were developed to measure power and energy, then an equivalent factor was computed to give way to the calculation of emissions, afterwards, a second case study was presented to analyze the energy consumption and the relationship with roughness at specific machining conditions. This work aims at achieving the most suitable parameters combination to get the best surface finish with the minimum electricity consumption and consequently the least generated GHG emissions [20].

Li et al. implement their proposed analytical method to quantify the total CO_2 emissions produced indirectly by any CNC based machining system, where in the first place they declare based on the literature that the boundaries of a CNC system must be well defined. Its accounting method considers the electricity, production and use of cutting tools, cutting fluid, production of machining chips, chips disposal. The authors make it clear that although CNC machining systems are widespread in the manufacturing industry, nowadays, the developed work on CNC´s low carbon manufacturing is not enough, which represents a field of opportunity for future research [17].

Zhou et al. proposed a feature-based method to carbon emission accounting of a machined part, particularly the strategy analyses the carbon emissions of material, energy, and waste by mathematical models, then geometrical features are classified as basics and composites. Even though the results achieve the correct calculation of carbon emissions for a machined part, the mathematical models provide an alternative to estimate carbon emissions before a product is manufactured but do not result suitable to be adopted in this work as they use more than 28 equations to predict values that we are going to measure with a power logger during the experiments [1].

Pavanaskar measured the potential to improve energy efficiency to decrease carbon footprint in the CNC milling process, his work demonstrated that by selecting an appropriate toolpath and process parameters in a milling machine, it is possible to reach up to 20% electricity savings [6].

3.4 Plastic Injection Molding

While energy costs are ever rising and environmental policies are more stringent, in the XXI century plastic injection molding appears as one of the most widespread manufacturing processes, for those reasons substantial research is developed on this field. Some authors address the issue of energy efficiency in plastic injection molding from machine component level by measuring electrical consumption, another group of researchers focus the problem from thermodynamical models, besides various authors deal with the research field from mold design perspective.

Godec et al. analyzed the different possibilities to save energy in the plastic injection molding process, which would mean a reduction in GHG emissions. Such energy savings may be achieved from: thermoplastic selection, part design for molding, suitable material for mold cavity, suitable cooling channels design (conformal cooling channels are a good alternative), Injection Molding

Machine (IMM) selection, dryers, and cooling systems. According to the authors it is possible to obtain from 10% to 80% energy savings as a result of the sum of all subsystems [7].

Elduque et al. developed an experimental study on the electricity consumption at the machine level of the injection molding manufacturing process, this study over 36 different plastic parts is about measuring the electricity consumption involved into the various stages of the process to obtain the embodied environmental impacts. The study is handy for LCA practitioners and helpful to suitable choose an Injection Molding Machine (IMM) considering some criteria such as Specific Energy Consumption (SEC), capacity utilization percentage, and throughputs [37].

Sundmaeker et al. proposed a systematic approach that has as the main purpose to improve energy efficiency in plastic injection molding process, based on studies they stated that the design of a mold strongly influences the life cycle of plastic parts, also the design is the suitable phase to improve cooling efficiency. They structured energy information in phases to analyze the influence of different factors from the design stage, design of cooling system, analysis of production and maintenance, energy measurements, and identifying consequences of design related to energy. The authors found that the key factor towards energy efficiency is the residual cooling time, given that they reached to save 55% of the energy per part through the improvement of the residual cooling time [38].

Ribeiro et al. studied the behavior of different injected plastic parts and then they presented a new energy model that integrates thermodynamics and empirical data of the Injection Molding Machine (IMM). Their main contribution is the capacity of the model to estimate the power consumption before manufacturing at different process conditions, different IMM, and different plastic part geometries, the model showed an average error of 10%, which demonstrates high reliability of the model applied in practice. The authors highlight that great energy savings are possible to reach through minor efficiency improvements when dealing with high throughputs [39].

J. Ávila-Cedillo et al. developed an empirical study over two different injected plastic parts made of Acrylonitrile Butadiene Styrene (ABS) where their main focus was to analyze the energy distribution at an operation level, the Specific Energy Consumption (SEC), and the Power Usage Profile (PUP). A methodology was proposed, it started from experiment definition, design, and execution; followed by data gathering and data post-processing, it finished with data analysis of PUP, SEC, and energy usage shown in Sankey diagrams. Finally, with the obtained PUP and SEC, several assumptions were deducted as a product of results and analysis, all this information can be used to modify process parameters causing a reduction in energy consumption and consequently a reduction on the GHG emissions indirectly released while maintaining the desired quality of the parts [40].

Tranter et al. studied the influence of process parameters in injection molding over the energy consumption and part quality at every stage of the process by following a methodology that comprises from part and mold design, passing through experimental setup and definition of quality criteria, and applying Design of Experiments (DOE). The experiment was carried out with the purpose to get enough data to develop an optimization that allowed them to know the desired combination of parameters to achieve the least energy consumption required and at the same time the most approximated quality specification fulfillment [41].

3.5 Outline

According to the Energy Information Administration (EIA) in the U.S.A the industrial sector is a great energy consumer as it represents 33% of the total energy consumption nationwide, only the manufacturing sector share demanded the largest portion which was the 77% of the total industrial sector energy in 2020 [5]. Manufacturing processes generate a lot of indirect CO_2 emissions, which creates an enormous field to research, in this way what is really pursued in this work is energy efficiency of manufacturing processes to obtain therefore a reduction of indirect GHG emissions.

The nature of batch manufacturing is characteristic as the production is not continuous, here every batch waits until the previous is finished to be processed. The change between different batches involves some idle periods used for machinery reconfiguration. The machinery in batch manufacturing is specialized, however it allows flexibility to be adapted for the different batches as it is possible to set up each process individually and even change the material that is going to be processed. The batch processing is slower than continuum flow processing, this causes to increase cost of production per unit. On the other hand, continuum flow processes also use specialized machinery, but it is less flexible machinery, and it has higher levels of active use time, due to its high production volumes which enormously reduce unit costs compared to batch manufacturing.

The current LCA techniques and guidelines are strongly reliable, nevertheless one disadvantage is that when products are extremely varied from batch to batch it is not easy to apply gate-to-gate studies as data acquisition of the inputs and outputs of a product system involves costs to be executed and it is not yet a common practice in the whole manufacturing industry, but under these terms LCA becomes more feasible when the batch production volume is larger [42].

When the measurements are done by the LCA practitioner *in situ*, the analyses are developed only with information that can be validated, as a matter of fact there is no missing data as it could be the amount of consumed electricity, the used raw material, the amounts of used auxiliary supplies, the remaining scraps and waste, and the corresponding released pollutants owing to the processes, so you can trust all the collected information used to build any Life Cycle Inventory [28].

The LCA study of a plastic part for a thermometer´s case will be presented, then the LCA will be developed from a cradle-to-gate approach by focusing on two different processes, the first process is the manufacture of an injection mold made in CNC and the second one is the plastic injection into an Injection Molding Machine. Plastic injection molding process imply the CNC manufacture of a mold, and for a finished plastic part the cradle-to-gate LCA study offers a complete overview of what its own manufacture implies regarding the environmental impacts.

Conversely to batch manufacturing, generally when applying LCA to continuum flow processes does exist several pre-products, by-products, co-products and they use high volumes of water, which turns it complicated the whole mass and energy flow tracking. Therefore, it is possible to assert that studies on batch manufacturing can reach higher levels of completeness and reliability than studies on continuum flow processes, this is possible due to its particular characteristics as well as the simpler product system model. This opens a field of opportunity to develop LCA studies for carbon footprint labeling into the enormous world of consumer goods [26].

Under this context, it is expected to make more energy efficient manufacturing processes with the help of Design of Experiments (DOE) such as was found in the literature, with the purpose to reduce indirect GHG emissions generated in processes (both numerical control processes and plastic injection processes) while maintaining the required finish quality, considering that if it is not possible to produce completely clean energy at all, then by using energy in a more appropriate manner through the suitable selection of the process parameters involved in manufacturing, as mentioned by Rodrigues et al. [14], thereby it is possible to produce considerable energy savings and to obtain a decrease on the released GHG emissions that inside of the industry also could be translated into money savings.

4. Approach of the research project

Into this section will be stated the major and particular objectives of the thesis, it will be formulated a hypothesis which is an assumption that later on will be refused or accepted. This section justifies the research by highlighting the attention that this subject deserves and by making it clear that this work is meaningful and representative. Figure 3 shows the structure of the research approach.

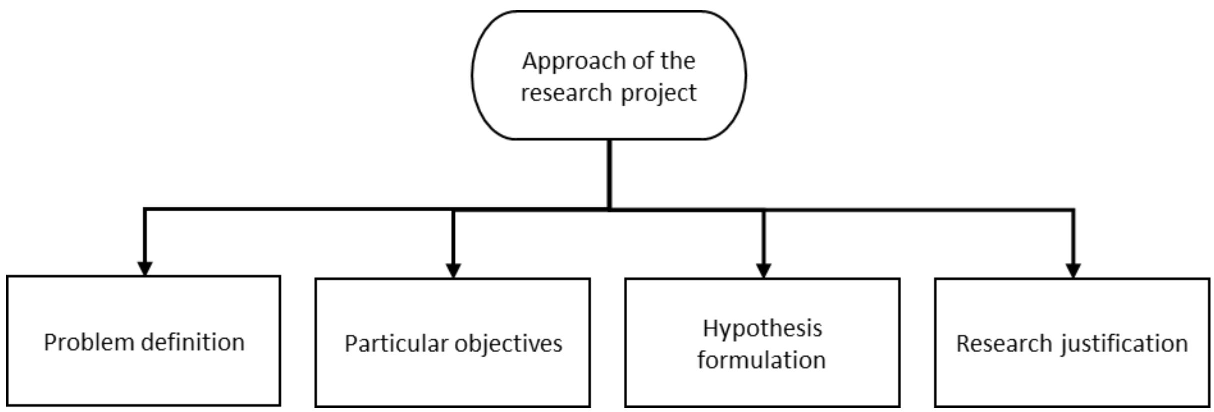

Figure 3. Research project approach structure

4.1 Problem definition

The major objective of this thesis is to obtain a reduction of emissions in CNC machining processes through Design of Experiments (DOE) and to conduct a cradle-to-gate LCA over a case study focused on the manufacturing of a plastic part considering the mold fabrication.

4.2 Particular objectives

The particular objectives are the following:

1- Address the CNC mold manufacture and the plastic injection molding from a sustainable approach.

2- Accomplish the quality criteria at every manufactured part.

3- Analyze in depth the indirectly generated GHG emissions during the addressed batch manufacturing processes.

4.3 Hypothesis formulation

Null hypothesis (H_0):

It is not possible to reduce the energy consumption nor the generated GHG emissions by an appropriate selection of parameters involved in CNC milling processes.

Alternative hypothesis (H_1):

It is possible to reduce the energy consumption and consequently the generated GHG emissions by an appropriate selection of parameters involved in CNC milling processes.

4.4 Research justification

The literature review made it very clear that nowadays low carbon manufacturing and eco-balances are forceful alternatives to measure and counteract air pollution and global warming. It is a fact that manufacturing sector must reduce electricity consumption in processes as a manner to face high energy costs and minimize all the environmental impacts. Thus, manufacturing sustainability can be achieved, and ecosystem health can improve.

The research focuses the case study on CNC milling and plastic injection processes since it was noticed that these two manufacturing processes are into the most widespread used in industrial sector and consumer goods sector, which means that some improvement in this field would be really significant for the environment. In addition, when the plastic injection process is carried out, most of the times it involves the CNC manufacturing of a mold.

Through the appropriate use of energy and resources in CNC milling and plastic injection molding processes, it is possible to getting closer to low carbon manufacturing. Moreover, if these processes are measured and assessed, the capacity to compare processes and products is acquired and you can also know the environmental impacts that a CNC machined mold and a plastic part manufacture entail. Under this context, better decisions can be made for the environment in manufacturing.

5. An approach to address the manufacturing

This section begins with the identification of manufacturing process parameters used in CNC milling and plastic injection molding, then afterwards Design of Experiments (DOE) is used to find and propose which are the best cutting parameters to be applied along the whole machining operations of the plastic injection mold. The last part of this section focuses on choosing suitable parameters for the plastic injection molding process considering the mold geometry, the thermoplastic material, and the injection molding machine.

A cradle-to-gate LCA study is going to be conducted and this is presented in the subsequent section, the purpose to address from this approach the manufacturing of the mold and the plastic part is to obtain better results during the LCA of the product system in terms of environmental impacts by reducing the energy consumption without decreasing the tool life but maintaining the specified surface finish of the mold.

5.1 Identification of variables and parameters

CNC milling machine parameters

CNC milling is a chip removal process where material is removed from an initial workpiece by a special cutter and the remaining material with the desired geometry turns out to be the manufactured part. Within this process, the manipulation of the different cutting parameters involved, strongly influence over the final product quality and also over the consumed resources during manufacturing including electricity consumption. As mentioned by Bergs et al. [36] inside of the milling process, the energy usage, tool life, and raw materials are significant contributors to the generated environmental impacts. For this present work an LCA study on CNC milling process demonstrate all of the causative elements of environmental impacts.

According to experiments conducted by Chen et al. [43], Ayala et al. [20], and Kurukulasuriya et al. [35] some influencing parameters affecting electricity consumption during milling machining process are A - Depth of cut (a_p), B - Feed per tooth (f_z), and C - Cutting speed (V_c), for that reason, this work focuses on the same three parameters.

One way to compare indirect GHG emissions of the CNC milling operations is by measuring energy consumption, therefore for this part of the present work the first response variable will be the total consumed power during the process, this response variable indicates us how much energy was consumed during every different machining process, the second response variable is the quality of the CNC machined part (the injection mold). The characteristic behavior of the involved parameters for this manufacturing process is explained below.

As depth of cut (a_p) increases, the power consumption intensity of the machine increases during the cutting time, while an increase of the depth of cut (a_p) reduces the machining time and consequently the consumed energy. In the case of feed per tooth (f_z), it is necessary to know previously the feed rate (V_f), the spindle speed (*n*), and the face effective cutting edges (ZEFF); but as feed per tooth (f_z) increases, the machining time is reduced while the power consumption intensity increases. The cutting speed (V_c) only behaves as a function of the cutting diameter and the spindle speed, as cutting diameter and spindle speed increase also the cutting speed does, then the machining time is reduced while power consumption intensity is augmented.

In this way, it is expected that a specific combination of parameters turns out to be the least energy consuming configuration, which has reached a good equilibrium between power consumption intensity and machining time, while maintaining the desired part quality.

Plastic injection molding parameters

Plastic injection molding is a process where a polymeric material is heated upon the melting point and then is injected inside a metallic mold, afterwards the mold is cooled and the part is plasticized, then the solidified part is ejected. It is especially important to have the control over the parameters affecting the process given that not only influences on the part quality but also over consumed electricity. According to Tranter et al. [41] the melt temperature, mold temperature, holding pressure, holding time, and cooling time are outstanding parameters affecting on the energy consumption and quality of injected parts, this previous statement is also supported by Rosato et al. [44] and by Moayyedian [45].

The Injection Molding Machine (IMM) onto the plastic injection is going to be developed includes a mold with cold runners, the mold works as a heat exchanger where the mold temperature rises and goes down cyclically, because of this mold temperature oscillation, it turns difficult to have a stable parameter to control and this could represent noise for the experiments, then the mold temperature will be discarded, therefore the important parameters to consider are as follows: V - Melt temperature ($\mathrm{T_m}$), X - Holding pressure ($\mathrm{P_h}$), Y - Holding time (t_h), Z - Cooling time (t_c).

As well as the energy efficiency, it is also important to know which of the different parameter's combination is the least environmentally harmful, that is, the most appropriate, also for this section of the work the first response variable will be the total consumed power during the process, while the second response variable is the quality of the molded parts.

A higher value of the Melt temperature ($\mathrm{T_m}$) means more energy consumption to heat up the polymer, but in this way the viscosity becomes lower, and it is required lower pressure to fill the cavity mold. Conversely, a lower value of Melt temperature ($\mathrm{T_m}$) means less energy consumption to heat up the polymer and Cooling time (t_c) also decrease, but the polymer viscosity increases which represents a higher pressure to fill the mold cavity.

After the filling stage, the filling pressure is increased until Holding pressure ($\mathrm{P_h}$) is reached, then this pressure is maintained to allow the material to conform appropriately before the cooling stage. A higher value of Holding pressure ($\mathrm{P_h}$) which demand more energy could become unnecessary and a lower value of Holding pressure ($\mathrm{P_h}$) which demand less energy could become insufficient, thus there must be an equilibrium between the energy that Holding pressure ($\mathrm{P_h}$) demands and the part quality fulfillment.

The required Holding time (t_h) depends upon two factors, the first is the polymer physical properties and the second is the cooling rate. A longer Holding time (t_h) results in higher energy consumption as it requires for a long period the Holding pressure ($\mathrm{P_h}$), a shorter Holding time (t_h) means a lower energy consumption. The Holding time (t_h) is a parameter closely related with the Cooling time (t_c).

The actual cooling time (t_c) comprises the addition of the injection time, packing time, holding time, and set cooling time, and this is measured from the beginning of the filling stage as illustrated in figure 4, passing through packing and holding stages until the ejection of the part, the cooling stage is the largest energy consuming stage, as it requires to cool down both the mold and the part. Cooling time (t_c) depends largely on the Melt temperature ($\mathrm{T_m}$), size and geometry of the mold, and the cooling channels.

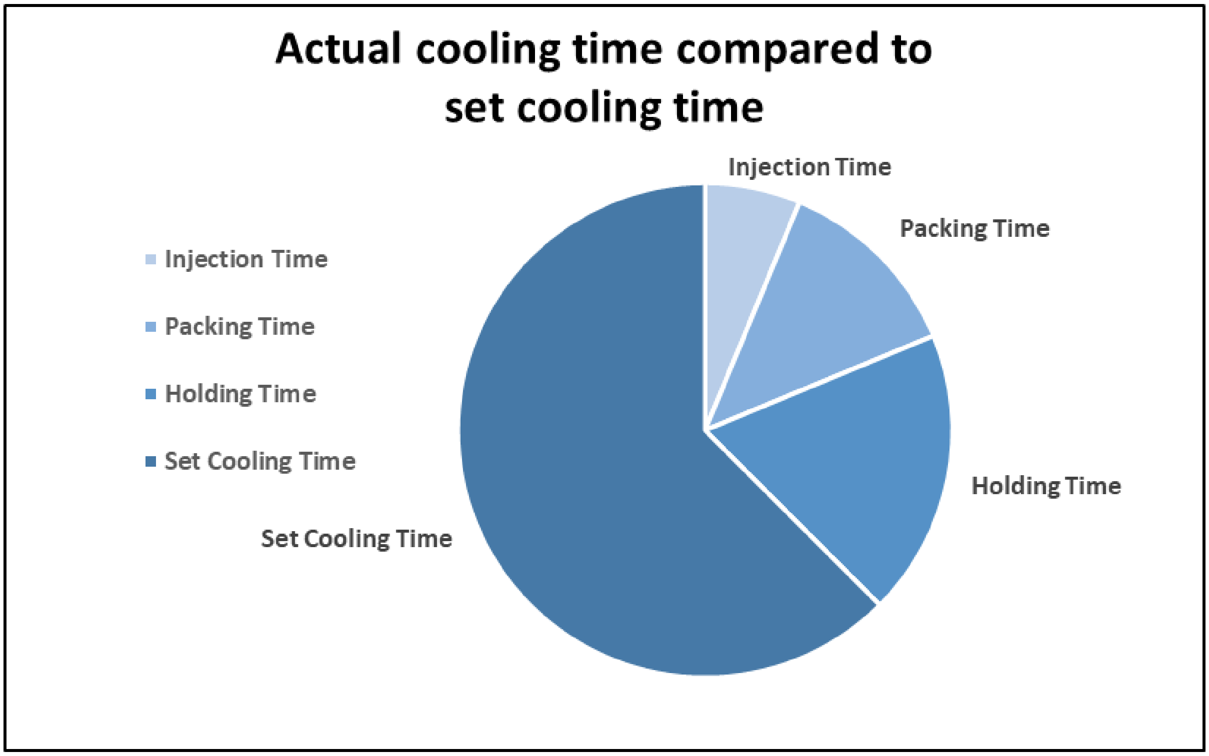

Figure 4. Set and actual cooling time

5.2 Design of Experiments (DOE)

According to Montgomery [46], the suitable approach to deal with an experiment where several factors are involved is by carrying out a factorial experiment. This strategy allows factors to vary together, and every possible combination of the levels of the factors is considered, moreover, the experimental information is used in the most efficient manner since there aren´t repeated runs of the experiments.

Through a Taguchi design which uses orthogonal arrays, it is possible to estimate precisely the effect caused by every factor in the mean response, which implies that every one of the factors can be evaluated without considering all other factors. Whenever an orthogonal array is used, it can be stated that the designed experiment is balanced since all the levels of the different factors are considered in an equitable manner. In the end, another one advantage found is that by using the

Taguchi design technique, it is possible to reduce the experiment cost and time, especially when using fractional design [47].

Design of experiments for CNC milling process

For the experiment on CNC manufacturing, a mold for plastic injection is going to be CNC machined in three different processes, this is: 1. Pre-machining, 2. Mold core machining, 3. Mold cavity machining. Since the required time for the mold machining is long, and the workpiece material and tooling increase the cost of the experiment, then the experiment has no repetitions.

In these three machining processes, the main objectives to achieve are:

- To obtain the desired geometries in the shortest possible time.
- Do not compromise the tool life nor the specified surface finish.
- To minimize energy consumption and the indirect GHG emissions as possible.

On the path towards obtaining a reduction of the machining time, appropriate selection of the cutting tools must be made. Bearing in mind that a bigger tool diameter will allow higher Material Removal Rate (MRR) and simultaneously will reduce the machining time, then the selected tools will be big enough to better resist the adverse machining conditions of roughing. Conversely, when the geometries of the operations require smaller cutting tools then small tool diameters will be used.

The machined parts include some curved surfaces where the use of ball end mills is necessary. In order to reach the surface finish objective, two formulas are used to compute the stepover (S) of the trajectories depending on some variables and conditions, the condition is whether the surface is a concave surface or a convex surface, the variables are the same in both cases, this is: R_C=Cutter radius, R_S= Surface radius, h=Scallop height (desired Ra value).

Concave surface ---------- $S = \sqrt{\frac{8\,h\,R_S\,R_C}{R_S - R_C}}$ ***Equation 1***

Convex surface ----------- $S = \sqrt{\frac{8\,h\,R_S\,R_C}{R_S + R_C}}$ ***Equation 2***

By using these formulas, the stepover is computed then by using this stepover in the machining process it is geometrically possible to achieve the desired roughness (Ra) on the machined surface.

The cutting tool life should not be compromised as the operations are performed under the cutting parameters suggested by the calculators of the tool manufacturer (Sandvik), for the generic tools made of M2 HSS the parameters are obtained and computed from tables suggested also by tool manufacturers. This way, it is expected to avoid premature wearing or chipping of the cutting tools without sacrificing the machining time reduction.

1. Pre-machining (face milling)

The first machining operation carried out on the stock material is a face milling, for this first phase of the mold machining a basic Design of Experiment (DOE) was elaborated, the experiment had a single run, this means that it had no repetitions. The workpiece material is made of A36 steel which falls into the category of low carbon steel, its hardness was measured and has a value of 150 HB in the Brinell hardness testing machine. The surface to be machined is 209 mm long and 114 mm wide.

The general dimensions of the initial workpiece are shown in figure 5, as mentioned before it is going to be machined one mold cavity and one mold core, this way it will be required to use two steel plates as the one shown in the figure 5. Previously to the machining operations the steel plate has already been cut, so it won´t be required to add any cutting process to the LCI.

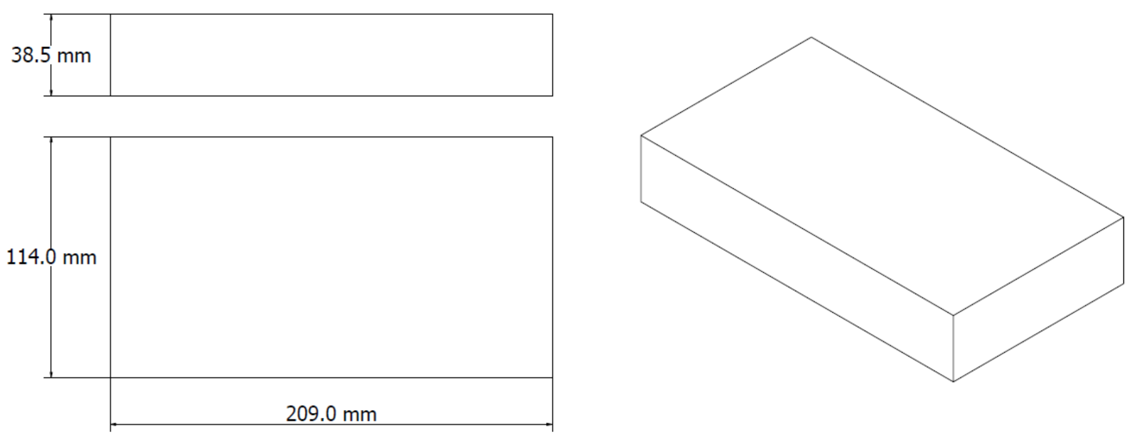

Figure 5. Initial workpiece dimensions of the A36 steel plates

For this operation a face milling cutter with 63 mm diameter and five inserts was used, the proper cutting parameters selection was taken from the tool manufacturer specifications. The tool features, toolpaths and the parameters were configured into the Autodesk Inventor CAM software, with the stepover that was introduced in the software, the radial depth of cut was controlled never exceeding 1/3 of the tool diameter (63 mm), there was a pass extension of 35 mm to reduce not desired effects on the surface finish when leading-in and leading-out the cutting area.

The five machining conditions were applied to five different face milling experiments while maintaining the depth of cut of 0.84 mm and the toolpaths exactly the same. Then by considering the cutting speed and feed rate suggested ranges a process window was built using spindle speed (rpm) and feed rate as shown in the figure 6.

Every point inside of the process window represent acceptable parameters for machining, each section of the process window behaves different when machining parts, while the lower left corner causes the highest energy consumption, the upper right corner causes the lowest energy consumption. It is possible to observe that machining in the upper left corner could cause poor tool life as it feeds too slow compared to the corresponding spindle speed, while machining in the lower right corner may cause tool breakage as it feeds too much compared to the spindle speed.

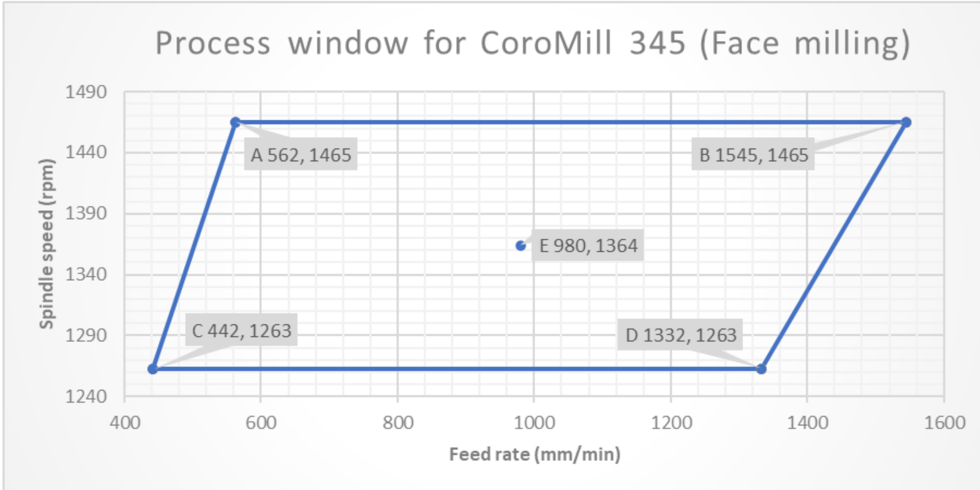

Figure 6. Process window for CoroMill 345

The power consumption was measured during each machining operation, then afterwards the surface finish was also measured with a roughness meter for each operation. The obtained results are shown as follows in table 1.

Table 1. Results from the face milling experiment

Face milling experiment results					
Spot	Feed rate (mm/min)	Spindle speed (rpm)	Machining time	Consumed energy (Wh)	Roughness Ra (µm)
A	562	1465	04m:25s	141.25	1.667
B	1545	1465	01m:30s	62.125	1.501
C	442	1263	05m:20s	242	1.868
D	1332	1263	01m:50s	71.75	1.625
E	980	1364	02m:10s	80.79	1.618

From the obtained data of this face milling operation, it can be stated that by cutting materials at the highest allowed cutting speeds and feed rates as on the spot B inside the process window it is reached the lowest level of consumed energy, the lowest machining time, and the best surface finish. Conversely, the highest consumed energy and machining time combined with the worst surface finish is obtained when machining with the conditions of low cutting speed and low feed rate as on the spot C.

From these observations it can be concluded that when feed rate and cutting speed increases also the drawn power by the machine does but as the machining time is reduced the energy consumption becomes reduced.

These results of the experiment will be used for proper cutting parameters selection of the remaining machining processes, in order to obtain good surface finish, decreased machining time, lower energy consumption and consequently release lower amounts of indirect GHG emissions when machining the mold core and the mold cavity.

2. Mold core machining

For the mold core machining two different work routes were compared where the very difference between them is the used tool for the roughing operation, the first one only uses a CoroMill® Plura solid carbide end mill with 16 mm diameter while the second alternative uses the same Plura solid carbide end mill with 16 mm diameter which is alternated with a CoroMill® 345 face milling cutter with 63 mm diameter each time 5.3 mm are roughed.

The following machining operation will be a scallop independently from the selected work route alternative for roughing, the scallop operation is carried out with a HSS M2 ball end mill 12.7 mm diameter. The CAD model of the mold core is shown in the figure 7, it was developed in Autodesk inventor 2021.

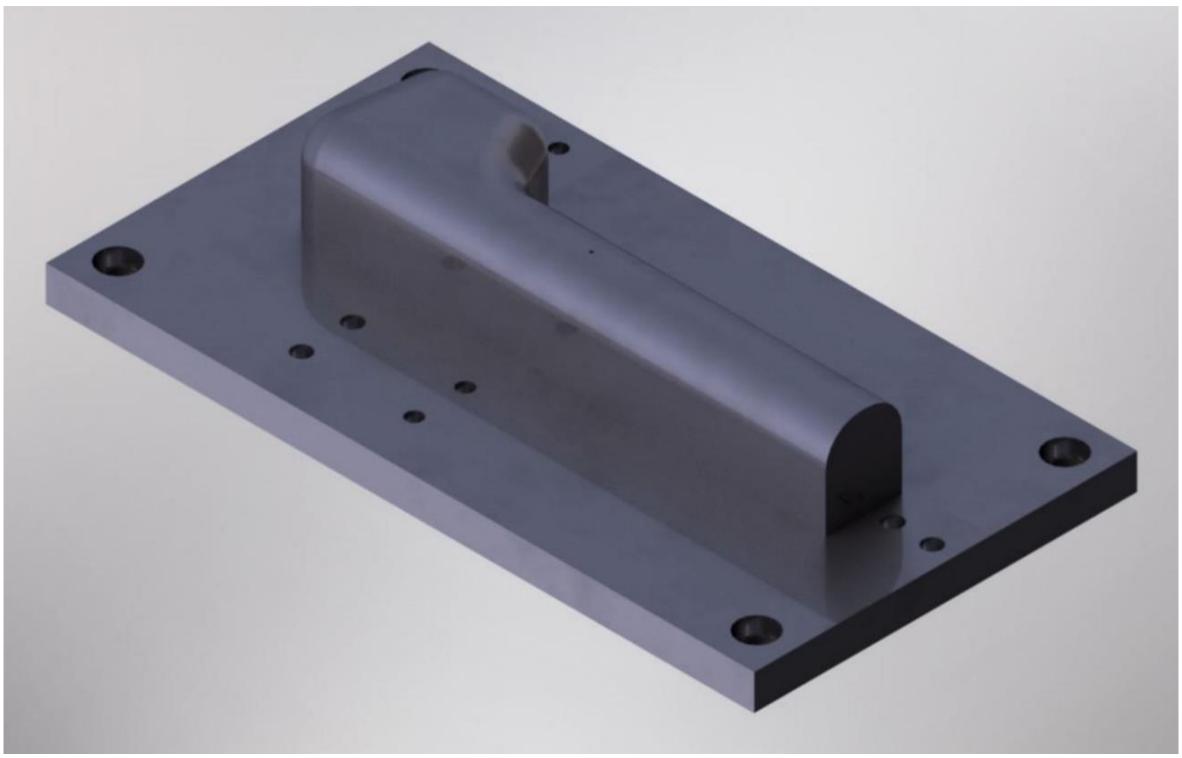

Figure 7. CAD model of the mold core, developed in Autodesk inventor 2021.

In the following page on the table 2, it is possible to observe photographs of all the different cutting tools used for the mold core machining. In the immediate aftermath of this, the figures 8, 9, 10, 11, 12, 13, 14 show every process window that was established for each one of the cutting tools used during the mold core machining, on these process windows it is possible to appreciate that every cutting tool demand specific cutting parameters that can be substantially different from each other.

Table 2. Mold core machining cutting tools

 ISO 40 Tool holder	 T1 CoroMill® 345 face milling cutter
 T2 CoroMill® Plura solid carbide end mill 16 mm for High Feed Side milling	 T3 HSS M2 Ball end mill 12.7 mm
 T4 YG-1 Center drill #3 extra long	 T5 Generic M2 HSS Drill-3/16”
 T6 Generic M2 HSS Drill-1/4”	 T7 Generic M2 HSS Flat end mill-7/16”

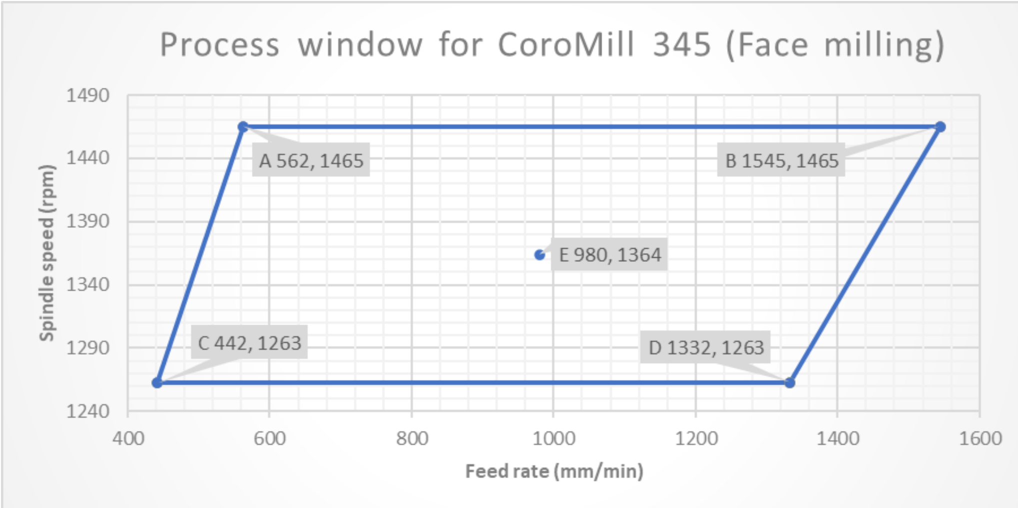

Figure 8. Process window for CoroMill 345

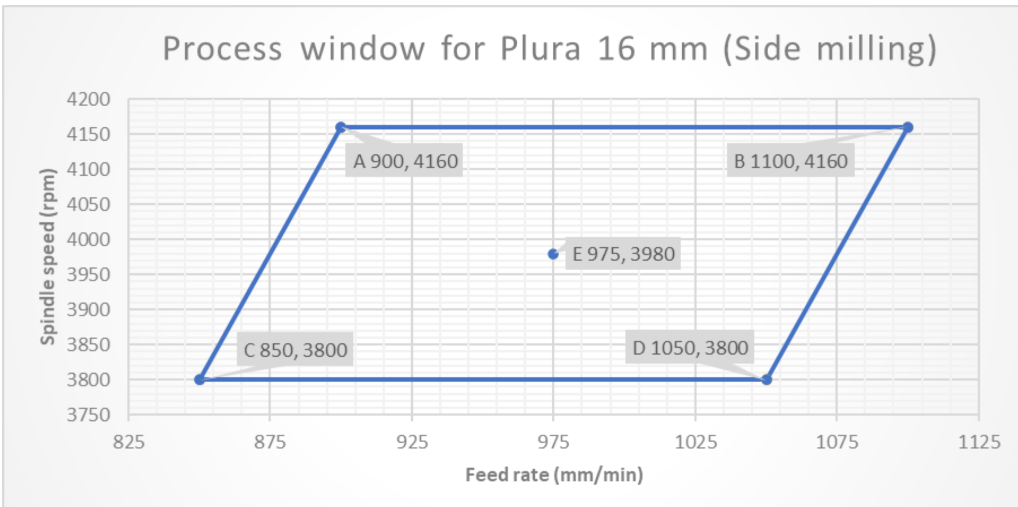

Figure 9. Process window for CoroMill Plura - 16 mm

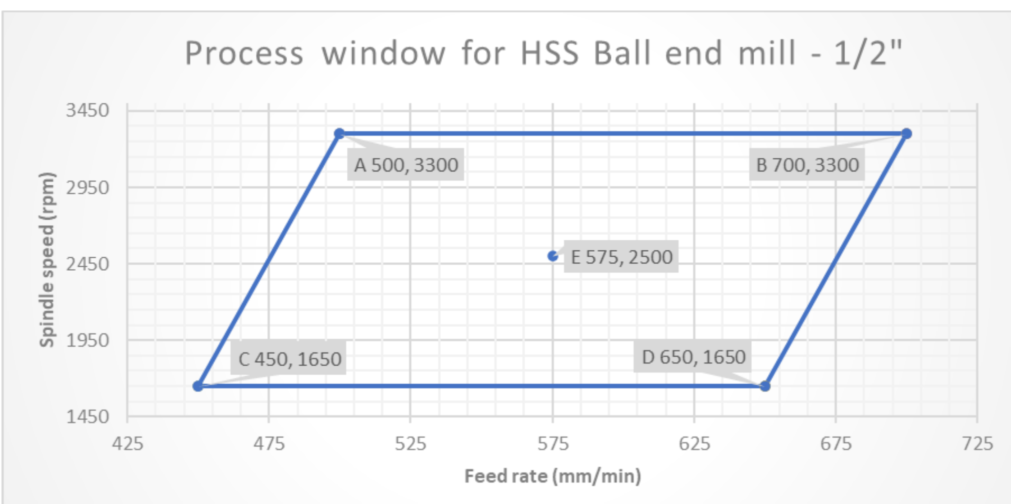

Figure 10. Process window for HSS Ball end mill – 1/2”

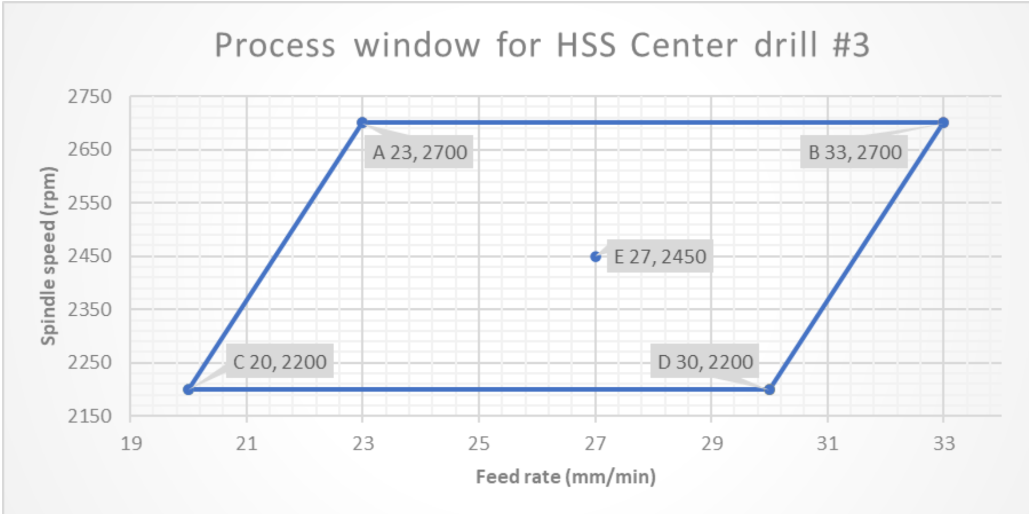

Figure 11. Process window for HSS Center drill #3

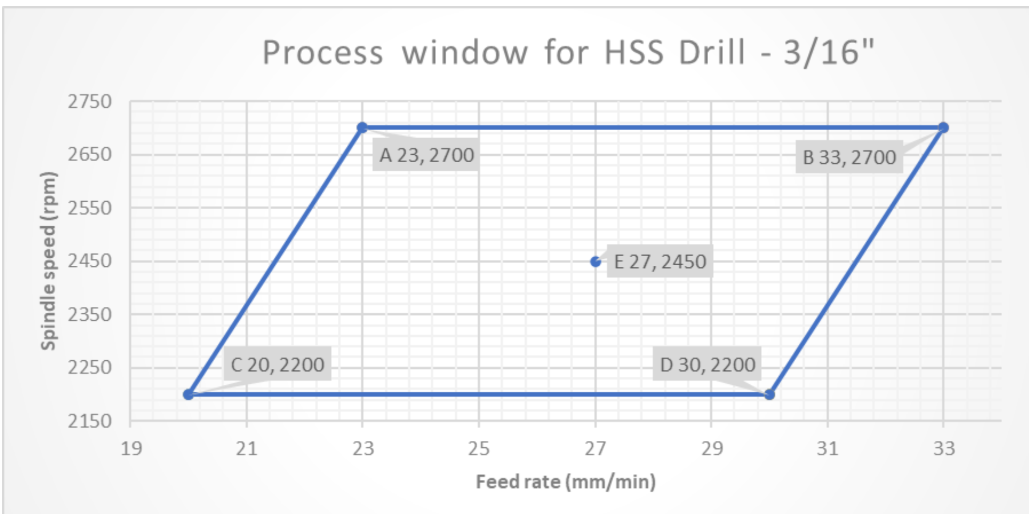

Figure 12. Process window for HSS Drill - 3/16"

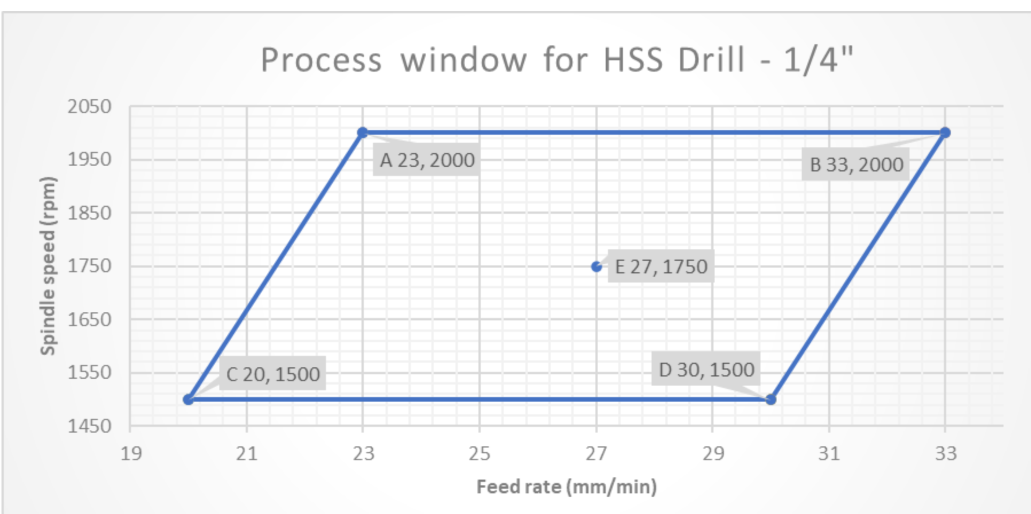

Figure 13. Process window for HSS Drill - 1/4"

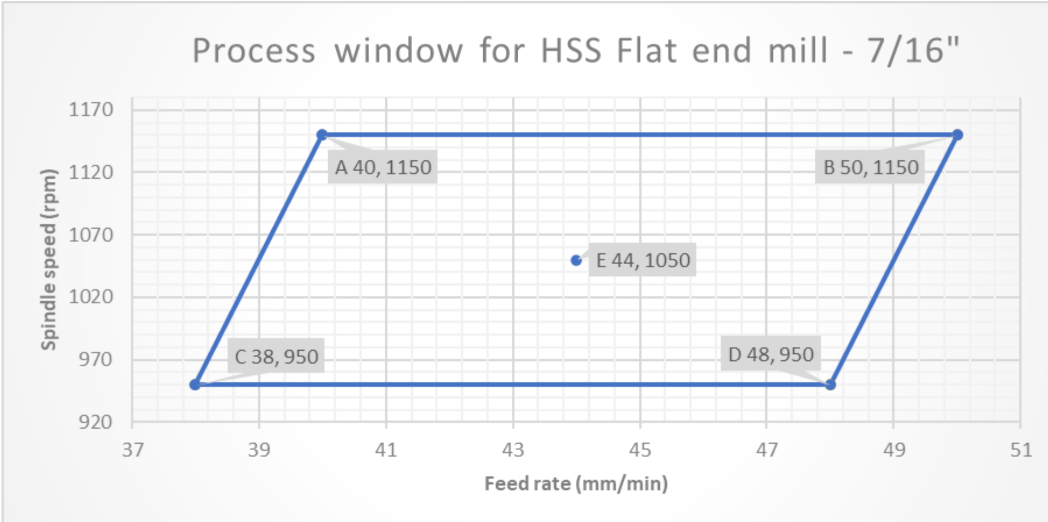

Figure 14. Process window for HSS Flat end mill - 7/16"

According to the CAM simulation, the alternative 1 results more time consuming and it involves premature tool wear as the machining time exceeds the tool life time provided by the tool manufacturer. The alternative 2 is not capable to remove most of the material in one operation, this only allows a maximum depth of cut of 6 mm for planning operations and the required operation is a contour that leaves cusps that exceed 6 mm at the outer diameter of the tool.

Then the proposed solution to use safely a face milling cutter in contour operations is to remove the machining cusps between operations before the maximum depth of cut is reached, then it is possible to perform once more a new contour operation without exceeding the maximum depth of cut and so on, until the desired geometry is obtained. This way the machining time is being reduced, additionally the tool is not at risk of damage as the cutting conditions for these contour operations remain the same as in planning operations, since all precautions has been taken.

Table 3 give a rough outline of the comparison between the two considered work route alternatives for roughing and finishing the mold core, it is also possible to observe that the alternative 2 is more convenient to implement since it involves the release of a smaller amount of indirect GHG emissions, for further details of the mold core machining work routes see appendix B.

Table 3. Work routes comparison for machining

Comparison between mold core machining work routes				
Comparison of work routes	**Alternative 1**	**Alternative 2**	**Score 1**	**Score 2**
T1 Face mill 63mm	✗	✓	1	-1
T2 Plura flat end mill 16 mm	✓	✓	-1	-1
T3 HSS ball end mill 12.7 mm	✓	✓	-1	-1
Number of machining operations	6	20	1	-1
Simulated machining time	03h:02m:24s	02h:20m:22s	-2	2
Expected tool´s life time	Shorter	Longer	-2	2
Consumed energy	Higher	Lower	-2	2
Global performance evaluation	**Worse**	**Better**	**-6**	**2**

3. Mold cavity machining

The machining process of the mold cavity is done by several roughing, pre-finishing, and finishing operations. In order to reduce the machining time, the strategy to follow is to remove as much material as possible with the big size tools, then proceed to use the medium size tools, to finally perform the finishing operations with relatively small size ball end mills.

It is first used a CoroMill® Plura 16mm-flat end mill as far as it allows to maintain the desired geometry, then afterwards in the same way a 3/8”-flat end mill is used, later a 6 mm-flat end mill is used to reduce as much as possible the remaining workpiece material. This sequence of operations considerably reduces the material to be removed by the 1/2"-ball end mill and the 1/4”-ball end mill used for pre-finishing and finishing operations respectively.

In the last part of the mold cavity machining, four drilling holes are performed according to a sequence that involves various drilling cycles, these are performed beginning with an extra-long center drill #3, followed by a Generic M2 HSS Drill-3/16”, then a Generic M2 HSS Drill-1/4” is used, in the end the counterbore is done with a Generic M2 HSS Flat end mill-7/16”. The table 4 illustrates the used tools in the mold cavity machining, the numbering of the tools in this table is the same as the used through all the machining process operations, for further details see appendix B.

The figure 15 illustrates the CAD model of the mold cavity, this model was not only used to get the blueprints of the part but also to generate the G & M code to be loaded in the CNC machine.

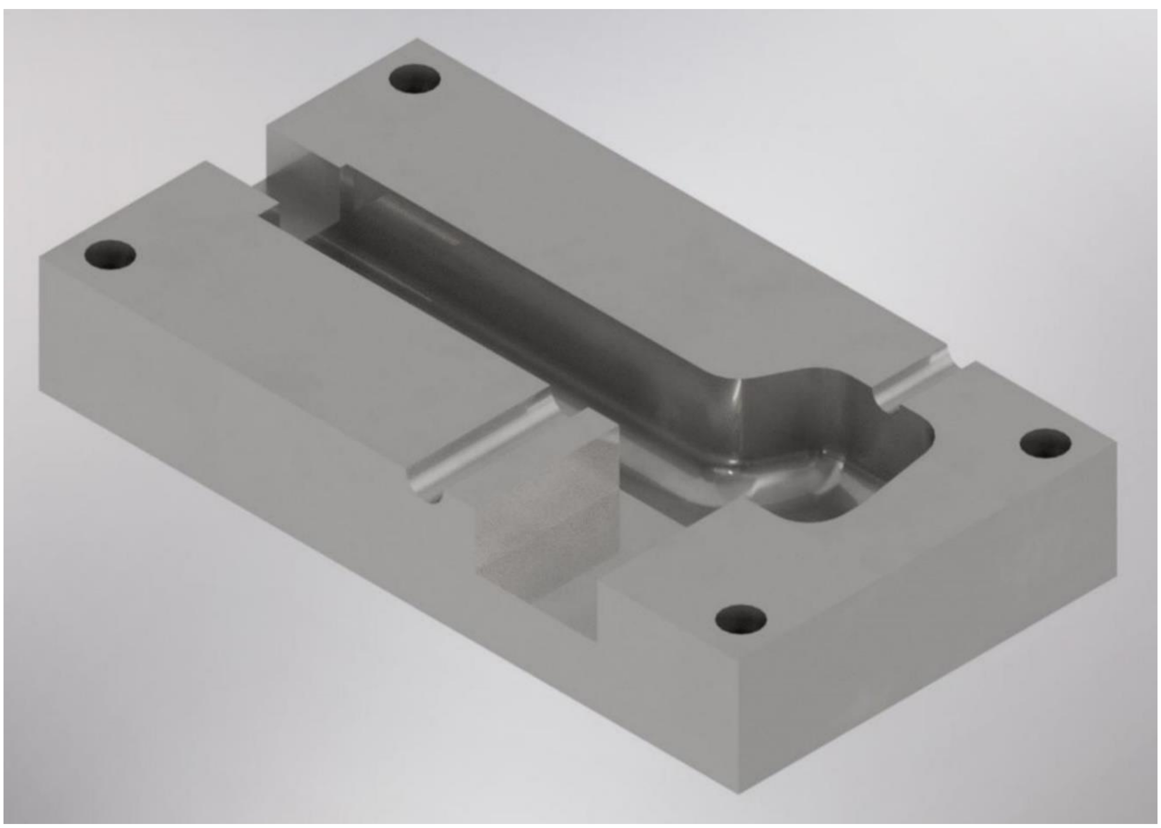

Figure 15. CAD model of the mold cavity, developed in Autodesk inventor 2021.

Table 4. Mold cavity machining cutting tools

 ISO 40 Tool holder	 T1 CoroMill® Plura solid carbide end mill 16 mm for High Feed Side milling
 T2 Generic M2 HSS Flat end mill-3/8”	 T3 Generic M2 HSS Flat end mill-6mm
 T4 Generic M2 HSS Ball end mill-1/2”	 T5 YG-1 Ball end mill-1/4" extra long
 T6 YG-1 Center drill #3 extra long	 T7 Generic M2 HSS Drill-3/16”
 T8 Generic M2 HSS Drill-1/4”	 T9 Generic M2 HSS Flat end mill-7/16”

The process windows which establish the cutting parameters used during the mold cavity machining are illustrated in the figures 16, 17, 18, 19, 20, 21, 22, 23, 24, 25. On these 10 different process windows it is possible to appreciate that every cutting tool demand specific cutting parameters that can be substantially different from each other, and this mainly depends upon the tool material, the tool diameter and the machining operation to be performed.

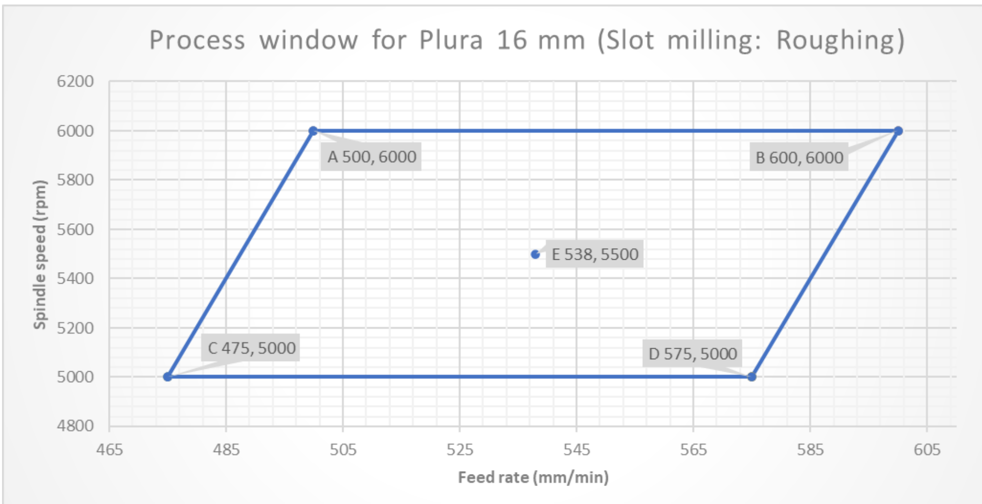

Figure 16. Process window for CoroMill Plura - 16 mm

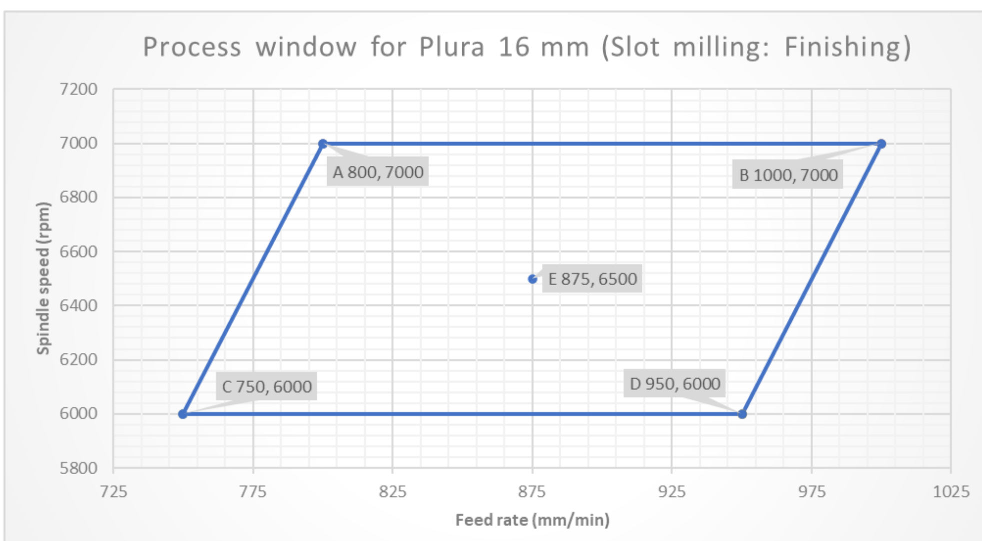

Figure 17. Process window for CoroMill Plura - 16 mm

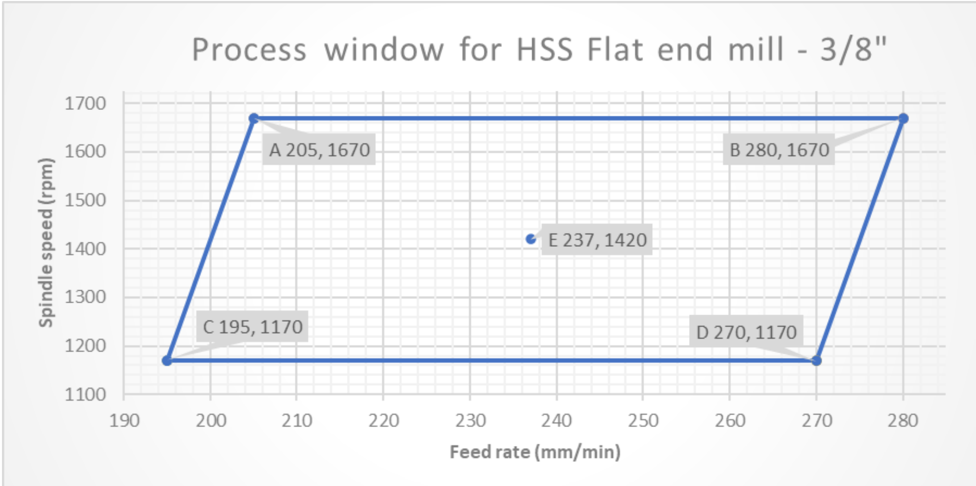

Figure 18. Process window for HSS Flat end mill – 3/8"

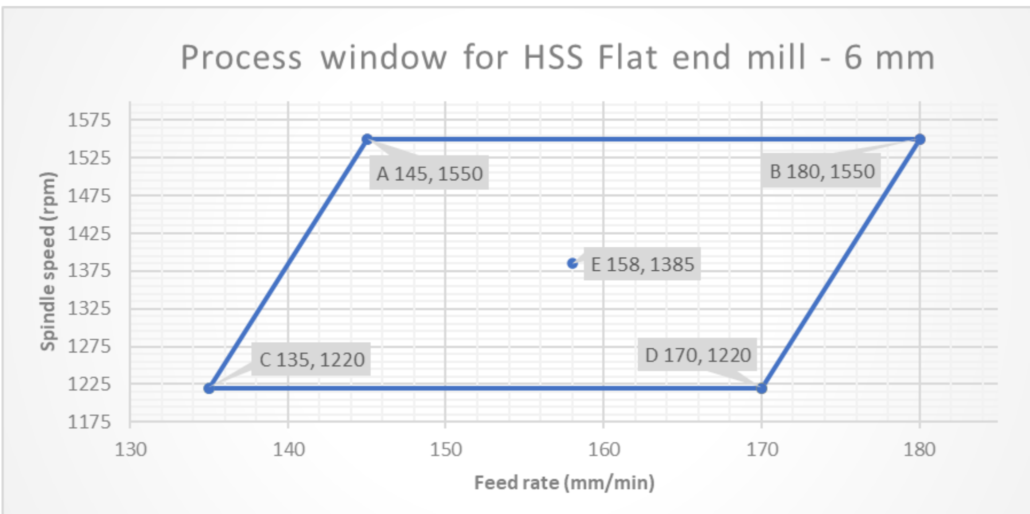

Figure 19. Process window for HSS Flat end mill – 6 mm

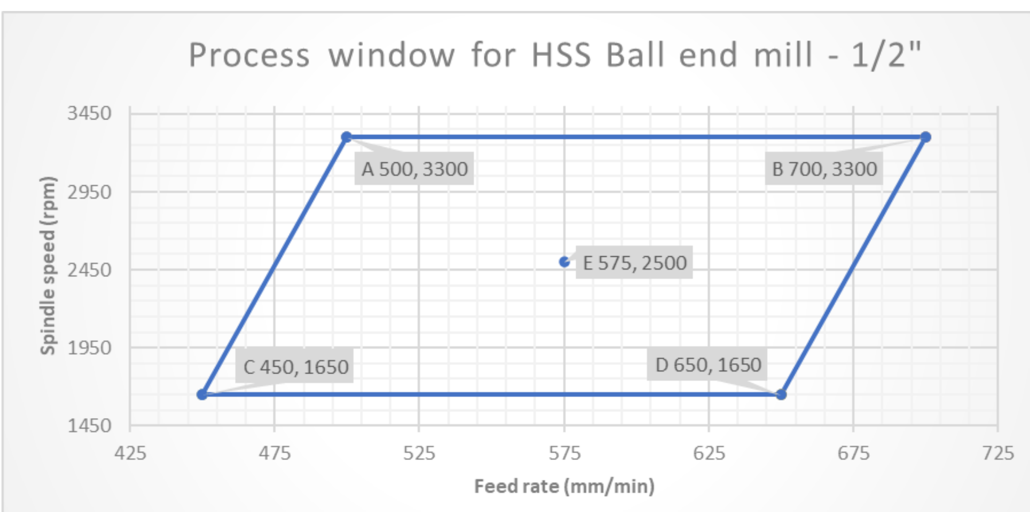

Figure 20. Process window for HSS Ball end mill – 1/2"

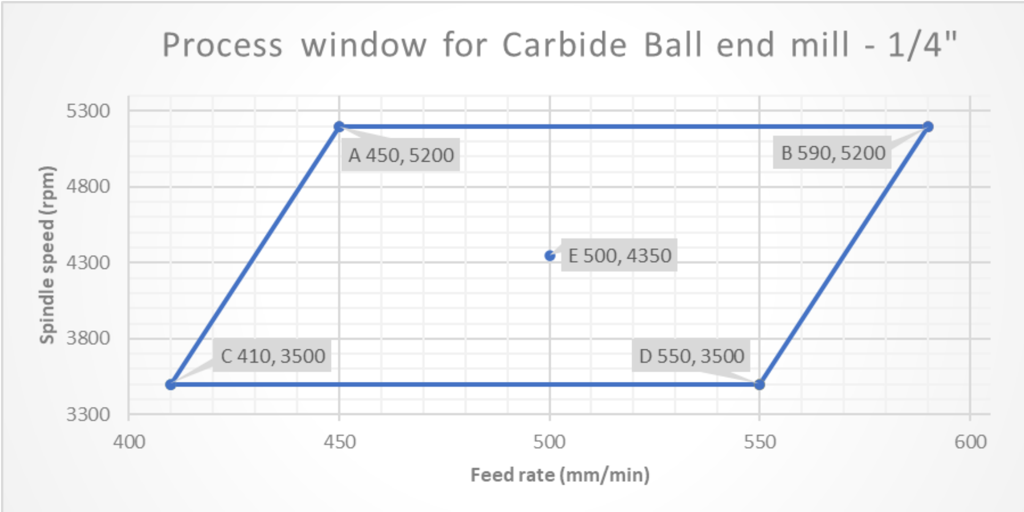

Figure 21. Process window for carbide Ball end mill – 1/4"

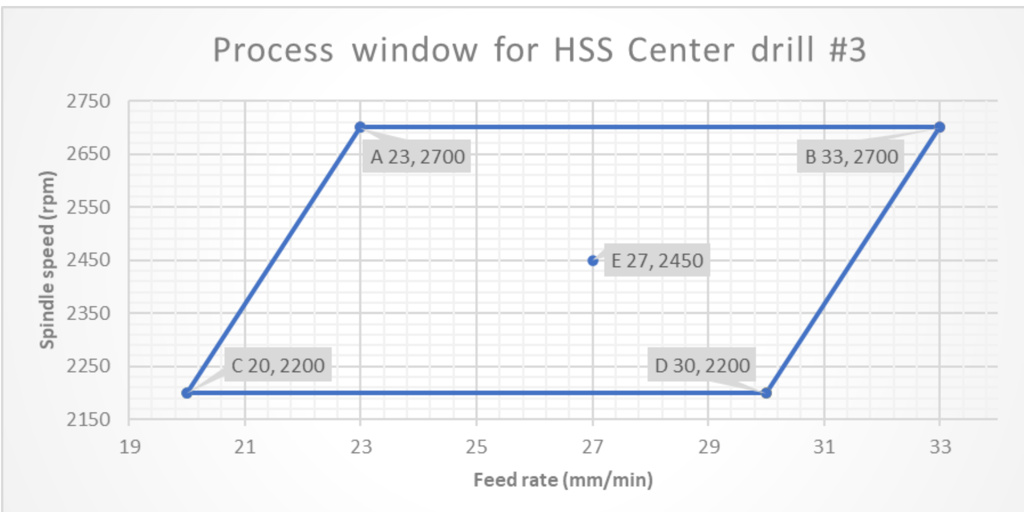

Figure 22. Process window for HSS Center drill #3

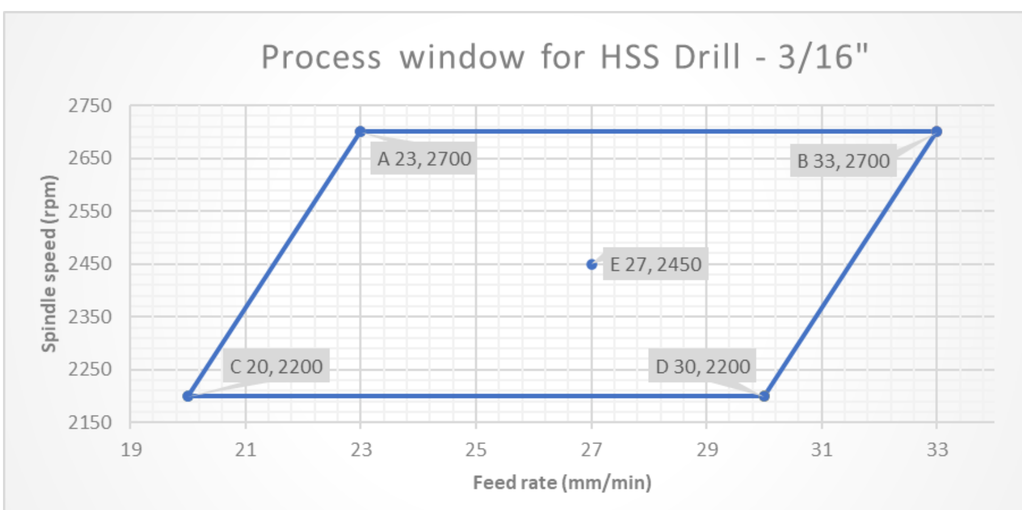

Figure 23. Process window for HSS Drill – 3/16”

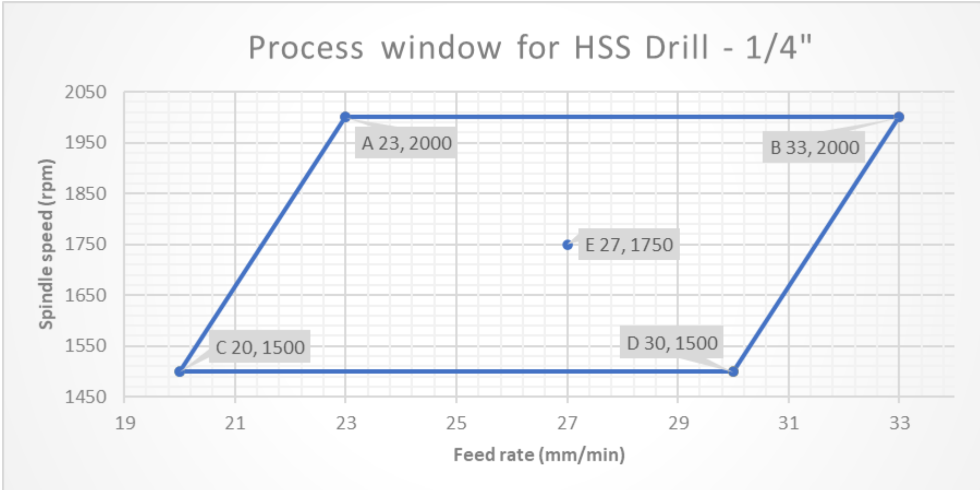

Figure 24. Process window for HSS Drill – 1/4”

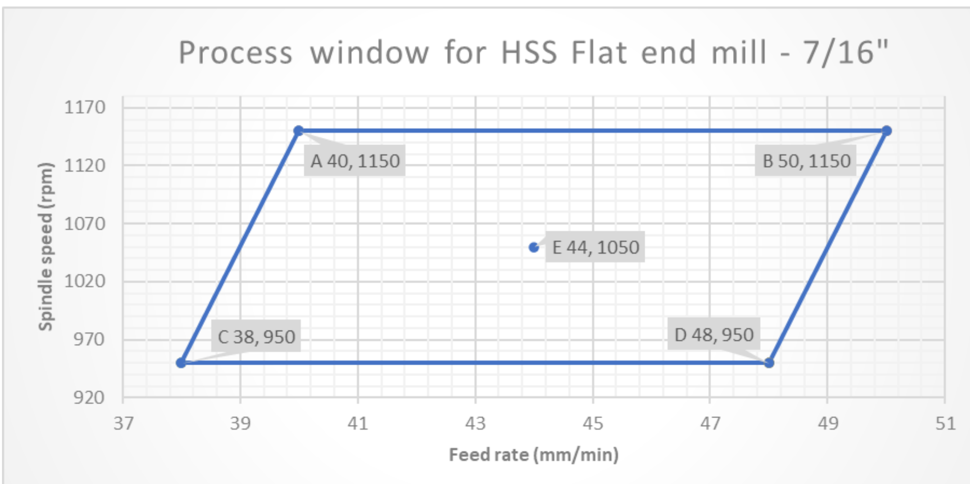

Figure 25. Process window for HSS Flat end mill – 7/16”

Experiments for plastic injection

Once the mold has been completely manufactured, the plastic part is going to be injected, for this experiment the Injection Molding Machine to be used is a Demag Ergotech 50-270 pro, the technical specifications of the machine are shown in the table 5, additionally it is required to set the injection parameters according to the injection mold, the part geometry, and the thermoplastic material.

Table 5. Demag Ergotech 50-270 pro technical specifications

Demag Ergotech 50-270 pro technical specifications	
Feature	**Capacity**
Clamping force	50 ton
Maximum injection pressure	1890 bar
Maximum injection volume	144 cm3
Motor power	11 kW
Barrel heater power	7.5 kW

The LCA focuses on the study of the injected part using polypropylene (PP) as injection material, however the mold will only be used to inject Laprene® (TPE) to verify that the mold works properly. Moreover, it won´t be possible to make direct measurements of the energy consumption due to the conditions of the electrical facility, instead an empirical model [48] will be used to estimate the consumed electricity considering polypropylene (PP) as the injection material.

The physical properties of polypropylene (PP) were taken from material-properties.org [49], and these values match with the range (0.9-0.91 g/cm3) provided by Michel Biron in “Material selection for thermoplastic parts” [50], the properties are shown in table 6.

Table 6. Physical properties of polypropylene

Polypropylene (PP) properties	
Material property	**Value**
Density	0.9 g/cm3
Specific heat	1.5 kJ/kg K

The physical properties of the Thermoplastic Elastomer (TPE) are shown in table 7, the density corresponds to Laprene® 830.823 which has the same hardness as the polymer injected in the experiment, as the part has a volume of 30 cm^3 it is expected to weigh 35.4 grams after injection.

Table 7. Physical properties of Thermoplastic Elastomer (TPE)

Laprene (TPE) properties	
Material property	**Value**
Density	1.18 g/cm3
Specific heat	1.25 kJ/kg K

The process parameters to inject polypropylene (PP) and TPE Laprene® (90 Shore A hardness) are shown in the table 8, some of these values are linked to the plastic part and the mold, the remaining are processing conditions stated by the polymer manufacturer.

Table 8. Process parameters for injection of polypropylene and TPE Laprene®

Processing parameters		
Material property	**Value (PP)**	**Value (TPE)**
Plastic part volume	30 cm3	30 cm3
Cycle time	65s	65s
Clamping force	15 ton	15 ton
Injection pressure	200 bar	180 bar
Holding pressure	100 bar	80 bar
Holding time	5 s	5 s
Set cooling time	50 s	50 s
Mold temperature	25°C	25°C
Zone 1 temperature	230°C	180°C
Zone 2 temperature	240°C	190°C
Zone 3 temperature	240°C	190°C
Nozzle temperature	250°C	200°C

5.3 Quality verification of the injection mold and the plastic part

Once the mold has been CNC machined and the plastic part has been injected, some quality criteria must be verified in order to check if the plastic injection mold and the injected plastic part fulfill the design specifications when the manufacturing is made according to the defined process parameters. Summarizing, the quality of the injection mold and the quality of the injected plastic part resulted to be qualitatively acceptable, the detailed report of the quality criteria can be seen on the checklists presented in the appendix D and it can be reviewed jointly with the blueprints of the appendix C.

Relative to the fabrication of the injection mold, after the CNC machining process it was expected to obtain a surface roughness of 1.5 µm or better, additionally it was expected to obtain accuracy in some geometric dimensions considered critical, them must also be checked. In summary, it is possible to assert that the inserts of the mold assembled properly, the mold closed and sealed properly, the obtained surface finish of the mold is better than the specified in the design, some of the dimensions considered critical resulted to match with the design specifications while some others resulted very approximated to the design specification, nonetheless the proper function of the injection mold was completely guaranteed. The plastic injection mold (pre-product) machined and assembled to the inserts is shown in the figure 26.

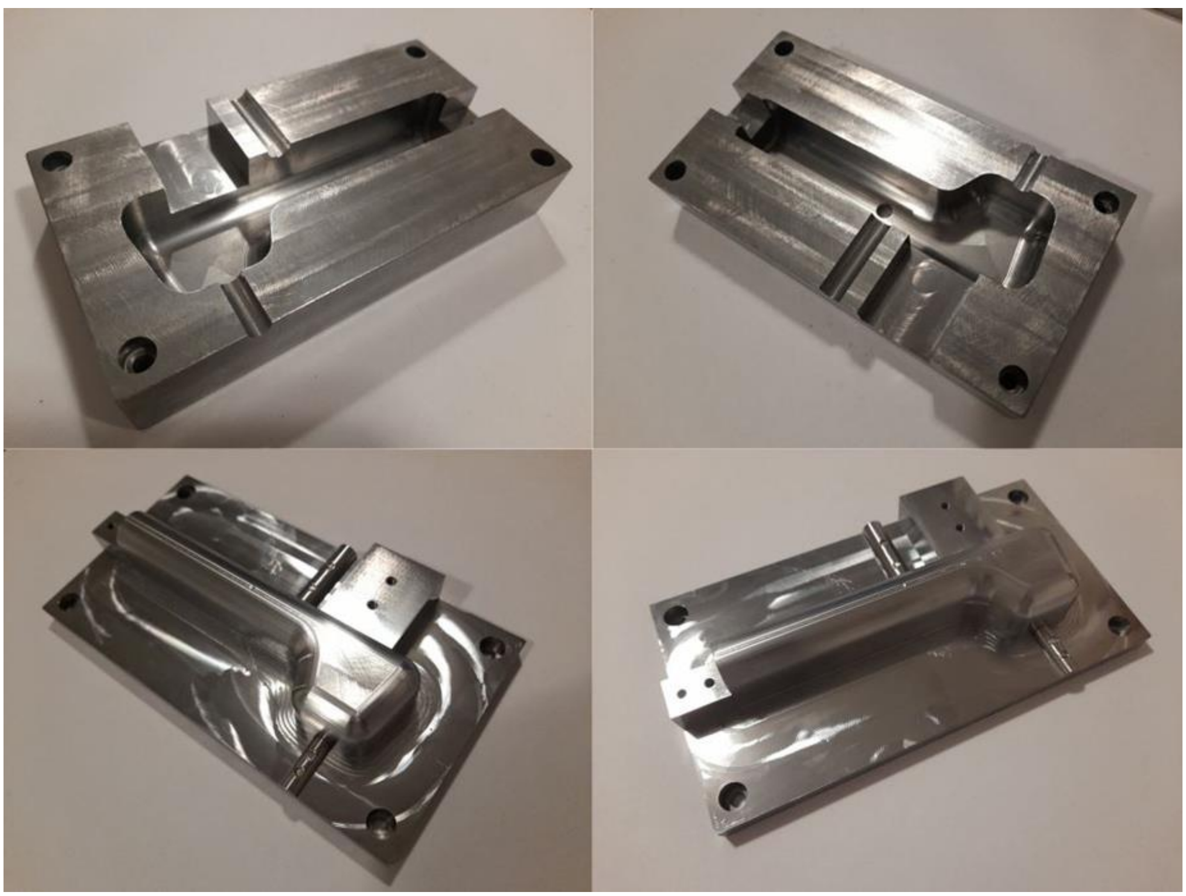

Figure 26. Photos taken to the mold after it was machined and assembled

When the quality of the injected plastic part was examined, first a visual inspection was made to determine if the part was cosmetically acceptable or not, then afterwards the mass of the injected part was measured with a precision scale, and finally with the help of a roughness meter the surface roughness was measured to be compared to the 27 µm design specification. Some photographs of the successfully injected part are shown in the figure 27.

Figure 27. Photos taken to the TPE Laprene® plastic part after it was injected by the IMM

Summarizing the plastic part manufacturing, the part resulted to be cosmetically acceptable, the surface roughness resulted to be better than the specified in the design, it was not possible to obtain precise measurements of the plastic part critical dimensions as it was made of a thermoplastic elastomer (TPE) which is known to have a very low elasticity modulus and it is considered a flexible material, however when the part was weighted the precision scale reported a value very close to the one specified in the design with a minimum difference of 0.01 grams. For further details of the plastic part quality criteria checklist see appendix D.

6. Cradle-to-gate LCA: A case study

The followed method for developing the cradle-to-gate LCA of the plastic part presented in this work is based on the ISO 14040 and 14044 standards [8] [9], and it comprises several activities to be performed in order to achieve the outcomes, figure 28 shows the LCA framework according to ISO.

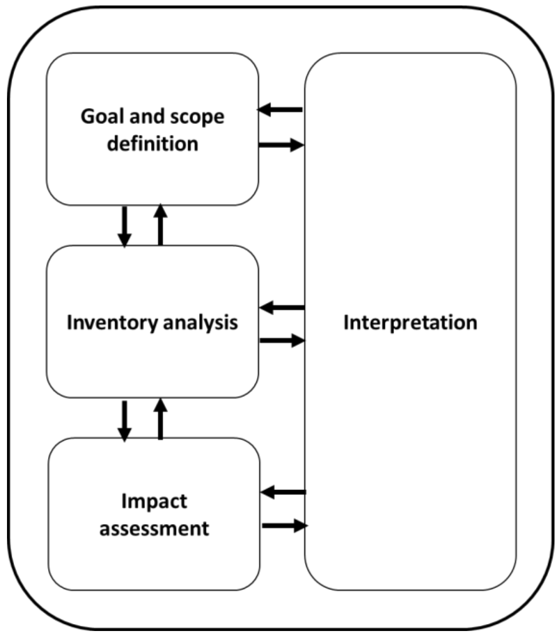

Figure 28. LCA framework according to ISO *[8] [9]*

6.1 Goal and scope definition

a. Goal definition

The LCA study will be developed only for research and academic purposes, the objective of this study is to conduct an LCA from a cradle-to-gate approach over a particular case study focused on the manufacture of an injected plastic part also considering the manufacture of the injection mold, then the study will consider two unitary manufacturing processes. This study will assess the life cycle from raw material production, passing through production of intermediate products, and it finishes with the production of an end product.

This LCA study will be conducted to find how much energy, materials, ancillary materials, and other resources are used for the case study, and how the manufacturing of a plastic part and its respective mold reverberates on the climate change impact category.

On the other hand, there is a special motivation as plastic injection is widespread in manufacturing sector and it will be outstanding and useful to know about the environmental impacts produced not only by the injection of the plastic part but also by the mold manufacturing.

The intended audience is the academic community, the results are intended to be of a public nature and not intended to make comparative assertions.

b. Scope definition

LCA Guidelines

The present study is developed according to the principles and framework of ISO 14040:2006 standard and it fulfills the requirements and guidelines contained in ISO 14044:2006 standard. These standards allow some kind of freedom regarding to the details of any LCA, then the general methodology need to be adapted to the particular problem of the plastic injected part and the mold manufacture, it is possible to achieve this by clearly defining the scope of the LCA.

Product system

It is shown the cradle-to-grave life cycle of a product system in the figure 29, on the left side and delimited by a dotted line it is possible to locate the system boundary of a cradle-to-gate study. As illustrated in the figure 29, the use phase and disposal or recycling phase are beyond the limits of the present study.

The product system to be studied is delimited from a cradle-to-gate approach and it spans the elements involved in the manufacture of a plastic part used for the assembly of the case of an infrared thermometer including the raw material extraction, material manufacture, the mold fabrication, and the plastic injection molding process of a part.

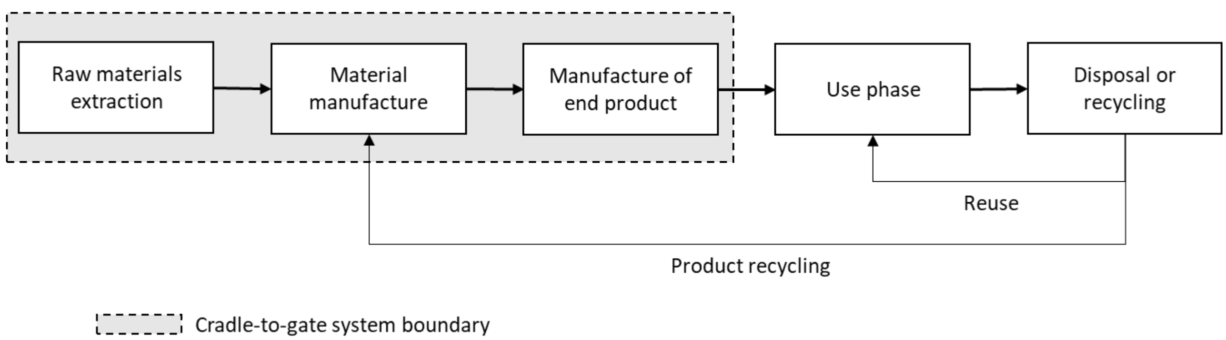

Figure 29. Cradle-to-grave life cycle of a product system

Functions of the system

The functions of the product system are two:

1. To produce a mold for plastic injection.

2. To produce a plastic part for the assembly of an infrared thermometer.

The graphical analysis of matter and energy shown in the figure 30 illustrates all the inputs and outputs of the product system to be studied.

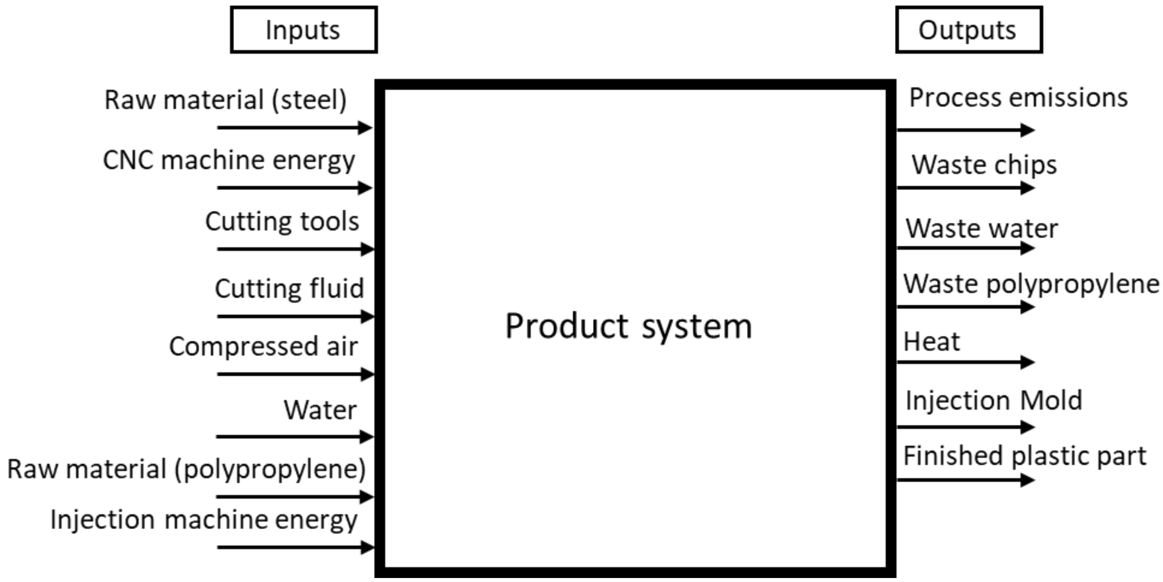

Figure 30. Analysis of matter and energy of the product system

Declared functional unit for the product system

One plastic part for the case of an infrared thermometer.

The mass of the part is 27 grams using polypropylene (PP) and 35.4 grams using Laprene® (TPE), the design specifications suggest an expected surface roughness of 27 µm or better, figure 31 and figure 32 illustrates the functional unit of the present LCA, for further details see appendix C.

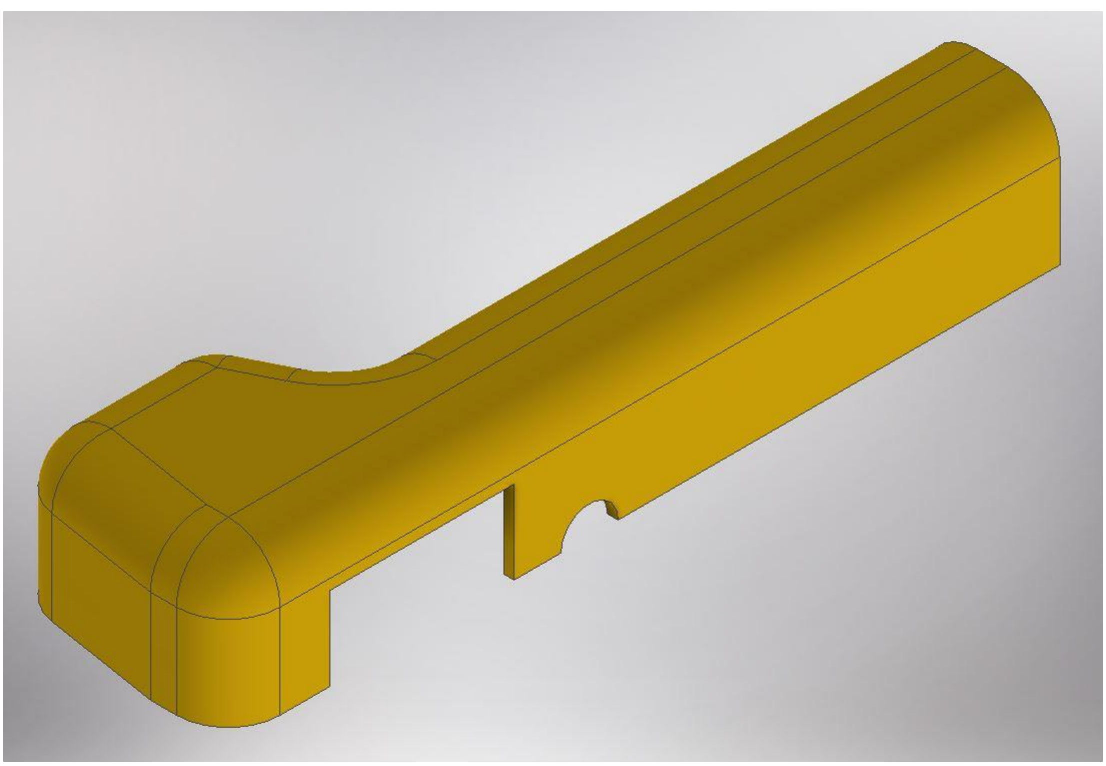

Figure 31. CAD model of the functional unit

The CAD model of the plastic part (the functional unit) for an infrared thermometer is shown in the figure 31 and figure 32, for further details as the main properties and specifications see appendix C.

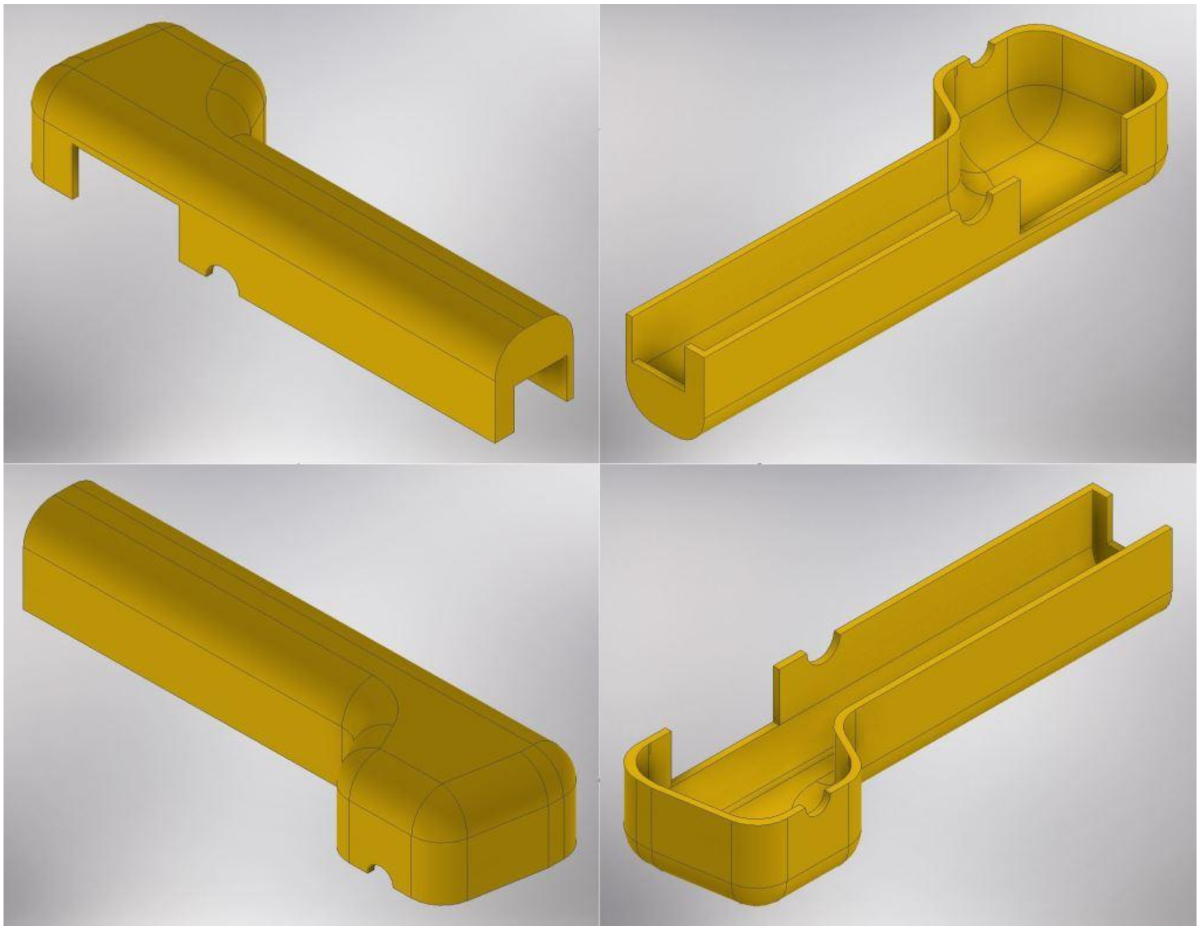

Figure 32. CAD model of the plastic part

Note: The whole case of the infrared thermometer is composed by 3 parts, the first one illustrated in figure 31 which is the right side of the case, the second one is the left side of the case which is precisely symmetric to the first one, finally the third one part is a cap for the case which allow the change of the infrared thermometer´s battery. The conducted LCA only evaluates the right side of the case shown in figure 31 and figure 32.

Description of the manufacturing processes

Mold machining

The CNC milling process is based on a CAD model design and the material selection, then tools, toolpaths and cutting parameters are configured in the CAM software to obtain the G & M code according to the workpiece material, subsequently the G & M code is loaded to the CNC machine, and it is run on the machine, finally the machine executes the code and the material is removed from the workpiece to leave the desired geometry of the mold. In addition to the raw material, cutting tools, and cutting fluid, the element to consider in the inventory for the present study will be the electrical energy from the machining process itself. The path to follow from CAD/CAM to the material removal process is shown in figure 33, while the figure 34 illustrate the used CNC machine.

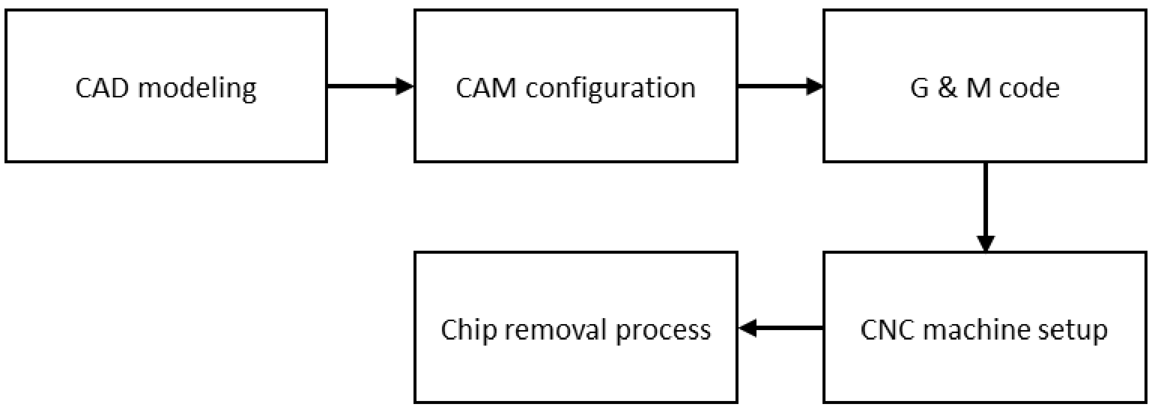

Figure 33. CAD/CAM and machining process flow

Figure 34. HAAS VF-1 CNC machine

Plastic injection

The plastic injection process starts with the heating of the polymeric material until the melting point is reached, then the material is injected inside the steel mold and the filling pressure is increased until holding pressure is reached, then the holding pressure is maintained to allow the material to conform appropriately, afterwards the mold is cooled, the part is plasticized and finally the solidified part is ejected. In addition to the raw material, all the electrical energy consumed by the phases of the plastic injection process shown in the figure 35 will be considered for the inventory. The figure 36 illustrates the Injection Molding Machine (IMM) used for the experiments.

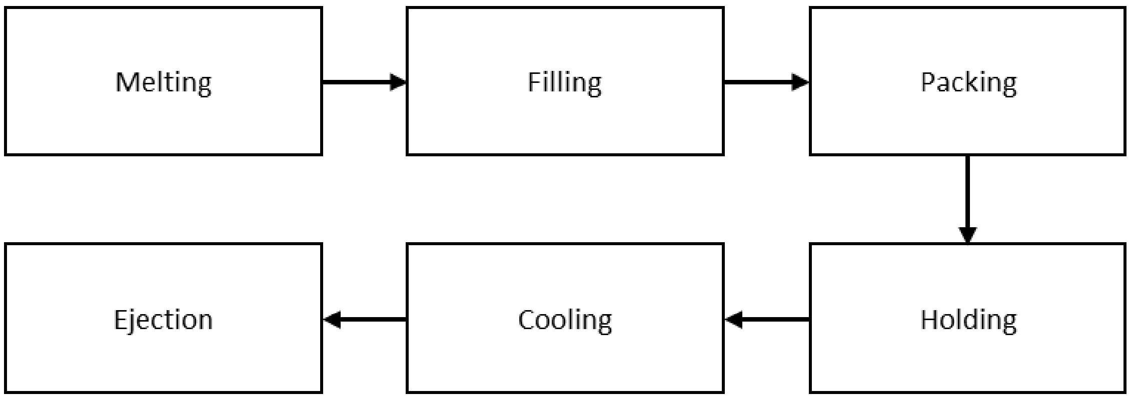

Figure 35. Plastic injection process flow

Figure 36. Demag Ergotech 50-270 pro

The system boundary

The product system boundary for this study includes inside the raw material extraction and production, the demanded energy, some ancillary materials, the mold machining process, and the injection molding process; the mold manufacture is included inside of the system boundary as it is fabricated specifically for the plastic part, this way it is considered that the inventory will not only depend upon polypropylene but also over the A36 steel plate used for the mold. The process flow and the product system boundary are shown in figure 37.

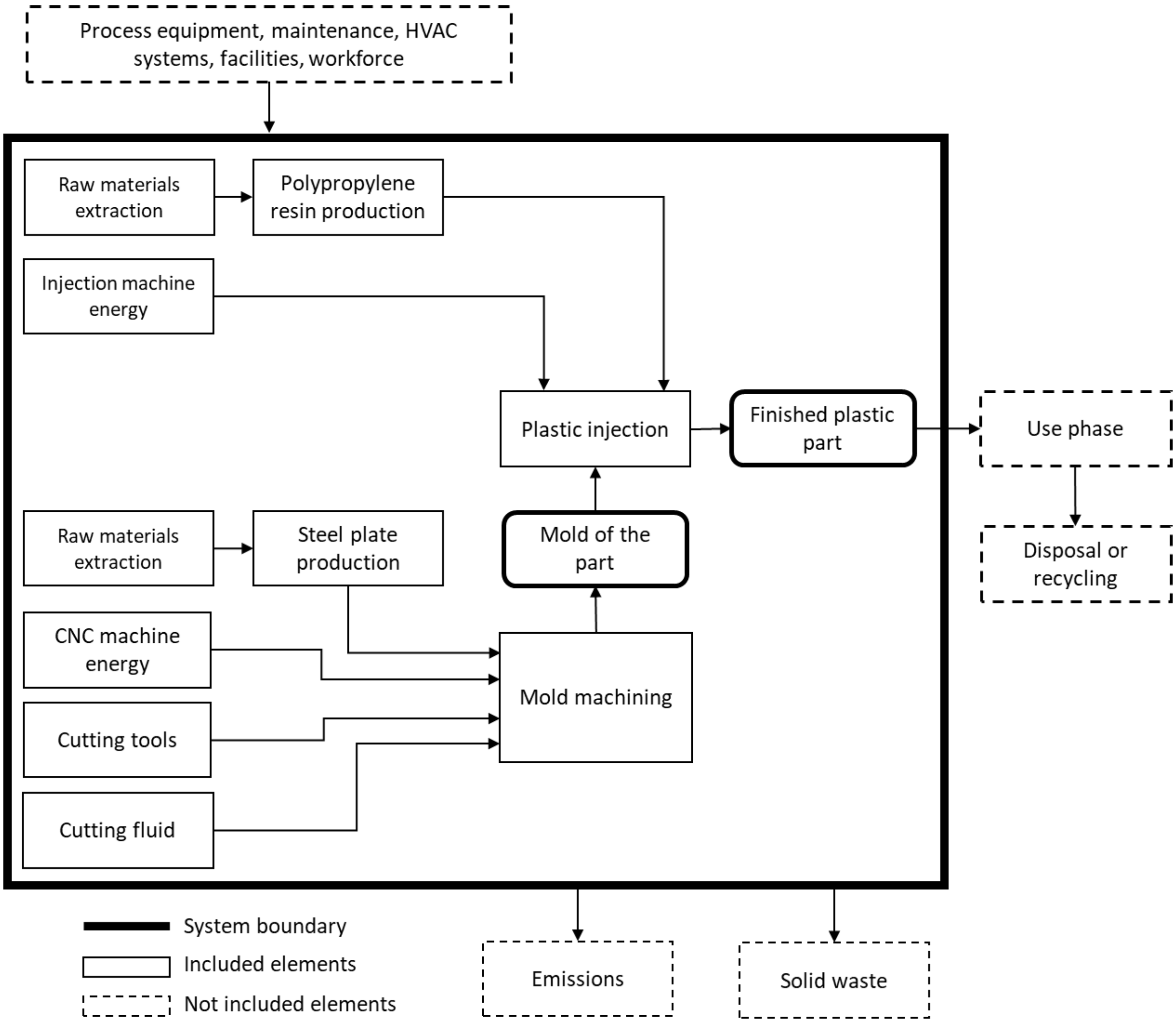

Figure 37. Process flow and product system boundary

Cut-off criteria

Outside of the system boundary remain the environmental burdens caused by:

- The machinery used for the manufacturing processes and its maintenance, raw material transportation, HVAC systems, laboratory infrastructure and facilities.
- The research personnel, administrative personnel, and workforce.

- The released emissions during manufacturing processes and the solid waste treatment.
- The water used to dilute the cutting fluid and the compressed air supply.
- Some miscellaneous materials used for cleaning the machinery, the oil that lubricates the machinery, and the hydraulic power unit oil.

Allocation procedure

According to the standard ISO 14044 it is required to state and carry out the allocation procedure to identify and locate the environmental burdens, wherein the different inputs and outputs of the system will be partitioned between its different functions. The allocation for this study is clearly illustrated in the figure 38 and the allocation procedure consists of five steps.

1. Identify the functions of the product system.

2. Identify the inputs and the outputs of the product system.

3. Identify the pre-product and the final product.

4. Allocate the inputs for each function accordingly.

5. Allocate the outputs for each function accordingly.

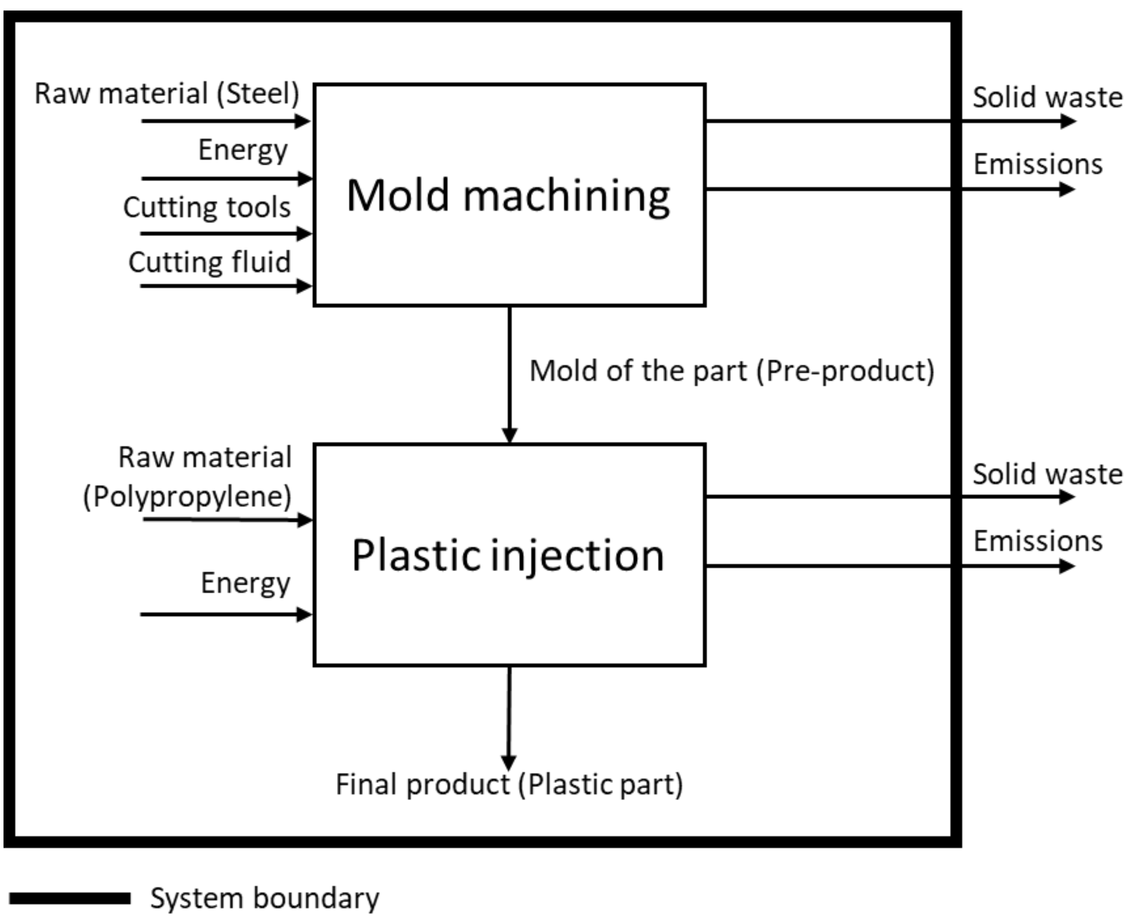

Figure 38. Allocation of the interconnected processes

Types of impacts and metrics

Impact category to assess: Climate change.

Category indicator: Infrared radiative forcing (Wm^{-2}).

Characterization model: Baseline model of 100-year time-horizon global warming potential (GWP) from the International Panel on Climate Change (IPCC) [40].

Characterization factor: Global warming potential (GWP_{100}) for GHG (kgCO_2eq / kg gas).

Inventory results: Amount of GHG emissions per functional unit.

Category indicator result (unit): kg CO_2e per functional unit.

Electrical energy units: Kilowatts-hour (kWh)

Electricity Carbon Emission Factor units: kg CO_2e / kWh

Interpretation to be used

- Significant issues based on the results of the LCI and LCIA phases of LCA will be identified.
- Conclusions, limitations, and recommendations will be declared.

Data sources

- Environmental Product Declaration (EPD) from a Mexican steel manufacturer (A36 steel).
- Direct measurements of electricity consumption from the CNC machine.
- Calculations to estimate the amount of carbon dioxide generated by cutting tools manufacturing.
- Calculations to estimate the amount of carbon dioxide generated by cutting fluid production.
- Cradle-to-gate LCA of polypropylene (PP) resin from a third party.
- Calculations to estimate the amount of carbon dioxide generated by the electricity consumption of the Injection Molding Machine (IMM).

Data quality requirements

- The measurements of electricity consumption during the CNC processes must consider only the processes itself, never considering the dead time of the CNC machine. This primary data measured directly from the machines ensure a trusted degree of accuracy for this part of the inventory.
- Third party providers of data for the LCI should be of a verified source or validated by national or international organizations.
- The study must demonstrate to have completeness. It is expected to measure and estimate almost the 100% of the mass flow, since the case study is focused on batch manufacturing.
- The study approaches, models, assumptions, and data sources must be shown transparently as far as possible in order to enable the reproducibility of the study.

Assumptions

- The used machine for the mold manufacturing is a Haas VF-1 and the used machine for the plastic injection molding is a Demag Ergotech pro 50-270.
- The A36 steel plate is purchased in the Metropolitan area of Mexico City, and it comes from national manufacturers.
- The polypropylene resin is purchased in the Metropolitan area of Mexico City, and it is supposed to be imported from American manufacturers.
- Previous LCAs studies addressing A36 steel plate manufacture and polypropylene (PP) resin production are used as other sources for the LCI.
- The third party LCAs used for the inventory are currently representative, the A36 steel LCA provide representative data from Mexico and the polypropylene LCA provide representative data from north America.
- The electricity consumed by the manufacturing laboratories is generated and distributed in Mexico by Federal Electricity Commission (CFE) and the declared emission factor of the National Electrical System in 2021 was 0.423 tCO_2e / MWh [21].
- The equivalent carbon emission factor used for accounting emissions from electricity is currently and geographically representative as it exemplifies data from Mexico´s National Electric System in 2021 [21].
- Energy data is collected on site for the CNC mold machining, then this information is added up to the Life Cycle Inventory.
- The adopted method for accounting emissions coming from the cutting fluid and the cutting tools is the one presented by Li et al. [17].
- The adopted mathematical model for accounting emissions coming from the electricity consumption of the Injection Molding Machine is the one presented by Elduque et al. [48].
- The information of the manufacturers of steel and polypropylene that were used as other sources for the LCI will be protected in anonymity since it is required.

Limitations

- The obtained data from measurements and calculations only apply to the specific used machines in the CNC mold manufacturing and the plastic injection molding, when other machines are used for the same experiments, there is no guarantee of reproducibility, nevertheless the obtained results should be similar.
- As the present study focuses over batch manufacturing processes, neither the described procedure for the inventory analysis nor the one for the impact assessment would be applicable for continuum flow processes.
- Since the third-party studies and the Electricity Carbon Emission Factor that are used for the inventory and the scope, define a specific date and a specific region for the study, it will not be possible to obtain the same results in a different date or geographical region.

6.2 Life Cycle Inventory Analysis (LCI)

The execution of the LCI involves several activities, it is proposed to start from the manufacturing experiments, then to collect and calculate data, and finally to allocate the environmental burdens to their corresponding functions, the pathway to be followed is illustrated in figure 39.

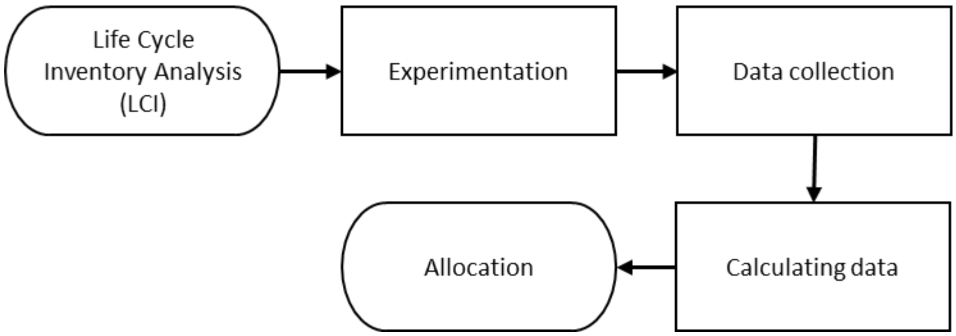

Figure 39. Life Cycle Inventory Analysis (LCI) pathway

Raw material inputs for mold manufacturing

The steel plates used for the CNC machined mold manufacturing are made of A36 steel, according to MatWeb-Material property data [51], the density of this material is 7.80 g/cm^3. There were used 2 steel plates of the same size, the first one for manufacturing the core of the mold and the second one to fabricate the cavity of the mold. The initial dimensions of the 2 steel plates are shown in the table 10, the mold also includes four inserts, these inserts are made of the same material as the mold. The initial dimensions of the 4 workpieces material used to fabricate the mold inserts are also shown in the table.

Table 10. Core, cavity, and mold inserts workpieces, dimensions and volumes

Initial workpiece dimensions (mm) and volumes (cm^3)					
Part	Width	Height	Diameter	Length	**Volume**
Mold core	114	39	***	209	**929.214**
Mold cavity	114	39	***	209	**929.214**
Circular insert #1	***	***	12.7	30	**3.8**
Circular insert #2	***	***	12.7	55	**6.967**
Rectangular insert #1	19	19	***	30	**10.83**
Rectangular insert #2	38.1	19	***	55	**39.814**

A third party LCA study addressing the A36 steel plate manufacturing including raw materials, transportation, and manufacturing was reviewed. This study indicates that the fabrication of 1000 kg of A36 steel plate produce the release of 1053 kg CO_2e.

This previous assertion gives the guideline to calculate the mass of equivalent carbon dioxide released to the atmosphere to extract, transport and manufacture the steel plates used for the mold manufacturing. The table 11 allows to make out the volume and mass each part embodies, considering initial workpiece material, additionally it includes the total released equivalent carbon emissions.

Table 11. Corresponding volume, mass, and carbon emissions

Equivalent carbon emissions released by the steel plate production					
Part	Original volume (cm^3)	Density (g/cm^3)	Mass (kg)	CEF_Steel (kg CO_2 e/kg)	CE_Steel (kg CO_2 e)
Mold core	929.214	7.8	7.248	1.053	7.632
Mold cavity	929.214	7.8	7.248	1.053	7.632
Circular insert #1	3.8	7.8	0.030	1.053	0.031
Circular insert #2	6.967	7.8	0.054	1.053	0.057
Rectangular insert #1	10.83	7.8	0.084	1.053	0.089
Rectangular insert #2	39.814	7.8	0.311	1.053	0.327
Total results	**1919.839**	**7.8**	**14.975**	**1.053**	**15.768**

The calculation to obtain the equivalent carbon dioxide emissions released by the steel production is shown below in the equation 3.

$$\frac{X\ (Kg\ CO_2e)}{14.975\ (kg)} = \frac{1053\ (Kg\ CO_2e)}{1000\ (kg)}$$ ***Equation 3***

$$\frac{X\ (Kg\ CO_2e)}{1} = \frac{1053\ (kg\ CO_2e) * 14.975\ (kg)}{1000\ (kg)}$$

$$X = 15.768\ kg\ CO_2\ e$$

This literally means that when producing 14.975 kg of A36 steel plate, it is released to the atmosphere and the environment an amount of 15.768 kg CO_2e. The table 12 show the mass difference between the original workpieces and the machined parts.

Table 12. Mass and volume of the parts, before and after the machining process

Mass and volume before and after machining the workpiece				
Part	Original volume (cm^3)	Final volume (cm^3)	Original mass (kg)	Final mass (kg)
Mold core	929.214	345.132	7.248	2.692
Mold cavity	929.214	616.721	7.248	4.810
Circular insert #1	3.8	0.541	0.030	0.004
Circular insert #2	6.967	2.017	0.054	0.016
Rectangular insert #1	10.83	5.292	0.084	0.041
Rectangular insert #2	39.814	25.879	0.311	0.202
Total results	**1919.839**	**995.581**	**14.975**	**7.766**

Energy consumption

With the purpose of ensuring the quality and the truthfulness of the data acquisition, a procedure for making the measurements was documented, these guidelines can be found in the appendix A of this thesis. This procedure is followed in each and every one of the measurements. By making the data acquisition always in the same manner it is added consistency to the obtained measurements.

The treatment of the acquired data is important to avoid measuring energy that does not belong to the process itself (say idle state of the machines), the measurements will begin just before initiating the processes and will finish just after ending the processes, then afterwards the measurement lapses that remain outside the duration of the process will be discarded from the analysis.

It is possible to identify the beginning of the process by the presence of an instantaneous jump in power consumption preceded by a horizontal line, the end of the process is limited by a sudden decrease in power consumption followed by a horizontal line, in the graph it is possible to discern the idle time of the machine as the horizontal straight lines at the beginning and at the end as illustrated in the figures 40 and figure 41.

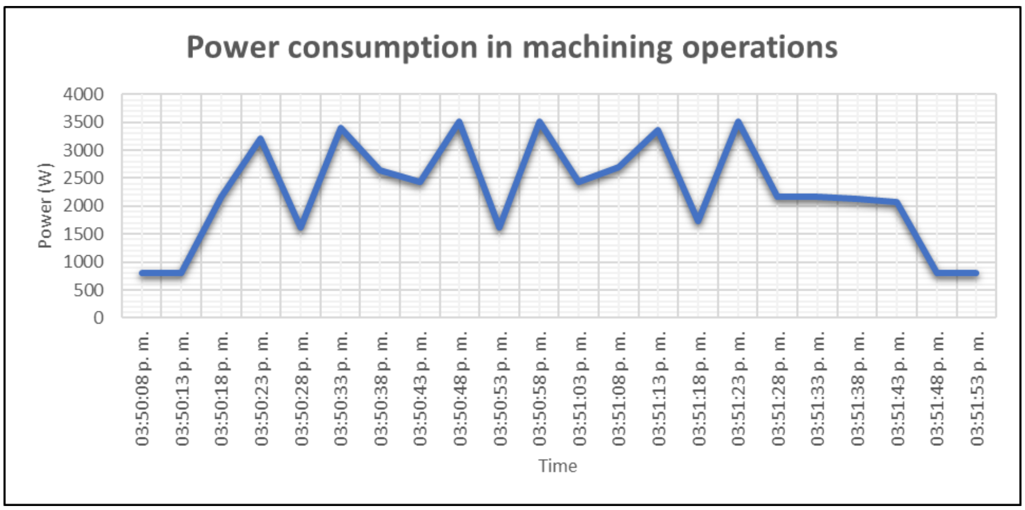

Figure 40. Power consumption of a face milling operation including idle time

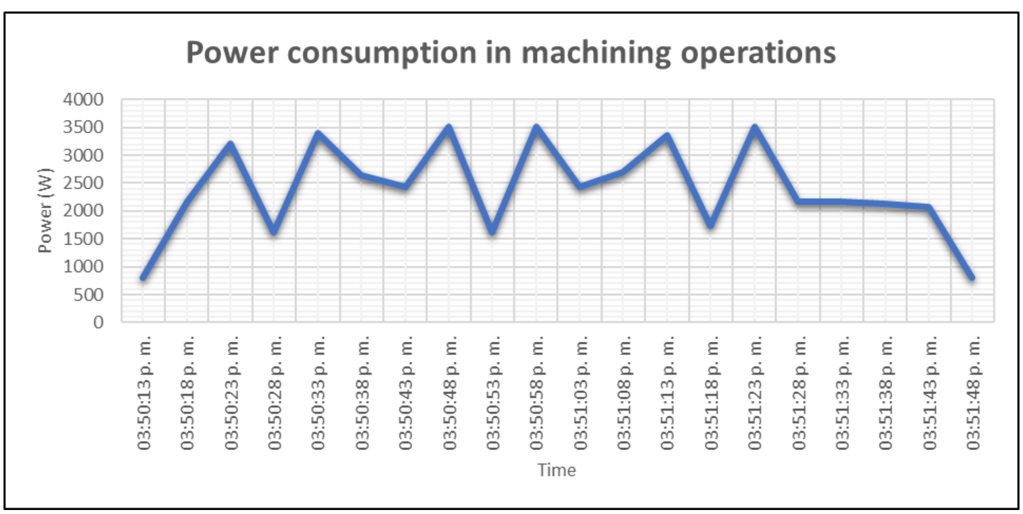

Figure 41. Power consumption of a face milling operation not including idle time

CNC machine energy consumption

Below is shown in tables 13, 14, 15, and 16, a summary of the electrical energy consumption involved in the CNC mold machining operations and its corresponding equivalent carbon dioxide emissions. Finally, the table 17 illustrates the whole machining time, energy consumption, and the total emissions indirectly released by the injection mold manufacturing.

Table 13. Energy consumption and corresponding carbon emissions in pre-machining operations

Pre-machining operations developed on raw material				
Machining Operation	Machining time	Active energy consumption (Wh)	CEF_electricity (kg CO2e/KWh)	CE_electricity (kg CO2e)
Face milling 1	01m:30s	65.125	0.423	0.028
Face milling 2	01m:30s	65.125	0.423	0.028
Face milling 3	01m:30s	65.125	0.423	0.028
Face milling 4	02m:10s	80.791	0.423	0.034
Face milling 5	04m:25s	141.25	0.423	0.060
Face milling 6	01m:30s	65.125	0.423	0.028
Face milling 7	05m:20s	242	0.423	0.102
Face milling 8	01m:50s	71.75	0.423	0.030
			Total	**0.337**

Table 14. Energy consumption and corresponding carbon emissions in mold core machining

Mold core machining				
Machining Operation	Machining time	Active energy consumption (Wh)	CEF_electricity (kg CO2e/KWh)	CE_electricity (kg CO2e)
Contour and pocket 1	56m:20s	3585.558	0.423	1.517
Finishing scallop 1	01h:06m:55s	3346.866	0.423	1.416
Center drilling	04m:01s	197.916	0.423	0.084
Round holes 1 - 3/16"	04m:54s	252.433	0.423	0.107
Round holes 2 - 1/4"	01m:34s	78.658	0.423	0.033
Counterbored holes 1	00m:55s	47.666	0.423	0.020
			Total	**3.176**

Table 15. Energy consumption and corresponding carbon emissions in mold cavity machining

Mold cavity machining				
Machining Operation	Machining time	Active energy consumption (Wh)	CEF_electricity (kg CO2e/KWh)	CE_electricity (kg CO2e)
Roughing pocket 1	03m:41s	247.25	0.423	0.105
Roughing pocket 2	00m:51s	61.141	0.423	0.026
Pre-finishing pocket 3 and 4	00m:47s	47.625	0.423	0.020
Finishing pocket 5 and 6	01m:16s	91.383	0.423	0.039
Roughing pocket 7 (16 mm)	11m:08s	791.816	0.423	0.335
Roughing pocket 8 (3/8")	04m:12s	200.975	0.423	0.085
Roughing pocket 9 (6mm)	19m:35s	939.65	0.423	0.397
Pre-finishing pocket 10 and 11	37m:03s	1904.133	0.423	0.805
Roughing pocket 14	20m:38s	1061.208	0.423	0.449
Roughing pocket 14-2	01m:02s	55.475	0.423	0.023
Finishing pocket 12 and 13	02h:19m:18s	6857.791	0.423	2.901
Roughing pocket 15	04m:41s	242.008	0.423	0.102
Finishing scallop 1	08m:40s	436.008	0.423	0.184
Center drilling	01m:22s	68.625	0.423	0.029
Round holes 1 - 3/16"	04m:58s	221.797	0.423	0.094
Round holes 2 - 1/4"	04m:58s	246.441	0.423	0.104
Counterbored holes 1	00m:55s	47.666	0.423	0.020
			Total	**5.719**

Table 16. Energy consumption and corresponding carbon emissions in mold inserts machining

Mold inserts machining				
Machining Operation	Machining time	Active energy consumption (Wh)	CEF_electricity (kg CO2e/KWh)	CE_electricity (kg CO2e)
Circular insert #1	20m:00s	834	0.423	0.353
Circular insert #2	20m:00s	834	0.423	0.353
Rectangular insert #1	20m:00s	834	0.423	0.353
Rectangular insert #2	20m:00s	834	0.423	0.353
			Total	**1.411**

Table 17. Total energy consumption and corresponding carbon emissions in mold machining

Total equivalent carbon emissions released by the electricity production used in the CNC machine				
Machining Operation	Machining time	Active energy consumption (Wh)	CEF_electricity (kg CO2e/KWh)	CE_electricity (kg CO2e)
Total	**08h:19m:29s**	**25162.38**	**0.423**	**10.644**

Cutting tools

In order to estimate the carbon emissions caused by the production of cutting tools $\mathrm{CE_{tool}}$, it is required previously to compute the Carbon Emission Factor of the cutting tool materials $\mathrm{CEF_{tool}}$, both carbide and HSS tools. It is important to note that only perishable tools will be considered. The inserts for milling are made of cemented tungsten carbide, all the generic tools used are made of M2 High Speed Steel.

Particularly in the case of all CoroMill® Plura end mills the steel which the tool body is made of, is unknown because it is an industrial secret, and it is not publicly available information. It was reviewed that end mill shanks and cutting tools are usually made of AISI D3 steel, AISI M3-2 or AISI M2, these three alloys are high carbon content steels and contain above 4% of chromium, due to the lack of information and for practical purposes these CoroMill® Plura end mills will be assumed to be made of HSS M2 which would not imply a big difference in the results of the inventory due to the similarity in composition of the mentioned steels.

Carbon emission factor for cemented tungsten carbide cutting tools

According to Rajemi et al. [52] the required energy for manufacturing a cemented carbide insert weighting 9.5 g is 5.3 MJ, it is equivalent to say that every 1 kg of tool material accounts by 557.894 MJ of energy. Moreover, in order to obtain 1 kg of cemented tungsten carbide from scratch it is required 400 MJ/kg of embodied tool material energy. The electricity Carbon Emission Factor of the National Electrical System in Mexico 2021 was 0.423 $\mathrm{tCO_2e/MWh}$, say 0.423 $\mathrm{kgCO_2e/kWh}$.

As 1 kWh=3.6 MJ, the $\mathrm{CEF_{tool}}$ is obtained as follows:

$$CEF_{C\ tool} = 0.423\ kgCO_2e/kWh\ X\ \frac{(1kWh)}{(3.6\ MJ)}\frac{(957.894MJ)}{(1)} \quad \textbf{\textit{Equation 4}}$$

$\mathrm{CEF_{C\ tool}}$= 112.552 $\mathrm{kg\ CO_2e/kg}$

Carbon emission factors for M2 HSS cutting tools

According to Angioletta et al. the required energy for HSS tools manufacturing is 129.1 MJ/kg, moreover 9.25 Kg of CO_2 emissions are released to obtain 1 Kg of High-Speed Steel (HSS) from scratch [53]. Then it is possible to compute the corresponding CEF of the HSS tools as follows:

$$CEF_{HSS\ tool} = 0.423\ kgCO_2e/kWh\ X\ \frac{(1kWh)}{(3.6\ MJ)}\frac{(129.1\ MJ)}{(1)} + 9.25\ kg\ CO_2e \quad \textbf{\textit{Equation 5}}$$

$\mathrm{CEF_{HSS\ tool}}$= 15.169 $\mathrm{kg\ CO_2e}$ + 9.25 $\mathrm{kg\ CO_2e}$

$\mathrm{CEF_{HSS\ tool}}$= 24.419 $\mathrm{kg\ CO_2e/kg}$

Now that the Carbon Emission Factors of the cutting tool materials have been obtained, then it is possible to use the formula proposed by Li et al. [17] to calculate the equivalent carbon dioxide emissions released by the entire production of the cutting tools. Where t_c is the cutting time, T_{tool} is the tool life, $\mathrm{CEF_{tool}}$ is the Carbon Emission Factor of the tool material, and $\mathrm{W_{tool}}$ is the mass of the tool, the used formula is shown below.

$$CE_{tool} = \frac{t_c}{T_{tool}}\ X\ CEF_{tool}\ X\ W_{tool} \quad \textbf{\textit{Equation 6}}$$

In order to obtain the required geometries in the material removal processes, several cutting tools are used for the mold machining, the used cutting tools, quantities and the corresponding carbon emissions are listed in the table 18, this table also display the total released emissions during the production of all the cutting tools.

Table 18. Equivalent carbon emissions caused by tools production

Equivalent carbon emissions released by cutting tools production					
Quantity	Tool	Material	Weight (g)	CEF_tool (kg CO2e/kg)	CE_tool (kg CO2e)
5	CoroMill® 345 insert for milling	Tungsten Carbide	9.15	112.552	5.149
1	CoroMill® Plura 16mm end mill	High Speed Steel	245.44	24.419	5.993
1	Generic M2 HSS Ball end mill-1/2”	High Speed Steel	63.83	24.419	1.559
1	YG-1 Ball end mill-1/4" extra long	High Speed Steel	40.01	24.419	0.977
1	Generic M2 HSS Flat end mill-3/8”	High Speed Steel	30.37	24.419	0.742
1	Generic M2 HSS Flat end mill-6mm	High Speed Steel	26.75	24.419	0.653
1	YG-1 Center drill #3 extra long	High Speed Steel	20.69	24.419	0.505
1	Generic M2 HSS Drill-3/16”	High Speed Steel	8.5	24.419	0.208
1	Generic M2 HSS Drill-1/4”	High Speed Steel	16.69	24.419	0.408
1	Generic M2 HSS Flat end mill-7/16”	High Speed Steel	34.46	24.419	0.841
				Total	**17.035**

Cutting fluid

The used cutting fluid is a mixture of mineral oil diluted in water at a proportion of 5%, the machine tank was filled with a total of 150 liters of cutting fluid where 7.5 liters is mineral oil, and the remaining 142.5 liters is water. In order to obtain the equivalent carbon dioxide emissions of the cutting fluid, it is going to be used the following formula proposed by Li. et al. [17]:

$CE_{Oil} = CEF_{Oil} \text{ X } (CC + AC)$ ***Equation 7***

where:

$\mathrm{CE_{Oil}}$ = Carbon emissions of the cutting fluid production

$\mathrm{CEF_{Oil}}$ = Carbon Emission Factor of the cutting fluid

CC = Initial volume of cutting fluid

AC = Additional volume of cutting fluid

It is taken valid the assumption that the used mineral oil has much similar properties to the exemplified by Li. et al. where the Carbon Emission Factor of the mineral oil production ($\mathrm{CEF_{Oil}}$) is 2.85 $\mathrm{kgCO_2/L}$, then it is possible to calculate the carbon emissions of the mineral oil, as follows:

$\mathrm{CE_{Oil}}$= 2.85 $\mathrm{kg\ CO_2e/L}$ X (7.5 L + 0 L)

$\mathrm{CE_{Oil}}$= 21.375 $\mathrm{kg\ CO_2}$

The summary of the obtained estimation of equivalent carbon dioxide emissions indirectly caused by the cutting fluid is shown in the table 19.

Table 19. Carbon emissions corresponding to the cutting fluid

Equivalent carbon emissions released by cutting fluid production			
Cutting fluid (5%)	Volume (L)	CEF_Oil (kg CO_2e /L)	CE_Oil (kg CO_2e)
OAKFLO DSY 910	**7.5**	**2.85**	**21.375**

The different contributors of equivalent CO_2 and their results are summarized in the table 20, it is also possible to observe the total emissions attributed to the CNC mold machining.

Table 20. Total equivalent carbon emissions in mold machining

Total equivalent carbon emissions indirectly released in mold machining	
Contribution	Carbon Emissions (kg CO_2e)
Steel plate production	15.768
CNC machine energy	10.644
Cutting tools	17.035
Cutting fluid	21.375
Total	**64.822**

LCI of the plastic injected part

A third party LCA study was reviewed, this study address virgin Polypropylene resin production including cradle-to-incoming materials and production of the virgin resin. This study indicates that during the production of 1000 kg of virgin Polypropylene resin are released 1548 kg CO_2e.

Then it is possible to use this previous assertion as guideline for calculate the mass of equivalent CO_2 released to the atmosphere to extract and produce the polypropylene used for each plastic injected part, the calculations are shown below and the results are presented in the table 21.

$$\frac{X\ (kg\ CO_2e)}{0.027\ (kg)} = \frac{1548\ (kg\ CO_2e)}{1000\ (kg)} \quad \textbf{\textit{Equation 8}}$$

$$X\ (kg\ CO_2e) = \frac{1548\ (kg\ CO_2e) * 0.027\ (kg)}{1000\ (kg)}\ ,\ X = 0.042\ kg\ CO_2e$$

Table 21. Equivalent carbon emissions corresponding to polypropylene production

Equivalent carbon emissions released by the polypropylene production (Per functional unit)					
Part	Volume (cm^3)	Density (g/cm^3)	Mass (kg)	CEF_Polypropylene (kg CO_2e/kg)	CE_Polypropylene (kg CO_2e)
One plastic part	**30**	**0.9**	**0.027**	**1.548**	**0.042**

According to Elduque et al. [48], it is possible to calculate the Specific Energy Consumption (SEC) per produced part in any Injection Molding Machine (IMM) with high level of accuracy, for this purpose they developed an empirical mathematical model which is applicable to different types and sizes of

IMM, this model offers an alternative solution whenever it is not possible to measure the energy consumption. Due to the conditions of the electrical supply system of the IMM, it was not possible to record the energy consumption during the plastic injection process, for that reason the empirical model proposed by Elduque et al. will be used in order to obtain the consumed energy in the injection of one plastic part, which is the functional unit of the present LCA study.

Before the use of the empirical model shown below, it is necessary to calculate some factors as the percentage of utilization of the IMM (η), the Correction Factor of the Throughput (CFT) and the Correction Factor of the Polymer (CFP). The empirical model is illustrated by the equation 9.

$$SEC = (7.5 - (5 \times (E/100) \times \frac{CFT\hat{}0.15}{CFP\hat{}0.1} \times (\eta)\hat{}0.5 \quad \textbf{\textit{Equation 9}}$$

$$\eta = (w \times 100)/(\rho \times V_{max})$$

$$\mathrm{CFT} = (\mathrm{w} \times 3.6/\mathrm{tc})/0.0052 \times \mathrm{Fc}$$

$$\mathrm{CFP} = (\mathrm{Ce} \times (\mathrm{Ti} - \mathrm{Ta}))/350.255$$

In order to make the necessary calculations, all the required values to substitute in the equations presented above are shown in the table 22.

Table 22. Factors used to calculate the SEC per injected kg of polypropylene

Empirical model factors		
Symbol	Factor	Substitution value
E	Efficiency of the IMM	80%
w	Weight of the part	27 g
ρ	Material´s density	0.9 g/cm3
V_{max}	Maximum injection volume	144 cm3
t_c	Cycle time	65 s
F_c	Clamping force	15000 kN
Ce	Material´s specific heat	1.5 kJ/kg·K
T_i	The injection temperature	523.15 K
T_a	The ambient temperature	298.15 K

Then the model used to calculate the Specific Energy Consumption (SEC) per injected kilogram of polypropylene is shown below, the Correction Factor of the Throughput (CFT) and the Correction Factor of the Polymer (CFP) have been substituted in the equation 9.

$$\mathrm{SEC} = (7.5 - (5 \times (\mathrm{E}/100) \times \frac{((\mathrm{w} \times 3.6/\mathrm{tc})/(0.0052 \times \mathrm{Fc}))\hat{}0.15}{(\mathrm{Ce} \times (\mathrm{Ti} - \mathrm{Ta})/350.255)\hat{}0.1} \times (\mathrm{w} \times 100/(\rho \times \mathrm{Vmax}))\hat{}0.5$$

SEC = 425.303 Wh per produced kg

Then afterwards these calculations, it resulted that the Specific Energy Consumption per injected kg is SEC = 425.303 Wh. As the plastic part, say the functional unit of the LCA only weights 27 grams, the 425.303 Wh value will be multiplied by 0.027, then it results the active energy consumption during the injection of one plastic part, this is **SEC = 11.483 Wh per produced part.**

A summary of the consumed energy and the corresponding indirectly released emissions during the injection of one plastic part is presented in the table 23.

Table 23. Equivalent carbon emissions corresponding to electricity consumption in IMM

Equivalent carbon emissions released by the electricity production used in the Injection Molding Machine (Per functional unit)				
Injection Molding Process	Cycle time (s)	Active energy consumption (Wh)	CEF_electricity (kg CO_2e /KWh)	CE_electricity (kg CO_2e)
One injected plastic part	**65**	**11.483**	**0.423**	**0.005**

The table 24 shows the equivalent carbon dioxide emissions attributed to the polypropylene production, the IMM energy consumption, and the total which represent the emissions that correspond to the function 2 of the product system, say to produce the plastic part.

Table 24. Equivalent carbon emissions corresponding to the production of one plastic part

Total equivalent carbon emissions indirectly released by the production of a plastic part	
Contribution (per functional unit)	**Carbon Emissions (kg CO_2e)**
Polypropylene production	0.042
Injection Molding Machine energy	0.005
Total	**0.047**

Allocation

According to the stated allocation procedure previously declared in the scope definition, for the interconnected manufacturing processes the product system involves inputs, outputs, functions, one pre-product and the final product. The table 25 and table 26 show the allocation of the environmental burdens to the functions of the product system, allowing to discern between inputs and outputs.

Table 25. Allocation of environmental burdens to mold machining

Environmental burdens allocated to function 1. Mold machining			
Inputs	Carbon Emissions (kg CO_2e)	Output (Pre-product)	Carbon Emissions (kg CO_2e)
Steel plate production	15.768	Mold of the part	64.822
CNC machine energy	10.644		
Cutting tools	17.035		
Cutting fluid	21.375		

Table 26. Allocation of environmental burdens to plastic injection

Environmental burdens allocated to function 2. Plastic injection			
Inputs	Carbon Emissions (kg CO_2e)	Output (Final product)	Carbon Emissions (kg CO_2e)
Mold of the part	64.822	(PP) Plastic part	64.869
Polypropylene production	0.042		
IMM energy	0.005		

In the scope definition of the present LCA study, it was declared the functional unit as one plastic part for the case of an infrared thermometer, then this functional unit is a reference to measure the category indicator result, which is measured in kg CO_2e per functional unit. Subsequently, the obtained kg CO_2e per functional unit are used to calculate the Global Warming Potential (GWP_{100}).

The table 27 shows the allocation of the environmental burdens to the pre-product and the final product per functional unit (fU), it must be highlighted that the 64.869 kg CO_2e per fU embodies the emission coming from the mold and the plastic part but this value represent the emissions accumulated to obtain the final product.

Table 27. Allocation of environmental burdens to pre-product and final product

Environmental burdens allocated to Pre-product and final product (per functional unit)	
Pre-product and final product	Carbon Emissions (kg CO_2e)
Mold of the part	64.822
(PP) Plastic part	0.047
Total	**64.869**

6.3 Life Cycle Impact Assessment (LCIA)

Selection of impact categories, category indicator, and characterization model

As it was stated in the scope definition, it will only be assessed the climate change impact category. Table 28 illustrates the selected characterization model, the category indicator, the characterization factor, the expected results from the inventory, and the category indicator result which is quite relevant to assess and make the impacts of any product quantifiable. This table comprises essential information of a specific impact category and it helps to identify and understand where the environmental metrics comes from.

Table 28. Statement of indicators, models, and factors for climate change

Indicators, characterization model, and factors used to assess the impact category: Climate change
Characterization model: Baseline model of 100-year time-horizon global warming potential (GWP) from the International Panel on Climate Change (IPCC) [40].
Category indicator: Infrared radiative forcing ($\mathrm{Wm^{-2}}$).
Characterization factor: Global warming potential ($\mathrm{GWP_{100}}$) for GHG (kg$\mathrm{CO_2}$eq / kg gas).
Inventory results: Amount of GHG emissions per functional unit.
Category indicator result (unit): kg $\mathrm{CO_2}$e per functional unit.

Environmental relevance of the category indicator: Infrared radiative forcing ($\mathbf{Wm^{-2}}$)

The infrared radiative forcing is the change in energy flux inside or outside the atmosphere produced by natural or human activities as it is the manufacture of any product which involves the use of energy, materials and the direct or indirect release of emissions.

The radiative forcing represents a mean for potential effects on the climate change, the earth will experience warming (positive radiative forcing) if it receives more energy than is radiated into space, conversely, the earth will experience cooling (negative radiative forcing) if it radiates more energy than is received. The equilibrium of a net-zero radiative forcing is susceptible to change for various reasons, as it is the atmospheric concentration of GHGs and aerosols, the reflectivity of gases and clouds, and the intensity level of solar radiation.

Assignment of the LCI results to the selected impact categories (Classification)

Table 29 shows specifically which are the LCI results assigned to the climate change impact category. It was possible to assign LCI results to more than one impact category, but this research work only focuses on one of them, namely “Climate change”.

Table 29. Assignment of LCI results to the impact categories

Assignment of the LCI results to the selected impact category	
LCI results	**Impact category**
Amount of GHG emissions per functional unit	Climate change

Calculation of category indicator results

This part of the LCIA is well known as characterization but sometimes it is also referred as the LCIA profile of the product system. Table 30 shows the amount of $\mathrm{CO_2}$e per functional unit (fU) assigned directly to the climate change impact category.

Table 30. Indicator results assigned to the impact category

Category indicator results assigned to the selected impact category relative to the functional unit	
Category indicator result	**Impact category**
64.869 kg $\mathrm{CO_2}$e / fU	Climate change

According to the Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [54] the carbon dioxide referred as a specie, stands out as a reference to the rest of the species (the rest of the gases), the used characterization model is $\mathrm{GWP_{100}}$ and this way the equivalent CO_2 has GWP = 1, then $\mathrm{GWP_{100}}$ for this LCIA is directly obtained by multiplying the category indicator result times GWP as shown in the table 31.

Table 31. Global Warming Potential in 100-year time horizon per functional unit

Global Warming Potential relative to the category indicator results	
Category indicator results	$\mathbf{GWP_{100}}$
64.869 kg CO2e / fU	64.869 kg

Identification of the category endpoints

The identified category endpoints are shown below:

- Atmosphere: temperature
- Steric sea level
- Ocean heat content change

The IPCC in the 5th assessment report (2013) references the outstanding work of Joos et al. [55] which is used to estimate the Absolute Global Warming Potential (AGWP) and the Absolute Global Temperature change Potential (AGTP) along different time horizons taking as reference an emission pulse of 100 GtC added to an atmospheric concentration of 389 ppm, it is important to make it clear that 1 GtC = 3.667 GtCO_2 as it is stated in the IPCC (2013): Summary for Policymakers [56].

The obtained category indicator result was 64.869 kg CO_2e / fU, then with this value will be calculated how much it influences over the surface air temperature, sea level rise, and ocean heat content change.

Response in global mean surface air temperature (°C)

According to Joos et al. [55] the produced change in the global mean surface air temperature corresponds to a specific mean value of AGTP_{100}, for CO_2 is AGTP_{100}=0.49 x $10^{-15}\,°C/kg$, considering that the functional unit yields GWP_{100}= 64.869 kg, then the change in temperature induced by the studied functional unit is driven by:

$GTP_{100\,fU}$ = GWP_{100} x $AGTP_{100}$ ***Equation 10***

$\mathrm{GTP}_{100\ \mathrm{fU}}$ = (64.869 kg-CO_2) x (0.49 x 10^{-15} $\frac{°C}{kg\ CO2}$) = 3.17858 x $10^{-14}\,°C$

This means that in a 100-year time horizon the emission pulse represented by the category indicator results of 64.869 kg CO_2e / fU will cause a negligible increment of **3.17858 x $\mathbf{10^{-14}}\,°\boldsymbol{C}$** in the global mean surface air temperature.

Response in Steric Sea Level Rise (SSLR) (centimeters)

Joos et al. provide a value for the response in the Steric Sea Level Rise (SSLR) for different time horizons, likewise for this work the 100-year time horizon is taken, the reference value provided by the authors for the 100-year time horizon is 1.82 cm for 100GtC, in order to obtain the SSLR produced by 1 kg CO_2 it is required to multiply 1.82 cm by this expression (12 / (44 x 100 x 10^{12})).

SSLR_{100} = (1.82 cm) x (12 / (44 x 100 x 10^{12})) = 4.96364 x10^{-15} $\frac{cm}{kg\ CO2}$

$SSLR_{100\,fU}$ = GWP_{100} x $SSLR_{100}$ ***Equation 11***

Then the Steric Sea Level Rise produced by the functional unit yields:

$\mathrm{SSLR}_{100\ \mathrm{fU}}$ = (64.869 kg CO_2) x (4.96364 x 10^{-15} $\frac{cm}{kg\ CO2}$) x = 3.21986 x 10^{-13} cm

This means that in a 100-year time horizon the emission pulse represented by the category indicator results of 64.869 kg CO_2e / fU will cause a negligible increment of **3.21986 x $\mathbf{10^{-13}}$ $\boldsymbol{cm}$** in the global Steric Sea Level Rise.

Response in Ocean Heat Content Change (OHCC) (Joules)

The authors also provide a value for the response in the Ocean Heat Content Change (OHCC) for different time horizons, again the 100-year time horizon is taken for this LCA, the reference value provided by the authors for the 100-year time horizon is 15.7 x 10^{22} Joules per 100GtC, in order to obtain the OHCC produced by 1 kg CO_2 it is required to multiply 15.7 x 10^{22} Joules by the following expression (12 / (44 x 100 x 10^{12})).

OHCC_{100} = (15.7 x 10^{22} J) x (12 / (44 x 100 x 10^{12})) = 4.28182 x10^{8} $\frac{J}{kg\ CO2}$

$OHCC_{100\,fU}$ = GWP_{100} x $OHCC_{100}$ ***Equation 12***

Then the Ocean Heat Content Change produced by the functional unit yields:

$\mathrm{OHCC}_{100\ \mathrm{fU}}$ = (64.869 kg CO_2) x (4.28182 x10^8 $\frac{J}{kg\ CO2}$) = 2.77757 x 10^{10} J

This means that in a 100-year time horizon the emission pulse represented by the category indicator result of 64.869 kg CO_2e / fU will cause a negligible increment of **2.77757 x $\mathbf{10^{10}}$ $\boldsymbol{J}$** in the global Ocean Heat Content Change.

Definition of the category indicator result for the given category endpoints, degree of linkage and its corresponding environmental relevance

In this present study the category indicator result is expressed in kg CO_2e / fU and it is assigned to several category endpoints comprised into this impact category. The climate change behavior has already studied in depth, the degree of linkage between category indicator results and impact category endpoints is taken from the IPCC, 2013: Summary for Policy Makers [56].

The table 32 illustrates this relationship where the environmental relevance of the studied functional unit is negligible, but it must be said that mass production may completely change this standpoint, since an optional element to address LCIA is normalization, it will allow to understand the behavior of the category indicator result as a relative value and even to conceive this LCA from an alternative product system perspective.

Table 32. Relationship between results, endpoints, linkage and environmental relevance of the functional unit

Indicator results, category endpoints, degree of linkage and environmental relevance [49]			
Category indicator result	**Category endpoint**	**Degree of linkage between results and endpoints**	**Environmental relevance of the functional unit**
64.869 kg CO2e / fU	Atmosphere temperature	medium-high	Extremely low
64.869 kg CO2e / fU	Sea level rate	high	Extremely low
64.869 kg CO2e / fU	Ocean temperature	high	Extremely low

Optional elements of LCIA

Normalization

This optional element will serve for a better understanding of the relative magnitude of the category indicator result of the product system under study, for this product system the relativity of the category indicator result comes from the production volume of the functional unit. The environmental relevance of the LCIA per functional unit might seem quite small as the functional unit only weighs 27 grams and then the environmental impacts caused by injection molding processes seem to be negligible, but that is not really true at all, and it becomes evident as the production volume increases in the injection molding process.

When referring to batch manufacturing processes, the functional unit is the reference unit to measure a production volume for the defined product system of the LCA. In the conducted study it was assessed only one plastic part, but it is possible to represent a different alternative product system through the variation of the throughputs as it is shown in table 33.

This previous assertion also means that if any product system is assessed in the most basic unit, it won´t be required to conduct LCA studies on larger product systems with larger production volumes as the obtained results will allow to predict further from what is being measured and assessed with the initial functional unit.

Table 33. Category indicator results relative to the production volume

Category indicator results relative to the production volume		
Production volume in injection molding	**Category indicator results (kg CO2e / fU)**	**Category indicator result multiplied by production volume (kg CO2e)**
1	64.86900	64.869
10	6.52921	65.292
100	0.69522	69.522
1000	0.11182	111.822
10000	0.05348	534.822
100000	0.04765	4764.822
1000000	0.04706	47064.822
10000000	0.04701	470064.822
100000000	0.04700	4700064.822

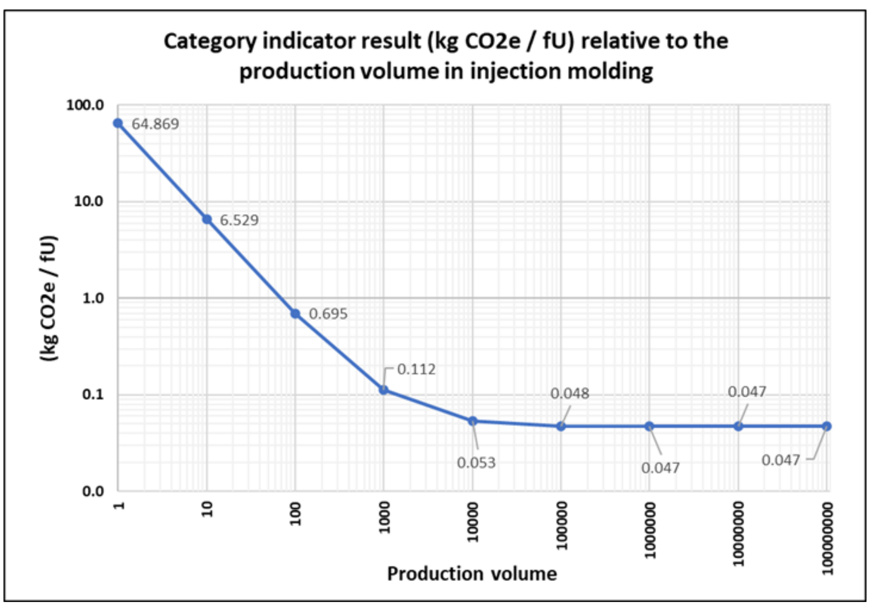

Figure 42. kilograms of CO_2e per fU relative to the production volume in injection molding

Additional LCIA data quality analysis

This section focuses on understanding better the significance behind the LCIA indicator results, in other words the significance of the different GHGs contributors. This will allow to discern if substantial differences between contributors are or not present, and for this purpose a Pareto analysis will be made, additionally it will serve to identify which is the part of the manufacturing that contributes the most to the generation of GHG emissions.

Some considerations must be understood to address the different production volumes, according to The Rodon Group® [57] and Wunder-Mold [58] which are specialized manufactures in plastic injection molding a low-volume production is less than 10,000 parts, a mid-volume production is usually between 10,000 and 750,000 parts, and a high-volume production is when the throughput exceeds 750,000 parts.

The primary data to develop the Pareto analysis are the emissions expressed in kg CO_2e and these are contained in the allocation section, the considered emissions contributors involved in the manufacturing phase are as follows:

- Steel plate production
- CNC machine energy
- Cutting tools
- Cutting fluid
- Injection molding machine energy

The first series of bar charts in figure 43 show the CNC mold machining emissions compared to the emissions caused by the Injection Molding Machine electricity generation at different production volumes, while the second series of bar charts in figure 44 show a Pareto analysis of the different contributors of GHG emissions involved in the manufacturing phase, and these charts clearly allow to analyze and distinguish the most significant equivalent CO_2 emitters during the manufacture of the functional unit.

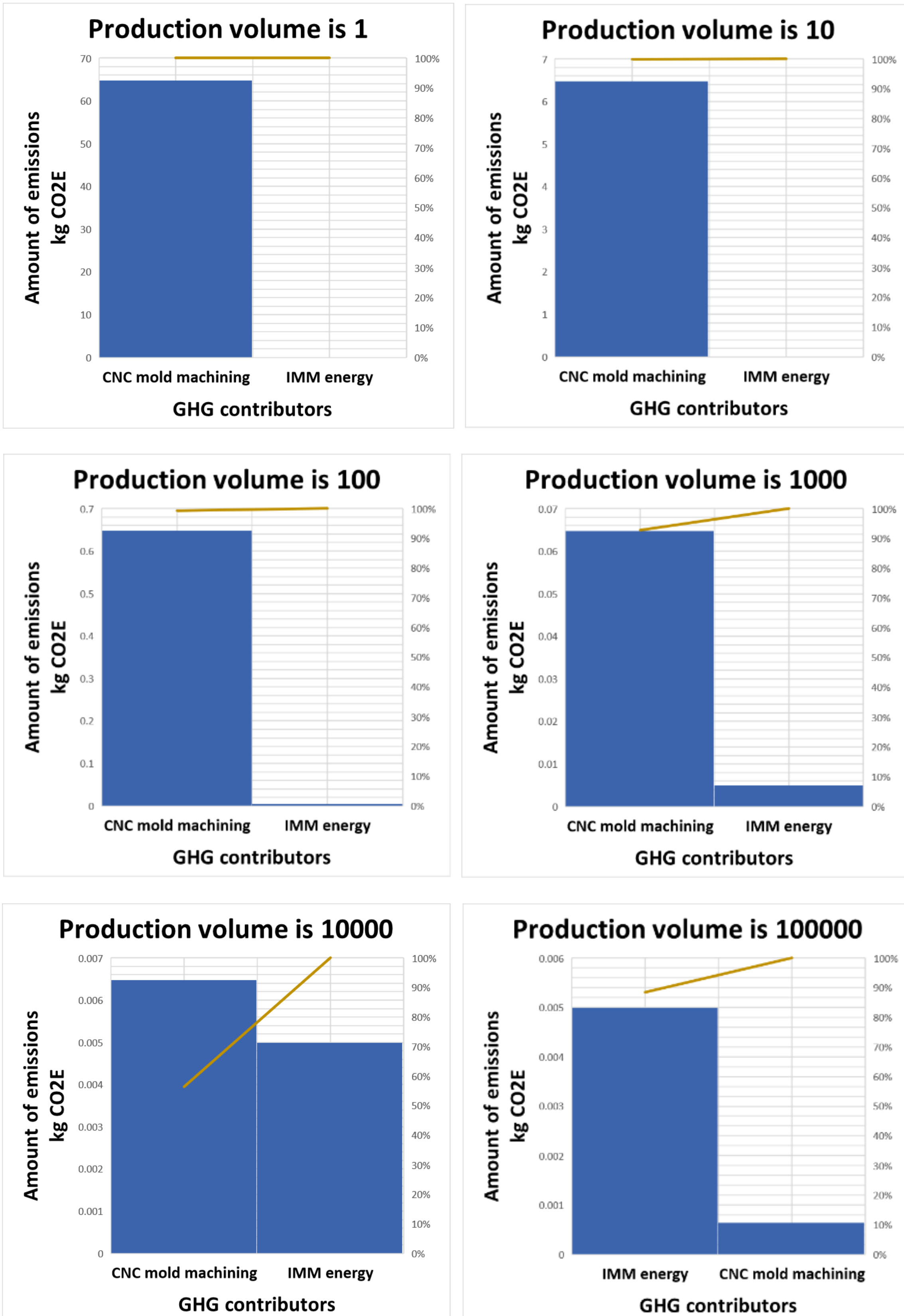

Figure 43. Comparison between CNC and IMM emissions

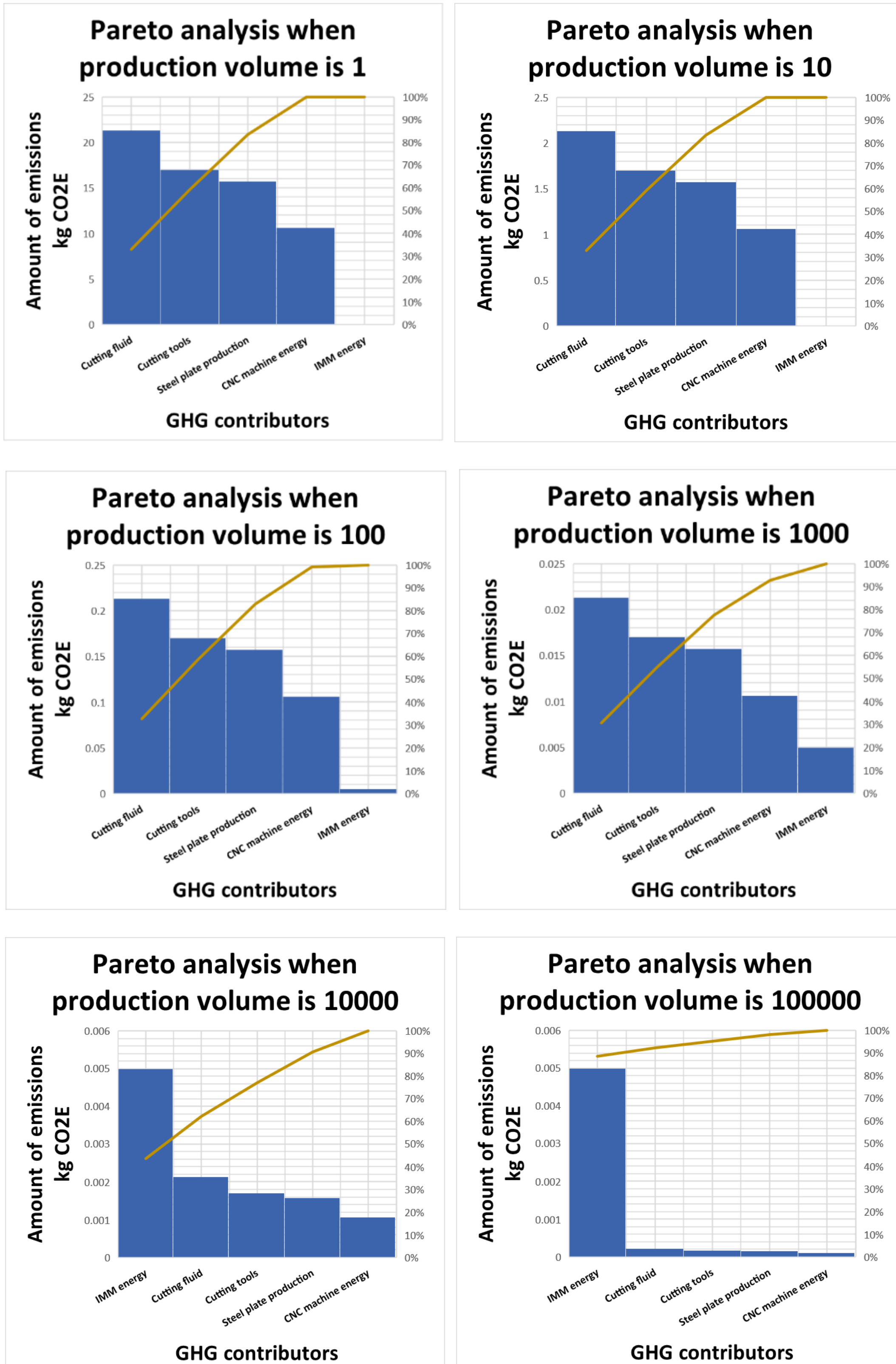

Figure 44. Pareto analyses of the different contributors of GHG emissions

6.4 Life Cycle interpretation

Identification of significant issues based on the results of the LCI and LCIA phases of LCA

Results of the LCI and the LCIA

The obtained results of the LCI are shown below, first in table 34 and 35 it is possible to observe every different contributor of CO_2e emission for the function 1 and the function 2 respectively, while table 36 displays the whole emissions assigned to each function of the product system. The values presented on this tables are referenced to the functional unit, considering the two system functions belonging to the defined system boundary declared in the goal and scope of the LCA study.

Table 34. Emission contributors assigned to the system function 1

Emission contributors assigned to function 1. Mold machining	
Inputs	**Carbon Emissions (kg CO2e)**
Steel plate production	15.768
CNC machine energy	10.644
Cutting tools	17.035
Cutting fluid	21.375

Table 35. Emission contributors assigned to the system function 2

Emission contributors assigned to function 2. Plastic injection	
Inputs	**Carbon Emissions (kg CO2e)**
Polypropylene production	0.042
IMM energy	0.005

Table 36. Emission contributions released by each system function

Emission contributions per functional unit assigned to the functions of the product system	
Pre-product and final product	**Category indicator results (kg CO2e / fU)**
Mold machining	64.822
(PP) Plastic injection	0.047
Total	**64.869**

Next in table 37 the results of the LCIA are shown considering the whole released emissions reflected in the category indicator result of the Global Warming Potential (GWP) impact category.

Table 37. Global Warming Potential of the corresponding functional unit

Global Warming Potential relative to the category indicator results	
Category indicator results	$\mathbf{GWP_{100}}$
64.869 kg CO2e / fU	64.869 kg

The results were displayed, then afterwards there will be a review of the significant issues associated to the obtained values in LCI and LCIA.

Significant issues associated to LCI and LCIA results

When analyzing the first system function of the assessed product system, it is possible to visualize that the most significant contributor of equivalent CO_2 emissions is the cutting fluid accounting for the 32.97% , the second most significant contributor are the cutting tools accounting for the 26.27%, the third most significant contributor is the steel plate production accounting for the 24.32%, and finally the least significant contributor is the CNC machine energy consumption accounting for the 16.42% of the total emissions involved into the mold machining.

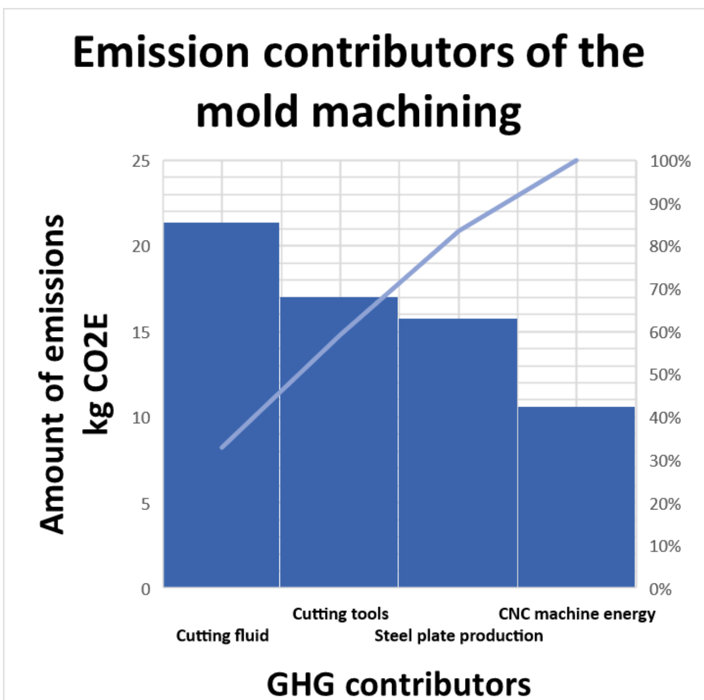

Figure 45. Emission contributors of the CNC machined mold

The second system function of the assessed product system only has two equivalent CO_2 emission contributors, it is possible to visualize that the one that contributes the most is the PP production accounting for the 89.36%, while a smaller amount of the emissions comes from the Injection Molding Machine energy accounting for the 10.63% of the total released emissions.

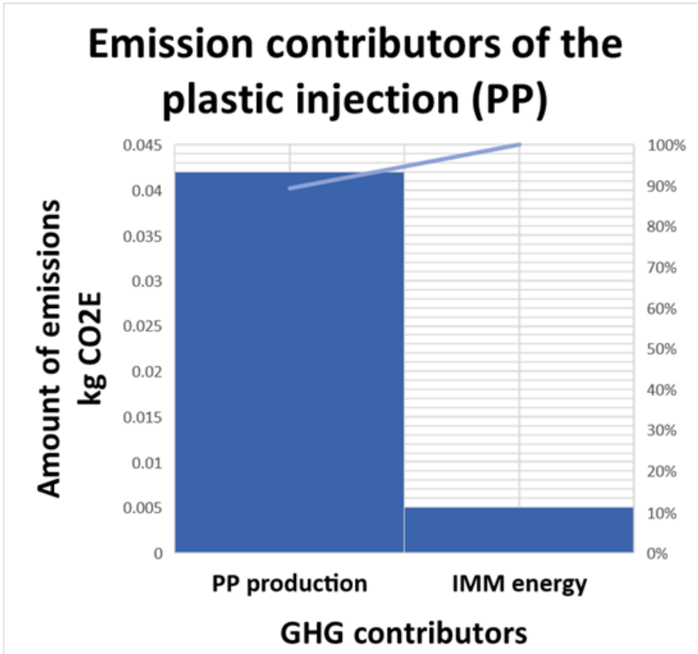

Figure 46. Emission contributors in the plastic injection process

When analyzing the results, it was observed a characteristic behavior that leaves a meaningful understanding, the amount of released emissions per functional unit strongly depends upon the production volume, this means that in low production volumes most of the released emissions correspond to the first function, say the CNC machined plastic injection mold. Conversely, when dealing with high production volumes above 750,000 injected plastic parts [57] [58] most of the released emissions per functional unit corresponds to the second function of the LCA, say the energy and raw material to produce an injected plastic part.

LCA Conclusions

The following conclusions will only apply to the defined product system addressing the defined manufacturing processes, one plastic part fabrication is the corresponding functional unit, and this is the reference to the whole assessment and the underlying outcomes.

Considering the equivalent CO_2 emissions obtained from the product system and the functional unit, the mold machining embodies 99.92% of the emissions while only the remaining 0.07% correspond to the plastic injection process.

According to the results of this present LCA where the climate change is the unique impact category to be analyzed, it is observed that the outcome is a very detailed study focused on the carbon footprint of a product system which can be useful for carbon footprint labeling, therefore this information can be used to compare products or manufacturing processes in order to choose the one that has the least impact on the climate change.

Based on the environmental impacts caused by the functional unit, the results from the LCIA section show that the responses in global mean surface air temperature, steric sea level rise and ocean heat content change are negligible, and according to the results there is no significant Global Warming Potential (GWP) coming from the manufactured plastic part.

According to the adopted approach, the defined product system boundary shown in the scope of the LCA spans the whole mass flow of the analyzed product, thereby it was possible to reach the expected level of completeness declared in the data quality requirements.

The assumptions reflected in the scope of the LCA gave a rough outline about the used machines, the materials to be processed, the sources of data to build the LCI, the electricity carbon emission factor to use, the procedure for energy measurements and the empirical model to complete the LCI. If it is reviewed every part of the inventory, it is possible to observe that the LCA resulted consistent to all the predefined assumptions, which are the features that best describe qualitatively this LCA.

LCA Limitations

The reproducibility of this LCA study largely depends upon the specific characteristics of the used machines, then it is required to consider that a **HAAS VF-1** machine was used for the CNC experiments and a **Demag Ergotech pro 50-270** was used for the plastic injection molding experiment, if other machines are used there is no guarantee to obtain similar results.

When undertaking the task to develop any LCA from a cradle-to-gate approach, it will be necessarily required to gather some information about raw materials from a third-party provider in order to build the LCI and analyze data in the LCIA, this entails to increase the level of uncertainty which is always variable and this can be caused by the parameters, the scenario, or the models.

Several assumptions were declared in the scope definition and these mainly reduced geographically the applicability of the information used in this LCA, it is also restricted the applicability of the information in a temporary way, therefore the used information for the LCI and all the underlying calculations only apply to Mexico in the year 2021.

LCA Recommendations

It is possible to improve the accuracy of any LCA when accounting GHG emissions in CNC machining processes, if it is estimated the wear of the cutting tools and the life of the cutting fluid, these analyses remained beyond the scope of the present study.

Moving towards obtaining more reliable information for the inventory of any LCA, it would be important to pay special attention on the feasibility to make direct measurements of the energy consumption in every one of the manufacturing processes using calibrated instruments and avoiding to measure the idle state of the machines.

Whenever a cradle-to-gate LCA is being conducted, it is required to use information to account the GHG emissions attributed to the raw material, studies provided by raw material manufacturers or by organizations dedicated to practice LCA are considered trusted information and can be used as an additional source of data and this help to reduce the time to conduct the study.

It is recommended the analysis of alternative product systems when assessing injected plastic parts because a baseline scenario can be modified if the production volume changes, these alternative product systems allow to understand how the emissions produced by a CNC machined mold will not cause the same environmental impacts per functional unit. This suggestion is also applicable to batch manufacturing processes where pre-products and products are present.

The results of this LCA suggest that when counteracting GHG emissions coming from CNC machining combined with injection molding, it must be first understood that it is more convenient to focus on the process that most reduce the emissions. A geometrically complex mold combined with a low production volume justify the importance of improve energy efficiency, extend tool life, and reduce raw material waste when machining a mold. Conversely, when dealing with high production volumes where predominate the emissions coming from thermoplastic and the IMM energy, it would be outstanding to use techniques such as DOE for the injection process and scientific molding.

7. Results and discussion

The manufacturing of the injection mold was analyzed from a sustainable approach where Design of Experiments (DOE) played an important role in building the process windows that served to obtain potential energy savings of 23% attributed to the selection of cutting parameters, where the high spindle speed and high feed rate of each process window were used for all the machining operations subsequent to the pre-machining operations.

Once the pre-machining operations were concluded, it was proceeded to the machining process of the mold core, for this purpose two work routes were proposed and compared mainly considering the expected machining time and the consumed energy, based on the results of this comparison it was chosen the alternative 2, according to the CAM simulation this choice reduced in 23% the machining time and the potential energy savings were 715 Wh, consequently the CO_2e emissions were reduced 302 grams which represent approximately 10% of the emissions attributed to the mold core machining.

The improvements in the mold machining process were reflected on the results of the conducted cradle-to-gate LCA, where it outstands that the total machining time of the mold was approximately 8 hours and 20 minutes, and the energy analyzer recorded an active energy consumption of 25162 Wh, the study indicates that the total released GHG emissions to fabricate the injection mold was nearly 65 kg CO_2e.

The process parameters obtained from DOE during the pre-machining operations of the mold also improved the surface finish for the remaining machining operations, random samples of roughness were taken to verify the quality criteria exclusively on the finished mold and the results indicate an average surface roughness of 0.58 µm which is inferior to the 1.5 µm specified in the design.

During the quality criteria verification it was observed that the machined mold did not match the design specification in 5 from 20 critical dimensions, this error is attributed to the tool offset of the CNC machine, notwithstanding the proper function of the 20 critical dimensions was guaranteed flawlessly as the mold was hand fitted to be correctly assembled.

The mold was used to inject plastic parts using Laprene® (TPE), the estimation of the energy used for the plastic injection molding process indicates that approximately 12 Wh per produced part were consumed, the injection of one plastic part caused a release of 0.047 kg CO_2e including the polymer and the energy. Although this is an estimated value, a reduction in energy consumption and GHG emissions can be achieved by applying scientific molding and DOE for the injection molding process.

The injected parts were cosmetically acceptable and apparently these results can be also obtained by using other different thermoplastic materials. The design specification of the surface roughness was 27 µm and this value was far overcome with the final product achieving an average surface roughness of 0.85 µm. The design specification of the part mass was stated on 35.40 grams and during the quality verification 9 different injected parts were measured resulting in an average part mass of 35.39 grams that resulted very close to the specified value, therefore the injected plastic parts fulfill the design specifications and the quality of the parts is acceptable.

8. Hypothesis testing and statistical analysis

Below are shown the null hypothesis and the alternative hypothesis. The stated significance level for the hypothesis testing is 90%, the aim is to carry out a right tailed test where the rejection region is $\propto = 0.1$. The assumed conditions to reject or accept are $H_0 : \mu \leq P(0.9)$ and $H_1 : \mu > P(0.9)$.

Null hypothesis (H_0): In CNC milling processes, it is not possible to reduce the energy consumption nor the generated GHG emissions when removing material based on the manufacturer productivity parameters.

Alternative hypothesis (H_1): In CNC milling processes, it is possible to reduce the energy consumption and consequently the generated GHG emissions when removing material based on the manufacturer productivity parameters.

The conditions under the face milling experiments were developed and its results are presented in table 38, this information will be used to make the hypothesis testing using statistical analysis.

Table 38. Results from face milling experiments

Face milling experiment results				
Spot	Feed rate (mm/min)	Spindle speed (rpm)	Consumed energy (kWh)	Roughness Ra (µm)
A	512	1465	0.14125	1.667
B	1545	1465	0.062125	1.501
C	442	1263	0.242	1.868
D	1332	1263	0.07175	1.625
E	1000	1364	0.08079	1.618

Considering the face milling experiment and the collected data, there will be implemented two multiple linear regression models to identify if exists or not a relationship between the two independent variables and the response variables, the two independent variables are the feed rate and the spindle speed for both models, while the analyzed response variables are the surface roughness and the energy consumption. Additionally, ANOVA for the multiple linear regression models will analyze the level of variability and will indicate the significance of the results.

The multiple linear regression model is first implemented to the surface roughness, and it is expected a linear behavior that fits to a linear trendline, the results of this regression are shown in table 39 where it is possible to identify that the R square also called the coefficient of determination resulted to be equal to 0.9433, this indicates that 94.33% of the variations in the surface roughness can be explained by the influence that the feed rate and the spindle speed exert, the standard error of 0.044 indicates that the measured values are very close to a mean value. The linear trendline is illustrated in the figure 47.

For this first multiple linear regression model, the confidence interval was stated in 0.1 and the results of the experiment placed the significance F-value on 0.056, this means that the two independent variables feed rate and spindle speed combined do have a statistically significant association with the obtained surface roughness on the CNC machined part.

Table 39. Multiple linear regression for the surface finish

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.97127							
R Square	0.94337							
Adjusted R Square	0.88674							
Standard Error	0.04499							
Observations	5.00000							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2.00000	0.06745	0.03372	16.65826	0.05663			
Residual	2.00000	0.00405	0.00202					
Total	4.00000	0.07149						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	2.75533	0.30448	9.04922	0.01199	1.44525	4.06541	1.86624	3.64441
(mm/min)	-0.00021	0.00005	-4.50250	0.04595	-0.00041	-0.00001	-0.00035	-0.00007
(rpm)	-0.00066	0.00023	-2.92013	0.09999	-0.00163	0.00031	-0.00131	0.00000

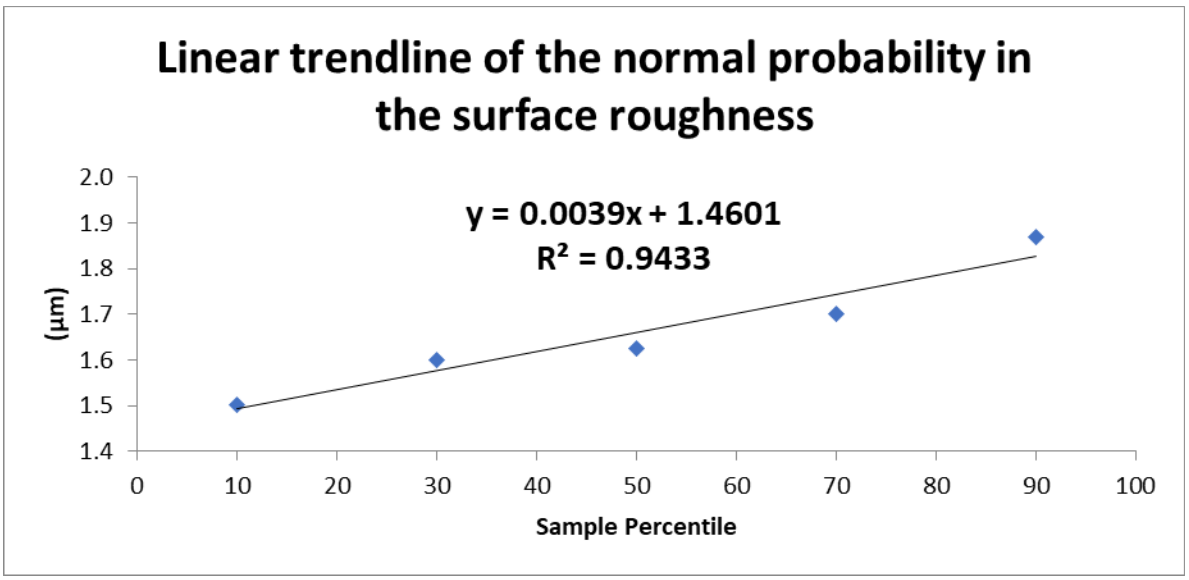

Figure 47. Exponential trendline of the response variable (surface roughness)

When considering the two independent variables as individual elements influencing on the response variable, the corresponding p-value for feed rate is p=0.045 and the p-value for spindle speed is p=0.099, these results indicate that individually both of the independent variables do have a statistically significant association to the response variable surface roughness.

The coefficients of the independent variables predict and indicates the mean expected change in the response variable, taking the assumption that the other independent variable remains constant. This means that assuming the stated conditions of the experiment, by reducing the feed rate by 1 mm/min when spindle speed remains constant would reduce the mean surface roughness in 0.0002 µm, also by increasing the spindle speed by 1 rpm while feed rate remains constant would reduce the mean surface roughness in 0.0006 µm.

The table 40 summarizes the multiple linear regression model in which the independent variables are the feed rate and the spindle speed, but here the response variable is the consumed energy and the results indicate that the standard error of the obtained values in the energy measurements is located at an average distance of 0.047 units from the regression line, it is also possible to observe that the R square is equal to 0.8013.

Table 40. Multiple linear regression for the consumed energy

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.89516							
R Square	0.80131							
Adjusted R Square	0.60262							
Standard Error	0.04733							
Observations	5.00000							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2.00000	0.01807	0.00903	4.03303	0.19869			
Residual	2.00000	0.00448	0.00224					
Total	4.00000	0.02255						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	0.49360	0.32030	1.54106	0.26322	-0.88453	1.87173	-0.44167	1.42886
(mm/min)	-0.00013	0.00005	-2.58969	0.12234	-0.00034	0.00008	-0.00027	0.00002
(rpm)	-0.00018	0.00024	-0.77791	0.51804	-0.00120	0.00083	-0.00088	0.00051

The obtained value indicates that in the linear regression 80.13% of the variations in the consumed energy can be explained by the influence that the feed rate and the spindle speed exerts, which would suppose to accept the null hypothesis, but it will be demonstrated that this is not true.

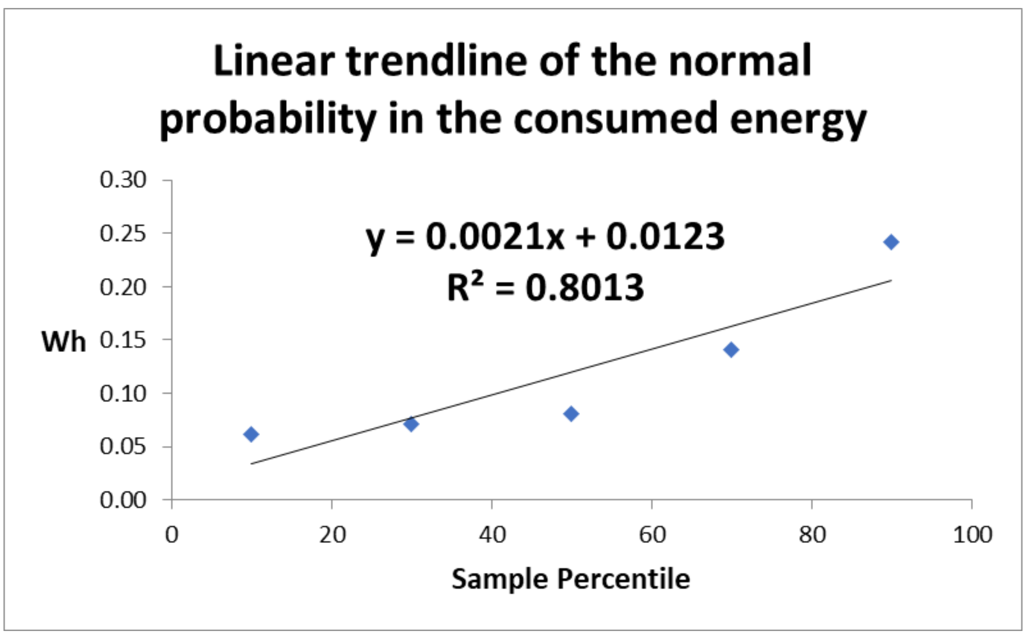

Figure 48. Linear trendline of the response variable (consumed energy)

The multiple linear regression that considers the energy consumption as the response variable was only analyzed in order to corroborate that its behavior is not linear as it can be observed in the figure 48 where the points do not fit accordingly to the linear trendline, instead of this it is observed a nonlinear behavior that can be verified with an exponential trendline, this exponential trend is clearly described by the mathematical models that govern the power and the energy consumption during the CNC machining processes [1].

The obtained values of the electrical energy consumption follow an exponential trendline that best fits to the results, this trendline returns a value of R square equal to 0.9385 and a significance F-value equal to 0.0615, which means that 93.85% of the variations in the consumed energy can be explained by the influence that the feed rate and the spindle speed exerts, the results showed that these parameters do have a statistically significant association with the consumed energy, since the significance level was stated in 0.1 and the results are situated below this value.

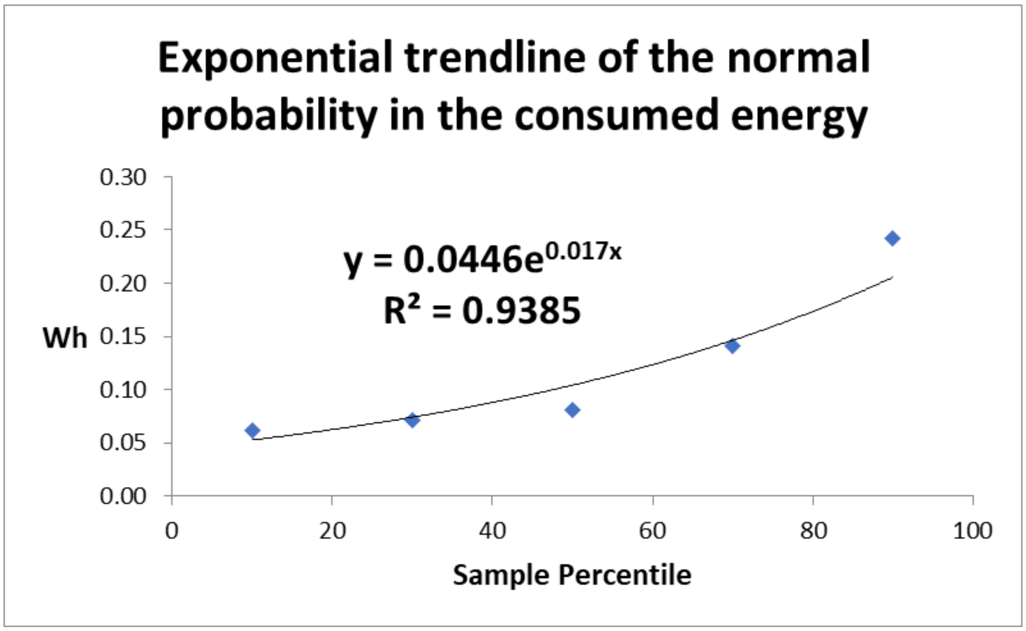

Figure 49. Exponential trendline of the response variable (consumed energy)

Considering the obtained results, it is possible to assert that as the coefficient of determination (R square) is placed on μ=0.9385, the following condition is fulfilled $H_1 : \mu > P(0.9)$, then it is rejected the null hypothesis $H_0 : \mu \leq P(0.9)$ and therefore the alternative hypothesis is accepted.

9. Conclusions

This work conducted a cradle-to-gate LCA focused on the climate change impact category to evaluate the indirectly released emissions associated to the manufacturing of an injection mold and a plastic part. Previously to the LCA, it was performed a Design of Experiments (DOE) from which was developed a process window helpful to determine the machining conditions to reduce the energy consumption and to mitigate the GHG emissions.

The manufacturing approach was capable of getting potential reductions in the CO_2e emissions related to energy consumption during the CNC mold machining, this was achieved through a mindful selection of the process parameters but also by the proposal and comparison of different machining work routes. The mold cavity machining reduced 10% the emissions, while the emissions from the mold core machining underwent a reduction about 8%, then the whole mold machining reduced approximately 18% the GHG emissions. None of these implicated process improvements compromised the quality of the mold nor the plastic part.

The results of the LCA indicates that the major contributions of CO_2e emissions during the CNC machining came from the cutting fluid (32.97 %) and the cutting tools (26.27 %), minor contributions came from the steel plate production (24.32 %) and the CNC machine energy (16.42 %). During the plastic injection most of the emissions came from the PP production (89.36 %) while the least corresponded to the IMM energy (10.63%).

This study covered the main CO_2e emitters and therefore this framework is a good starting point to undertake LCA studies focused on injected plastic parts and it is fully applicable to other particular injection molds. The injection mold, used materials, process parameters, and the production volume will drive the resulting environmental impacts of an LCA on this field of study.

Due to the nature of the addressed manufacturing processes, the cradle-to-gate approach and the product system allowed to register in the LCI the 100% of the mass flow, nonetheless, the accuracy of the CO_2e emissions accounting method needs to be verified.

After developing this thesis, I have understood how the energy consumption in manufacturing activities causes the release of pollutants that alter the equilibrium of a net-zero radiative forcing which changes the energy flux in the atmosphere and this modifies the temperature of the earth surface air and the oceans. In addition, I have also understood that it is possible to mitigate these adverse effects caused by the manufacturing processes through a mindful selection of process parameters.

The master's program provided a space to delve into specialized manufacturing studies and the fascinating field of mechanical engineering, but also to have close contact with the scientific world, which led to the development of this thesis. The path through the spaces of this university and the faculty of engineering gave me the fortune and the privilege of meeting my colleagues and mentors who inspire me to improve as a person and as a social individual.

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10. Appendices

Appendix A. Data acquisition procedure for electrical energy measurements

The instrument used to measure the consumed power and energy into the assessed manufacturing processes is a FLUKE 435 – Series II, it is shown in the figure 39, this is a power and energy quality analyzer that store data into an SD card inside the device, subsequently the data is loaded to a PC to be analyzed in the software Power Log 430-II.

Figure 50. FLUKE 435 – Series II and its accessories

Then afterwards it is possible to export data into text document files (.txt), in the same way the text document file can be imported by Microsoft Excel for the desired purposes, this way it turns easy to handle data and to obtain charts and plots of the power and energy data acquisition for a better visualization of the energy behavior along each manufacturing process. The data acquisition steps to be followed are shown below in the corresponding chronological order.

1. Setup the date and time, choose triphasic mode with a star configuration of the electrical system, setup the nominal frequency to 60Hz, setup the nominal voltage to 120V, make sure you select the correct type of voltage and current probes. Figure 40 illustrates the setup screen as displayed in the FLUKE 435 – series II.

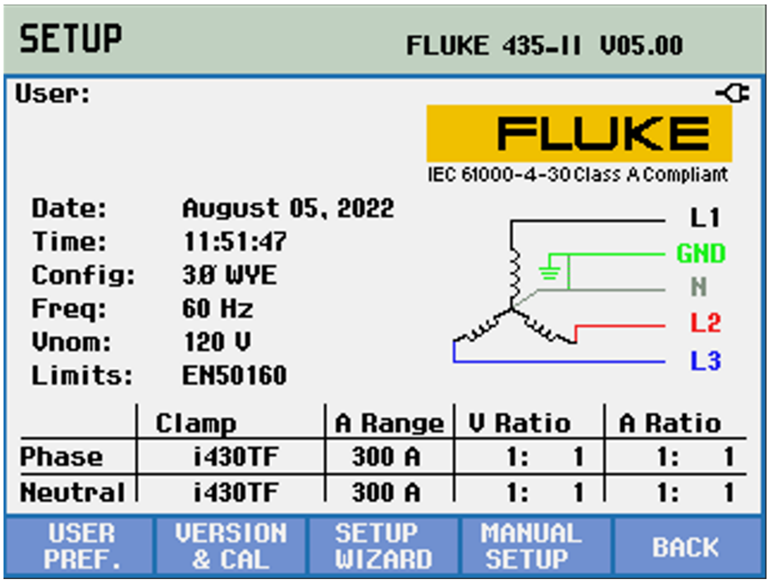


Figure 51. FLUKE 435 – Series II, setup screen

2. Make the connection of the probes of current, voltage and ground as illustrated in figure 41, this is the aid displayed by the FLUKE 435-Series II.

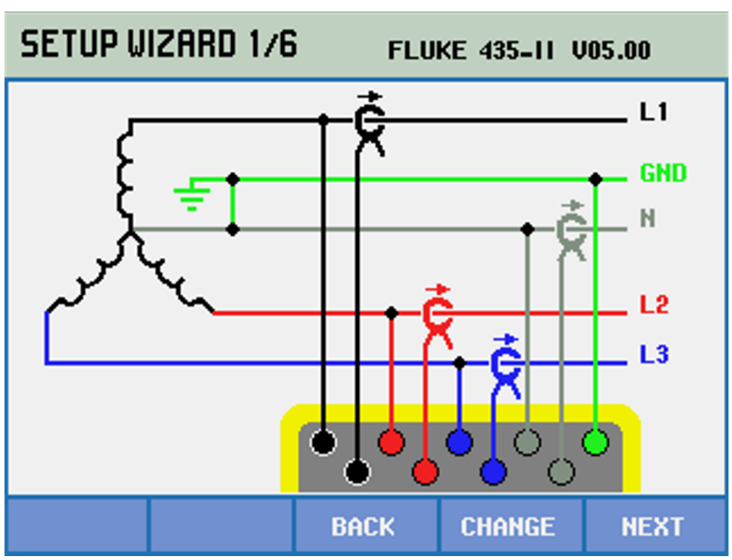


Figure 52. FLUKE 435 – Series II, connection diagram screen

3. Verify that the connection of the probes has been made correctly by helping you with the screen of the phasor diagram displayed by the measurement instrument, this is illustrated in figure 42.

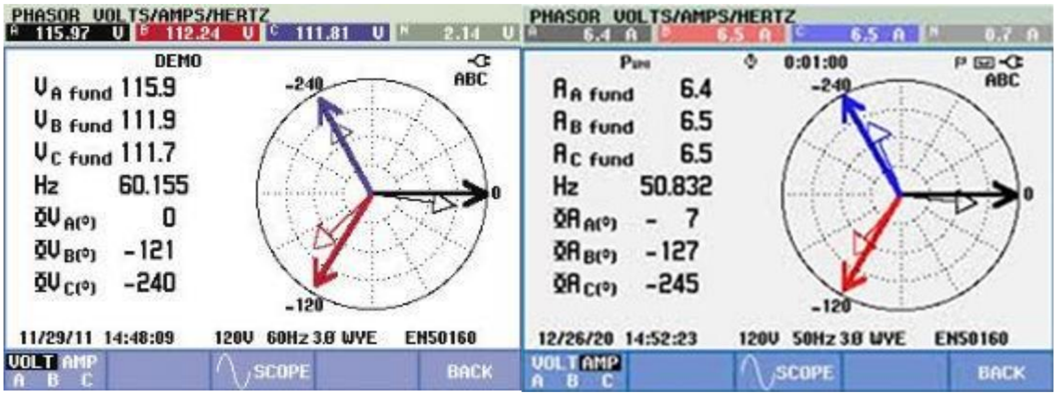


Figure 53 . FLUKE 435 – Series II, phasor diagram screen

4. Press the LOGGER button above the green power on/off button in order to setup how long the measurement will last and setup the sampling rate of the experiment, say the lapse between each recorded point e.g., 1s, 3s, 5s, 10s, etcetera. The figure 43 shows a close up of the keyboard included in the Fluke 435 – series II.

Figure 54. FLUKE 435 – Series II, keyboard

5. Then verify that the correct data you want to record is selected in the setup readings menu by pressing F1, for the present study Vrms, A-rms, watts, VA, VAR, PF, COS f, and Wh was selected to be recorded, after that you can press F5 button on the upper right side to start the measurement.

6. By pressing again F5, the measurement will stop and then you can save the file into the SD card. At this point, the files are ready to be loaded to the PC to be analyzed and handled in the software Power Log 430-II.

Appendix B. Work routes for mold machining (generated by Autodesk Inventor CAM)

Work route: Alternative 1 for mold core machining

Setup

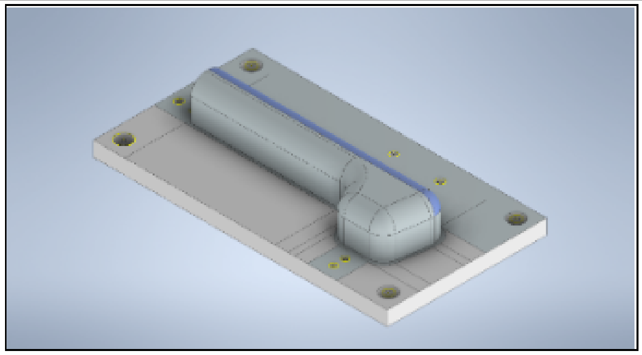
WCS: #0

Stock:
DX: 207mm
DY: 112mm
DZ: 37mm

Part:
DX: 207mm
DY: 112mm
DZ: 37mm

Stock Lower in WCS #0:
X: -103.5mm
Y: -56mm
Z: -37mm

Stock Upper in WCS #0:
X: 103.5mm
Y: 56mm
Z: 0mm



Total

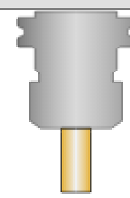
Number Of Operations: 8
Number Of Tools: 6
Tools: T2 T3 T4 T5 T6 T7
Maximum Z: 15mm
Minimum Z: -40.52mm
Maximum Feedrate: 1100mm/min
Maximum Spindle Speed: 4160rpm
Cutting Distance: 149315.27mm
Rapid Distance: 5049.62mm
Estimated Cycle Time: 3h:2m:24s

Tools

T2 D2 L2
Type: flat end mill
Diameter: 16mm
Length: 34.5mm
Flutes: 4
Description: 16mm Flat Endmill

Minimum Z: -26.52mm
Maximum Feed: 1100mm/min
Maximum Spindle Speed: 4160rpm
Cutting Distance: 102542.7mm
Rapid Distance: 956.4mm
Estimated Cycle Time: 1h:39m:54s (54.8%)

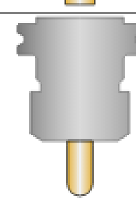
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T3 D3 L3
Type: ball end mill
Diameter: 12.7mm
Corner Radius: 6.35mm
Length: 27.94mm
Flutes: 4
Description: 1/2" Ball Endmill

Minimum Z: -16.49mm
Maximum Feed: 700mm/min
Maximum Spindle Speed: 3300rpm
Cutting Distance: 46302.58mm
Rapid Distance: 129.85mm
Estimated Cycle Time: 1h:6m:25s (36.4%)

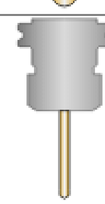
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T4 D4 L4
Type: center drill
Diameter: 6.35mm
Tip Angle: 118°
Length: 60mm
Flutes: 2
Description: #3 Center Drill

Minimum Z: -31.52mm
Maximum Feed: 33mm/min
Maximum Spindle Speed: 2700rpm
Cutting Distance: 120mm
Rapid Distance: 1306.1mm
Estimated Cycle Time: 3m:54s (2.1%)

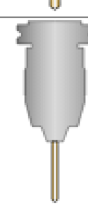
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35

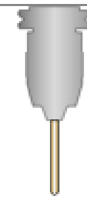
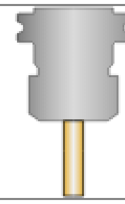


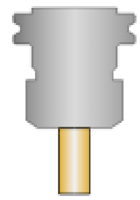
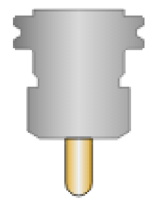
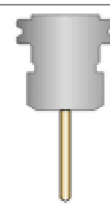
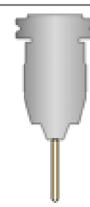
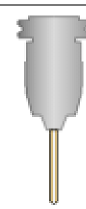
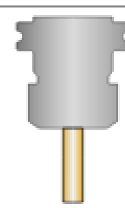
T5 D5 L5
Type: drill
Diameter: 4.76mm
Tip Angle: 118°
Length: 50.16mm
Flutes: 1
Description: 3/16

Minimum Z: -40.52mm
Maximum Feed: 33mm/min
Maximum Spindle Speed: 2700rpm
Cutting Distance: 228mm
Rapid Distance: 1337.55mm
Estimated Cycle Time: 7m:11s (3.9%)

Holder: Maritool CAT40-APU13 Drill Chuck
Comment: Maritool CAT40-APU13
Vendor: Maritool
Product: CAT40-APU13



T6 D6 L6 Type: drill Diameter: 6.35mm Tip Angle: 118° Length: 66.04mm Flutes: 1 Description: 1/4	Minimum Z: -40.52mm Maximum Feed: 33mm/min Maximum Spindle Speed: 2000rpm Cutting Distance: 76mm Rapid Distance: 674.86mm Estimated Cycle Time: 2m:26s (1.3%)	Holder: Maritool CAT40-APU13 Drill Chuck Comment: Maritool CAT40-APU13 Vendor: Maritool Product: CAT40-APU13	
T7 D7 L7 Type: flat end mill Diameter: 11.11mm Length: 42mm Flutes: 3 Description: 12mm Flat Endmill	Minimum Z: -33.02mm Maximum Feed: 50mm/min Maximum Spindle Speed: 1150rpm Cutting Distance: 46mm Rapid Distance: 644.86mm Estimated Cycle Time: 1m:3s (0.6%)	Holder: Maritool CAT40-ER32-2.35 Comment: Maritool CAT40-ER32-2.35 Vendor: Maritool Product: CAT40-ER32-2.35	

Operations			
Operation 1/6 Description: Pocket1 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 3mm Maximum stepover: 3mm	Maximum Z: 15mm Minimum Z: -26.52mm Maximum Spindle Speed: 4160rpm Maximum Feedrate: 1100mm/min Cutting Distance: 102542.7mm Rapid Distance: 956.4mm Estimated Cycle Time: 1h:39m:54s (54.8%) Coolant: Flood	**T2 D2 L2** Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	
Operation 2/6 Description: Scallop2 Strategy: Scallop WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepover: 0.22mm	Maximum Z: 15mm Minimum Z: -16.49mm Maximum Spindle Speed: 3300rpm Maximum Feedrate: 700mm/min Cutting Distance: 46302.58mm Rapid Distance: 129.85mm Estimated Cycle Time: 1h:6m:25s (36.4%) Coolant: Flood	**T3 D3 L3** Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 27.94mm Flutes: 4 Description: 1/2" Ball Endmill	
Operation 3/6 Description: Drill1 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -31.52mm Maximum Spindle Speed: 2700rpm Maximum Feedrate: 33mm/min Cutting Distance: 120mm Rapid Distance: 1306.1mm Estimated Cycle Time: 3m:54s (2.1%) Coolant: Flood	**T4 D4 L4** Type: center drill Diameter: 6.35mm Tip Angle: 118° Length: 60mm Flutes: 2 Description: #3 Center Drill	
Operation 4/6 Description: Drill1 (2) Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -40.52mm Maximum Spindle Speed: 2700rpm Maximum Feedrate: 33mm/min Cutting Distance: 228mm Rapid Distance: 1337.55mm Estimated Cycle Time: 7m:11s (3.9%) Coolant: Flood	**T5 D5 L5** Type: drill Diameter: 4.76mm Tip Angle: 118° Length: 50.16mm Flutes: 1 Description: 3/16	
Operation 5/6 Description: Drill2 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -40.52mm Maximum Spindle Speed: 2000rpm Maximum Feedrate: 33mm/min Cutting Distance: 76mm Rapid Distance: 674.86mm Estimated Cycle Time: 2m:26s (1.3%) Coolant: Flood	**T6 D6 L6** Type: drill Diameter: 6.35mm Tip Angle: 118° Length: 66.04mm Flutes: 1 Description: 1/4	
Operation 6/6 Description: Drill2 (2) Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -33.02mm Maximum Spindle Speed: 1150rpm Maximum Feedrate: 50mm/min Cutting Distance: 46mm Rapid Distance: 644.86mm Estimated Cycle Time: 1m:3s (0.6%) Coolant: Flood	**T7 D7 L7** Type: flat end mill Diameter: 11.11mm Length: 42mm Flutes: 3 Description: 12mm Flat Endmill	

Work route: Alternative 2 for mold core machining

Setup

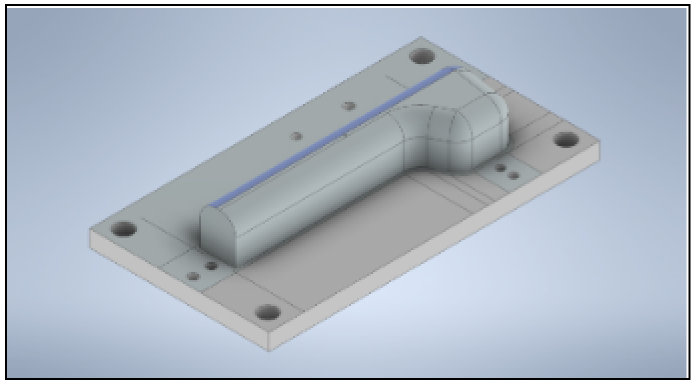
WCS: #0

Stock:
DX: 207mm
DY: 112mm
DZ: 37mm

Part:
DX: 207mm
DY: 112mm
DZ: 37mm

Stock Lower in WCS #0:
X: -103.5mm
Y: -56mm
Z: -37mm

Stock Upper in WCS #0:
X: 103.5mm
Y: 56mm
Z: 0mm



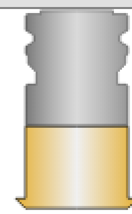
Total

Number Of Operations: 20
Number Of Tools: 7
Tools: T1 T2 T3 T4 T5 T6 T7
Maximum Z: 15mm
Minimum Z: -40.52mm
Maximum Feedrate: 1545mm/min
Maximum Spindle Speed: 4160rpm
Cutting Distance: 114973.35mm
Rapid Distance: 5452.11mm
Estimated Cycle Time: 2h:20m:22s

Tools

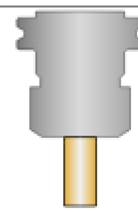
T1 D1 L1

Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	Minimum Z: -26.52mm Maximum Feed: 1545mm/min Maximum Spindle Speed: 1465rpm Cutting Distance: 46903.24mm Rapid Distance: 575.44mm Estimated Cycle Time: 36m:7s (25.7%)	Holder: BT40 - B4C3-0040



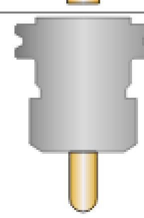
T2 D2 L2

Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	Minimum Z: -26.52mm Maximum Feed: 1100mm/min Maximum Spindle Speed: 4160rpm Cutting Distance: 21312.73mm Rapid Distance: 998.21mm Estimated Cycle Time: 20m:8s (14.3%)	Holder: Maritool CAT40-ER32-2.35 Comment: Maritool CAT40-ER32-2.35 Vendor: Maritool Product: CAT40-ER32-2.35



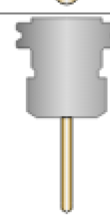
T3 D3 L3

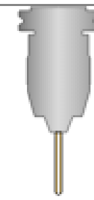
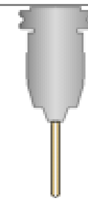
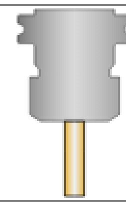
Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 27.94mm Flutes: 4 Description: 1/2" Ball Endmill	Minimum Z: -16.54mm Maximum Feed: 700mm/min Maximum Spindle Speed: 3300rpm Cutting Distance: 46307.38mm Rapid Distance: 129.92mm Estimated Cycle Time: 1h:6m:26s (47.3%)	Holder: Maritool CAT40-ER32-2.35 Comment: Maritool CAT40-ER32-2.35 Vendor: Maritool Product: CAT40-ER32-2.35

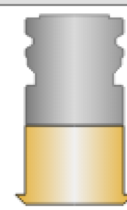
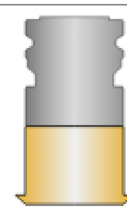
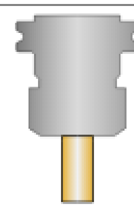
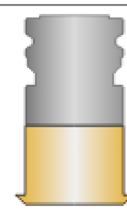
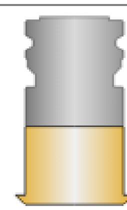


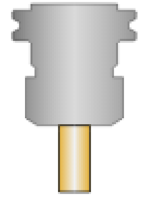
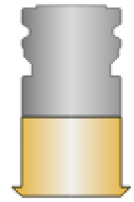
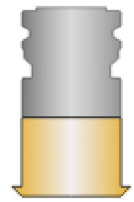
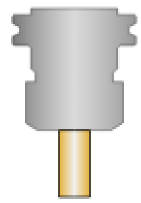
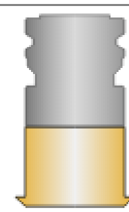
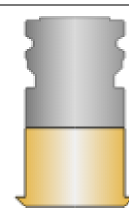
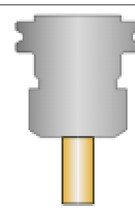
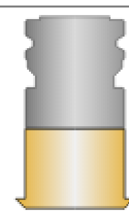
T4 D4 L4

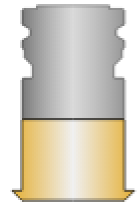
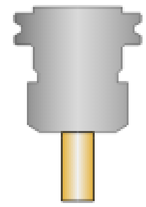
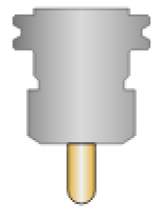
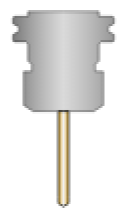
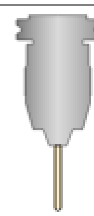
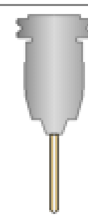
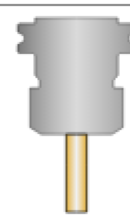
Type: center drill Diameter: 6.35mm Tip Angle: 118° Length: 60mm Flutes: 2 Description: #3 Center Drill	Minimum Z: -31.52mm Maximum Feed: 33mm/min Maximum Spindle Speed: 2700rpm Cutting Distance: 100mm Rapid Distance: 1091.26mm Estimated Cycle Time: 3m:15s (2.3%)	Holder: Maritool CAT40-ER32-2.35 Comment: Maritool CAT40-ER32-2.35 Vendor: Maritool Product: CAT40-ER32-2.35



T5 D5 L5 Type: drill Diameter: 4.76mm Tip Angle: 118° Length: 50.16mm Flutes: 1 Description: 3/16	Minimum Z: -40.52mm Maximum Feed: 33mm/min Maximum Spindle Speed: 2700rpm Cutting Distance: 228mm Rapid Distance: 1337.55mm Estimated Cycle Time: 7m:11s (5.1%)	Holder: Maritool CAT40-APU13 Drill Chuck Comment: Maritool CAT40-APU13 Vendor: Maritool Product: CAT40-APU13	
T6 D6 L6 Type: drill Diameter: 6.35mm Tip Angle: 118° Length: 66.04mm Flutes: 1 Description: 1/4	Minimum Z: -40.52mm Maximum Feed: 33mm/min Maximum Spindle Speed: 2000rpm Cutting Distance: 76mm Rapid Distance: 674.86mm Estimated Cycle Time: 2m:26s (1.7%)	Holder: Maritool CAT40-APU13 Drill Chuck Comment: Maritool CAT40-APU13 Vendor: Maritool Product: CAT40-APU13	
T7 D7 L7 Type: flat end mill Diameter: 11.11mm Length: 42mm Flutes: 3 Description: 12mm Flat Endmill	Minimum Z: -33.02mm Maximum Feed: 50mm/min Maximum Spindle Speed: 1150rpm Cutting Distance: 46mm Rapid Distance: 644.86mm Estimated Cycle Time: 1m:3s (0.7%)	Holder: Maritool CAT40-ER32-2.35 Comment: Maritool CAT40-ER32-2.35 Vendor: Maritool Product: CAT40-ER32-2.35	

Operations			
Operation 1/20 Description: Contour1 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 21mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -5.31mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 4247.55mm Rapid Distance: 36.31mm Estimated Cycle Time: 3m:16s (2.3%) Coolant: Flood	**T1** D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 2/20 Description: Contour2 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 3mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -5.31mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 3800.51mm Rapid Distance: 36.31mm Estimated Cycle Time: 2m:59s (2.1%) Coolant: Flood	**T1** D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 3/20 Description: Pocket1 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 6mm Maximum stepover: 5mm	Maximum Z: 15mm Minimum Z: -5.3mm Maximum Spindle Speed: 4160rpm Maximum Feedrate: 1100mm/min Cutting Distance: 10873.46mm Rapid Distance: 26.62mm Estimated Cycle Time: 10m:8s (7.2%) Coolant: Flood	**T2** D2 L2 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	
Operation 4/20 Description: Contour3 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 21mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -10.62mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 3988.18mm Rapid Distance: 47.02mm Estimated Cycle Time: 2m:59s (2.1%) Coolant: Flood	**T1** D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 5/20 Description: Contour4 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 3mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -10.62mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 3923.97mm Rapid Distance: 47.02mm Estimated Cycle Time: 3m:4s (2.2%) Coolant: Flood	**T1** D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	

Operation 6/20 Description: Pocket2 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 6mm Maximum stepover: 5mm	Maximum Z: 15mm Minimum Z: -10.61mm Maximum Spindle Speed: 4160rpm Maximum Feedrate: 1100mm/min Cutting Distance: 2779.74mm Rapid Distance: 37.3mm Estimated Cycle Time: 2m:37s (1.9%) Coolant: Flood	T2 D2 L2 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	
Operation 7/20 Description: Contour5 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 21mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -15.93mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 4043.8mm Rapid Distance: 57.73mm Estimated Cycle Time: 3m:1s (2.2%) Coolant: Flood	T1 D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 8/20 Description: Contour6 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 3mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -15.93mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 3987.37mm Rapid Distance: 57.73mm Estimated Cycle Time: 3m:7s (2.2%) Coolant: Flood	T1 D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 9/20 Description: Pocket3 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 6mm Maximum stepover: 5mm	Maximum Z: 15mm Minimum Z: -15.92mm Maximum Spindle Speed: 4160rpm Maximum Feedrate: 1100mm/min Cutting Distance: 1513.33mm Rapid Distance: 415.14mm Estimated Cycle Time: 1m:34s (1.1%) Coolant: Flood	T2 D2 L2 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	
Operation 10/20 Description: Contour7 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 18.5mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -21.24mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 4377.37mm Rapid Distance: 68.44mm Estimated Cycle Time: 3m:22s (2.4%) Coolant: Flood	T1 D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 11/20 Description: Contour8 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 3mm/0mm Maximum stepdown: 1.8mm	Maximum Z: 15mm Minimum Z: -21.24mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 3991.41mm Rapid Distance: 68.44mm Estimated Cycle Time: 3m:7s (2.2%) Coolant: Flood	T1 D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 12/20 Description: Pocket4 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 6mm Maximum stepover: 5mm	Maximum Z: 15mm Minimum Z: -21.2mm Maximum Spindle Speed: 4160rpm Maximum Feedrate: 1100mm/min Cutting Distance: 1511.46mm Rapid Distance: 447.04mm Estimated Cycle Time: 1m:34s (1.1%) Coolant: Flood	T2 D2 L2 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	
Operation 13/20 Description: Contour9 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 19mm/0mm Maximum stepdown: 0.9mm	Maximum Z: 15mm Minimum Z: -26.52mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 7601.15mm Rapid Distance: 78.22mm Estimated Cycle Time: 5m:49s (4.1%) Coolant: Flood	T1 D1 L1 Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	

Operation 14/20 Description: Contour10 Strategy: Contour WCS: #0 Tolerance: 0mm Stock to Leave: 3mm/0mm Maximum stepdown: 0.9mm	Maximum Z: 15mm Minimum Z: -26.52mm Maximum Spindle Speed: 1465rpm Maximum Feedrate: 1545mm/min Cutting Distance: 6941.92mm Rapid Distance: 78.22mm Estimated Cycle Time: 5m:24s (3.8%) Coolant: Flood	**T1 D1 L1** Type: face mill Diameter: 63mm Taper Angle: 45° Length: 50mm Flutes: 5	
Operation 15/20 Description: Pocket5 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 3mm Maximum stepover: 3mm	Maximum Z: 15mm Minimum Z: -26.52mm Maximum Spindle Speed: 4160rpm Maximum Feedrate: 1100mm/min Cutting Distance: 4634.74mm Rapid Distance: 72.11mm Estimated Cycle Time: 4m:15s (3%) Coolant: Flood	**T2 D2 L2** Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 4 Description: 16mm Flat Endmill	
Operation 16/20 Description: Scallop1 Strategy: Scallop WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepover: 0.22mm	Maximum Z: 15mm Minimum Z: -16.54mm Maximum Spindle Speed: 3300rpm Maximum Feedrate: 700mm/min Cutting Distance: 46307.38mm Rapid Distance: 129.92mm Estimated Cycle Time: 1h:6m:26s (47.3%) Coolant: Flood	**T3 D3 L3** Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 27.94mm Flutes: 4 Description: 1/2" Ball Endmill	
Operation 17/20 Description: Drill1 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -31.52mm Maximum Spindle Speed: 2700rpm Maximum Feedrate: 33mm/min Cutting Distance: 100mm Rapid Distance: 1091.26mm Estimated Cycle Time: 3m:15s (2.3%) Coolant: Flood	**T4 D4 L4** Type: center drill Diameter: 6.35mm Tip Angle: 118° Length: 60mm Flutes: 2 Description: #3 Center Drill	
Operation 18/20 Description: Drill1 (2) Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -40.52mm Maximum Spindle Speed: 2700rpm Maximum Feedrate: 33mm/min Cutting Distance: 228mm Rapid Distance: 1337.55mm Estimated Cycle Time: 7m:11s (5.1%) Coolant: Flood	**T5 D5 L5** Type: drill Diameter: 4.76mm Tip Angle: 118° Length: 50.16mm Flutes: 1 Description: 3/16	
Operation 19/20 Description: Drill2 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -40.52mm Maximum Spindle Speed: 2000rpm Maximum Feedrate: 33mm/min Cutting Distance: 76mm Rapid Distance: 674.86mm Estimated Cycle Time: 2m:26s (1.7%) Coolant: Flood	**T6 D6 L6** Type: drill Diameter: 6.35mm Tip Angle: 118° Length: 66.04mm Flutes: 1 Description: 1/4	
Operation 20/20 Description: Drill2 (2) Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -33.02mm Maximum Spindle Speed: 1150rpm Maximum Feedrate: 50mm/min Cutting Distance: 46mm Rapid Distance: 644.86mm Estimated Cycle Time: 1m:3s (0.7%) Coolant: Flood	**T7 D7 L7** Type: flat end mill Diameter: 11.11mm Length: 42mm Flutes: 3 Description: 12mm Flat Endmill	

Work route for mold cavity machining

Setup

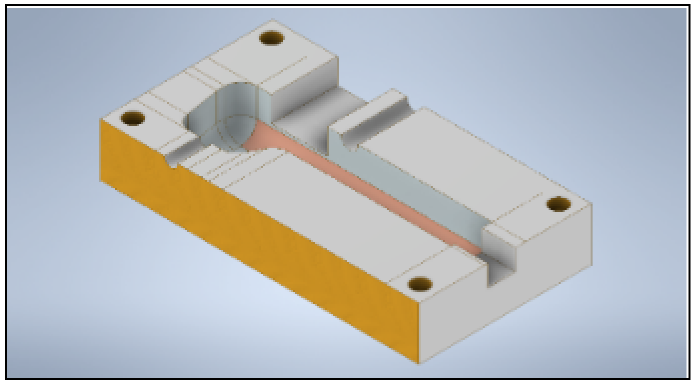
WCS: #0

Stock:
DX: 207mm
DY: 112mm
DZ: 34.3mm

Part:
DX: 207mm
DY: 112mm
DZ: 34.3mm

Stock Lower in WCS #0:
X: -103.5mm
Y: -56mm
Z: -34.3mm

Stock Upper in WCS #0:
X: 103.5mm
Y: 56mm
Z: 0mm



Total

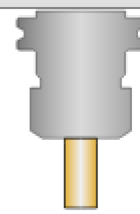
Number Of Operations: 21
Number Of Tools: 9
Tools: T1 T2 T3 T4 T5 T6 T7 T8 T9
Maximum Z: 15mm
Minimum Z: -37mm
Maximum Feedrate: 1000mm/min
Maximum Spindle Speed: 7000rpm
Cutting Distance: 117554.94mm
Rapid Distance: 9423.71mm
Estimated Cycle Time: 3h:46m:47s

Tools

T1 D1 L1
Type: flat end mill
Diameter: 16mm
Length: 34.5mm
Flutes: 3
Description: 16mm Flat Endmill

Minimum Z: -27.56mm
Maximum Feed: 1000mm/min
Maximum Spindle Speed: 7000rpm
Cutting Distance: 8342.32mm
Rapid Distance: 2133.37mm
Estimated Cycle Time: 16m:27s (7.3%)

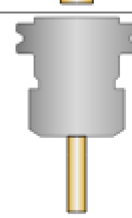
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T2 D2 L2
Type: flat end mill
Diameter: 9.53mm
Length: 40mm
Flutes: 4
Description: 3/8" Flat Endmill

Minimum Z: -28mm
Maximum Feed: 280mm/min
Maximum Spindle Speed: 1670rpm
Cutting Distance: 1011.61mm
Rapid Distance: 271.56mm
Estimated Cycle Time: 4m:9s (1.8%)

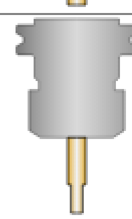
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T3 D3 L3
Type: flat end mill
Diameter: 6mm
Length: 40mm
Flutes: 3
Description: 6mm Flat Endmill

Minimum Z: -28.49mm
Maximum Feed: 180mm/min
Maximum Spindle Speed: 1550rpm
Cutting Distance: 3398.81mm
Rapid Distance: 600.88mm
Estimated Cycle Time: 19m:2s (8.4%)

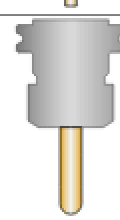
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T4 D4 L4
Type: ball end mill
Diameter: 12.7mm
Corner Radius: 6.35mm
Length: 50.8mm
Flutes: 3
Description: 1/2" Ball Endmill

Minimum Z: -28.91mm
Maximum Feed: 700mm/min
Maximum Spindle Speed: 3300rpm
Cutting Distance: 29066.23mm
Rapid Distance: 1747.1mm
Estimated Cycle Time: 42m:2s (18.5%)

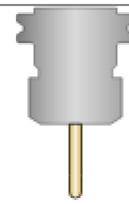
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T5 D5 L5
Type: ball end mill
Diameter: 6.35mm
Corner Radius: 3.17mm
Length: 40mm
Flutes: 3
Description: 1/4" Ball Endmill

Minimum Z: -30.32mm
Maximum Feed: 590mm/min
Maximum Spindle Speed: 5200rpm
Cutting Distance: 75299.99mm
Rapid Distance: 936.07mm
Estimated Cycle Time: 2h:8m:55s (56.8%)

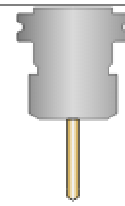
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T6 D6 L6
Type: center drill
Diameter: 6.35mm
Tip Angle: 118°
Length: 45mm
Flutes: 2
Description: #3 Center Drill

Minimum Z: -6mm
Maximum Feed: 33mm/min
Maximum Spindle Speed: 2700rpm
Cutting Distance: 44mm
Rapid Distance: 430.68mm
Estimated Cycle Time: 1m:25s (0.6%)

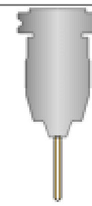
Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35



T7 D7 L7
Type: drill
Diameter: 4.76mm
Tip Angle: 118°
Length: 50.16mm
Flutes: 1
Description: 3/16

Minimum Z: -37mm
Maximum Feed: 33mm/min
Maximum Spindle Speed: 2700rpm
Cutting Distance: 170mm
Rapid Distance: 1432.68mm
Estimated Cycle Time: 5m:26s (2.4%)

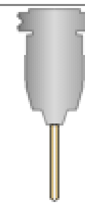
Holder: Maritool CAT40-APU13 Drill Chuck
Comment: Maritool CAT40-APU13
Vendor: Maritool
Product: CAT40-APU13



T8 D8 L8
Type: drill
Diameter: 6.35mm
Tip Angle: 118°
Length: 66.04mm
Flutes: 1
Description: 1/4

Minimum Z: -37mm
Maximum Feed: 33mm/min
Maximum Spindle Speed: 2000rpm
Cutting Distance: 170mm
Rapid Distance: 1432.68mm
Estimated Cycle Time: 5m:26s (2.4%)

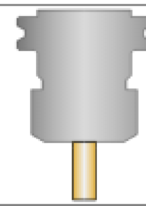
Holder: Maritool CAT40-APU13 Drill Chuck
Comment: Maritool CAT40-APU13
Vendor: Maritool
Product: CAT40-APU13



T9 D9 L9
Type: flat end mill
Diameter: 11.11mm
Length: 27.5mm
Flutes: 3
Description: 12mm Flat Endmill

Minimum Z: -8mm
Maximum Feed: 50mm/min
Maximum Spindle Speed: 1150rpm
Cutting Distance: 52mm
Rapid Distance: 438.68mm
Estimated Cycle Time: 1m:8s (0.5%)

Holder: Maritool CAT40-ER32-2.35
Comment: Maritool CAT40-ER32-2.35
Vendor: Maritool
Product: CAT40-ER32-2.35

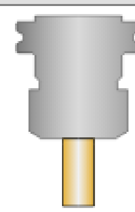


Operations

Operation 1/21
Description: Pocket1
Strategy: Pocket
WCS: #0
Tolerance: 0.01mm
Stock to Leave: 0.5mm/0.1mm
Maximum stepdown: 2.5mm
Maximum stepover: 15.2mm

Maximum Z: 15mm
Minimum Z: -16.22mm
Maximum Spindle Speed: 6000rpm
Maximum Feedrate: 600mm/min
Cutting Distance: 1767.2mm
Rapid Distance: 41.12mm
Estimated Cycle Time: 3m:21s (1.5%)
Coolant: Flood

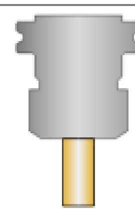
T1 D1 L1
Type: flat end mill
Diameter: 16mm
Length: 34.5mm
Flutes: 3
Description: 16mm Flat Endmill



Operation 2/21
Description: Pocket2
Strategy: Pocket
WCS: #0
Tolerance: 0.01mm
Stock to Leave: 0.5mm/0.1mm
Maximum stepdown: 2.5mm
Maximum stepover: 15.2mm

Maximum Z: 15mm
Minimum Z: -13.42mm
Maximum Spindle Speed: 6000rpm
Maximum Feedrate: 600mm/min
Cutting Distance: 292.35mm
Rapid Distance: 38.32mm
Estimated Cycle Time: 45s (0.3%)
Coolant: Flood

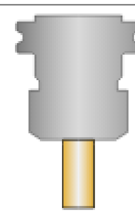
T1 D1 L1
Type: flat end mill
Diameter: 16mm
Length: 34.5mm
Flutes: 3
Description: 16mm Flat Endmill

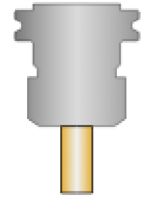
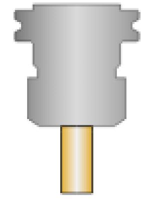
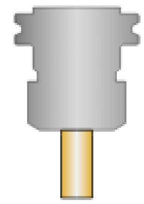
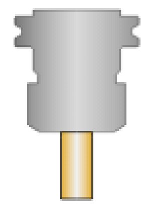
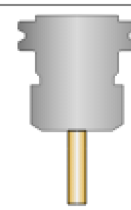
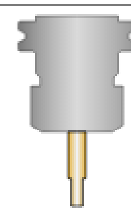
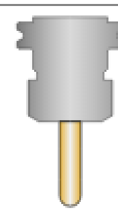
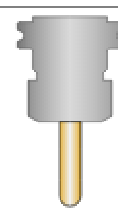


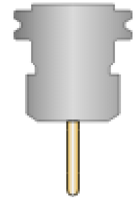
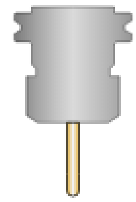
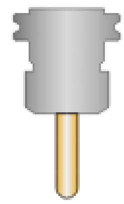
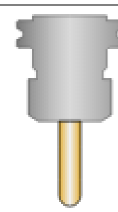
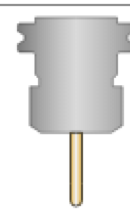
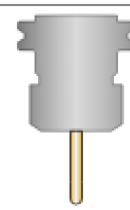
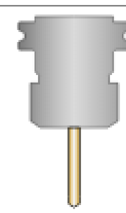
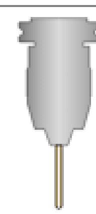
Operation 3/21
Description: Pocket3
Strategy: Pocket
WCS: #0
Tolerance: 0.01mm
Stock to Leave: 0.1mm
Maximum stepdown: 9mm
Maximum stepover: 15.2mm

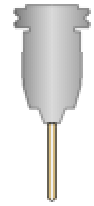
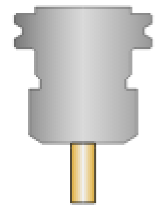
Maximum Z: 15mm
Minimum Z: -16.22mm
Maximum Spindle Speed: 7000rpm
Maximum Feedrate: 1000mm/min
Cutting Distance: 406.45mm
Rapid Distance: 34.62mm
Estimated Cycle Time: 25s (0.2%)
Coolant: Flood

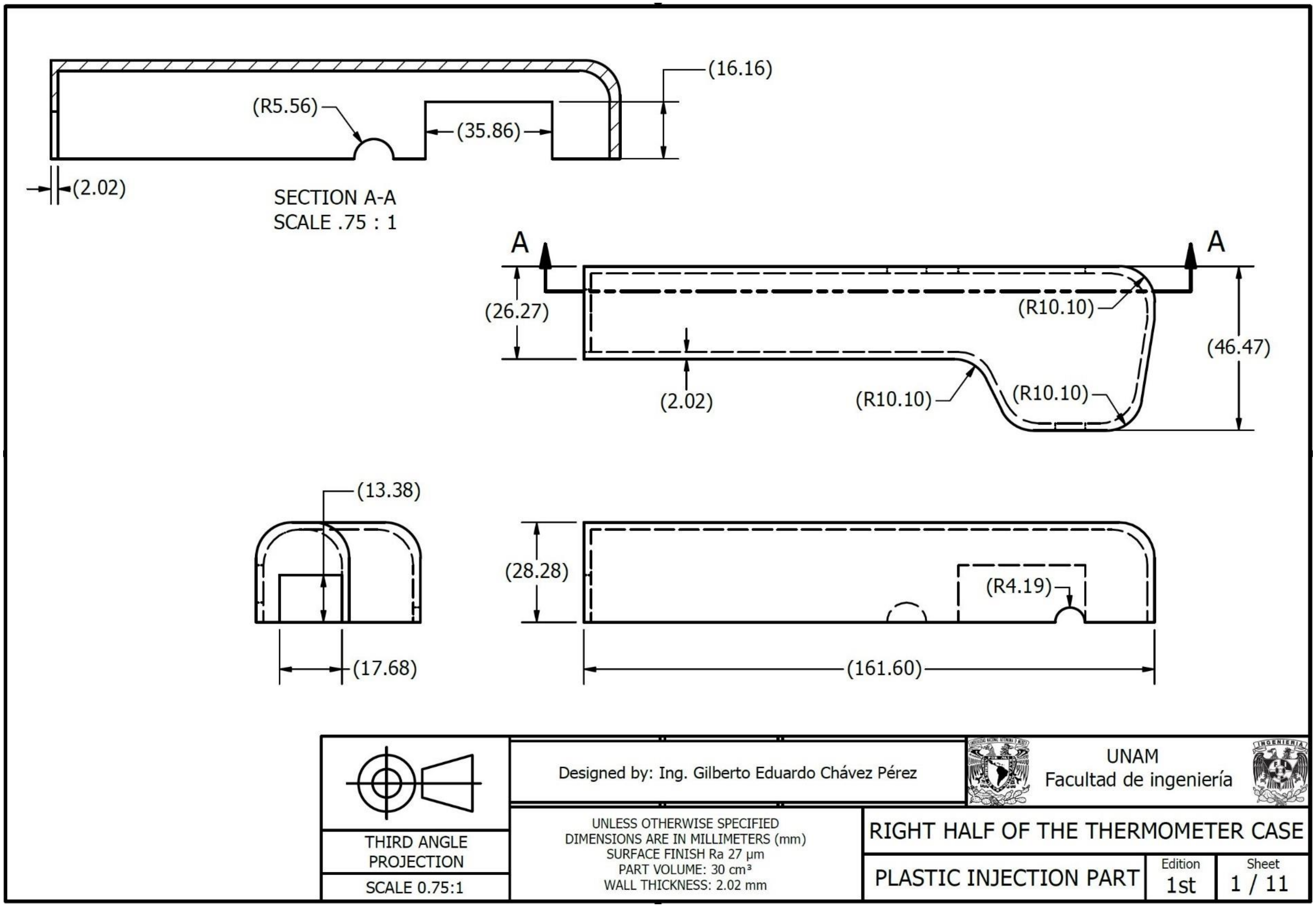
T1 D1 L1
Type: flat end mill
Diameter: 16mm
Length: 34.5mm
Flutes: 3
Description: 16mm Flat Endmill



Operation 4/21 Description: Pocket4 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm Maximum stepdown: 9mm Maximum stepover: 15.2mm	Maximum Z: 15mm Minimum Z: -13.42mm Maximum Spindle Speed: 7000rpm Maximum Feedrate: 1000mm/min Cutting Distance: 152.13mm Rapid Distance: 31.74mm Estimated Cycle Time: 17s (0.1%) Coolant: Flood	**T1** D1 L1 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 3 Description: 16mm Flat Endmill	
Operation 5/21 Description: Pocket5 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 9mm Maximum stepover: 15.2mm	Maximum Z: 15mm Minimum Z: -16.32mm Maximum Spindle Speed: 7000rpm Maximum Feedrate: 1000mm/min Cutting Distance: 504.57mm Rapid Distance: 34.72mm Estimated Cycle Time: 34s (0.3%) Coolant: Flood	**T1** D1 L1 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 3 Description: 16mm Flat Endmill	
Operation 6/21 Description: Pocket6 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 9mm Maximum stepover: 15.2mm	Maximum Z: 15mm Minimum Z: -13.52mm Maximum Spindle Speed: 7000rpm Maximum Feedrate: 1000mm/min Cutting Distance: 147.55mm Rapid Distance: 49.58mm Estimated Cycle Time: 32s (0.2%) Coolant: Flood	**T1** D1 L1 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 3 Description: 16mm Flat Endmill	
Operation 7/21 Description: Pocket7 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm/1mm Maximum stepdown: 2.5mm Maximum stepover: 15.2mm	Maximum Z: 15mm Minimum Z: -27.56mm Maximum Spindle Speed: 6000rpm Maximum Feedrate: 600mm/min Cutting Distance: 5072.07mm Rapid Distance: 1903.27mm Estimated Cycle Time: 10m:33s (4.7%) Coolant: Flood	**T1** D1 L1 Type: flat end mill Diameter: 16mm Length: 34.5mm Flutes: 3 Description: 16mm Flat Endmill	
Operation 8/21 Description: Pocket8 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 1.1mm/0.5mm Maximum stepdown: 2mm Maximum stepover: 9.05mm	Maximum Z: 15mm Minimum Z: -28mm Maximum Spindle Speed: 1670rpm Maximum Feedrate: 280mm/min Cutting Distance: 1011.61mm Rapid Distance: 271.56mm Estimated Cycle Time: 4m:9s (1.8%) Coolant: Flood	**T2** D2 L2 Type: flat end mill Diameter: 9.53mm Length: 40mm Flutes: 4 Description: 3/8" Flat Endmill	
Operation 9/21 Description: Pocket9 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.8mm/0.08mm Maximum stepdown: 1mm Maximum stepover: 5.7mm	Maximum Z: 15mm Minimum Z: -28.49mm Maximum Spindle Speed: 1550rpm Maximum Feedrate: 180mm/min Cutting Distance: 3398.81mm Rapid Distance: 600.88mm Estimated Cycle Time: 19m:2s (8.4%) Coolant: Flood	**T3** D3 L3 Type: flat end mill Diameter: 6mm Length: 40mm Flutes: 3 Description: 6mm Flat Endmill	
Operation 10/21 Description: Pocket10 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm Maximum stepdown: 0.21mm Maximum stepover: 1.2mm	Maximum Z: 15mm Minimum Z: -18.2mm Maximum Spindle Speed: 3300rpm Maximum Feedrate: 700mm/min Cutting Distance: 3511.2mm Rapid Distance: 300.94mm Estimated Cycle Time: 5m:5s (2.2%) Coolant: Flood	**T4** D4 L4 Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 50.8mm Flutes: 3 Description: 1/2" Ball Endmill	
Operation 11/21 Description: Pocket11 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm/0.2mm Maximum stepdown: 0.21mm Maximum stepover: 1.2mm	Maximum Z: 15mm Minimum Z: -28.91mm Maximum Spindle Speed: 3300rpm Maximum Feedrate: 700mm/min Cutting Distance: 22124.26mm Rapid Distance: 1386.57mm Estimated Cycle Time: 31m:54s (14.1%) Coolant: Flood	**T4** D4 L4 Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 50.8mm Flutes: 3 Description: 1/2" Ball Endmill	

Operation 12/21 Description: Pocket12 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 1mm Maximum stepover: 0.2mm	Maximum Z: 15mm Minimum Z: -18.3mm Maximum Spindle Speed: 5200rpm Maximum Feedrate: 590mm/min Cutting Distance: 12408.67mm Rapid Distance: 117.63mm Estimated Cycle Time: 21m:5s (9.3%) Coolant: Flood	**T5 D5 L5** Type: ball end mill Diameter: 6.35mm Corner Radius: 3.17mm Length: 40mm Flutes: 3 Description: 1/4" Ball Endmill	
Operation 13/21 Description: Pocket13 Strategy: Pocket WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepdown: 0.16mm Maximum stepover: 0.24mm	Maximum Z: 15mm Minimum Z: -30.32mm Maximum Spindle Speed: 5200rpm Maximum Feedrate: 590mm/min Cutting Distance: 56887.92mm Rapid Distance: 457.06mm Estimated Cycle Time: 1h:36m:56s (42.7%) Coolant: Flood	**T5 D5 L5** Type: ball end mill Diameter: 6.35mm Corner Radius: 3.17mm Length: 40mm Flutes: 3 Description: 1/4" Ball Endmill	
Operation 14/21 Description: Pocket14 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm Maximum stepdown: 0.21mm Maximum stepover: 1.2mm	Maximum Z: 15mm Minimum Z: -3.15mm Maximum Spindle Speed: 3300rpm Maximum Feedrate: 700mm/min Cutting Distance: 2826.24mm Rapid Distance: 30.61mm Estimated Cycle Time: 4m:10s (1.8%) Coolant: Flood	**T4 D4 L4** Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 50.8mm Flutes: 3 Description: 1/2" Ball Endmill	
Operation 15/21 Description: Pocket14 (2) Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm Maximum stepdown: 0.21mm Maximum stepover: 1.2mm	Maximum Z: 15mm Minimum Z: -1.47mm Maximum Spindle Speed: 3300rpm Maximum Feedrate: 700mm/min Cutting Distance: 604.52mm Rapid Distance: 28.99mm Estimated Cycle Time: 54s (0.4%) Coolant: Flood	**T4 D4 L4** Type: ball end mill Diameter: 12.7mm Corner Radius: 6.35mm Length: 50.8mm Flutes: 3 Description: 1/2" Ball Endmill	
Operation 16/21 Description: Pocket15 Strategy: Pocket WCS: #0 Tolerance: 0.01mm Stock to Leave: 0.1mm Maximum stepdown: 0.5mm Maximum stepover: 1.5mm	Maximum Z: 15mm Minimum Z: -6mm Maximum Spindle Speed: 4350rpm Maximum Feedrate: 520mm/min Cutting Distance: 1727.63mm Rapid Distance: 238.54mm Estimated Cycle Time: 3m:38s (1.6%) Coolant: Flood	**T5 D5 L5** Type: ball end mill Diameter: 6.35mm Corner Radius: 3.17mm Length: 40mm Flutes: 3 Description: 1/4" Ball Endmill	
Operation 17/21 Description: Scallop1 Strategy: Scallop WCS: #0 Tolerance: 0mm Stock to Leave: 0mm Maximum stepover: 0.24mm	Maximum Z: 15mm Minimum Z: -5.62mm Maximum Spindle Speed: 5200rpm Maximum Feedrate: 590mm/min Cutting Distance: 4275.76mm Rapid Distance: 122.84mm Estimated Cycle Time: 7m:16s (3.2%) Coolant: Flood	**T5 D5 L5** Type: ball end mill Diameter: 6.35mm Corner Radius: 3.17mm Length: 40mm Flutes: 3 Description: 1/4" Ball Endmill	
Operation 18/21 Description: Drill1 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -6mm Maximum Spindle Speed: 2700rpm Maximum Feedrate: 33mm/min Cutting Distance: 44mm Rapid Distance: 430.68mm Estimated Cycle Time: 1m:25s (0.6%) Coolant: Flood	**T6 D6 L6** Type: center drill Diameter: 6.35mm Tip Angle: 118° Length: 45mm Flutes: 2 Description: #3 Center Drill	
Operation 19/21 Description: Drill2 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -37mm Maximum Spindle Speed: 2700rpm Maximum Feedrate: 33mm/min Cutting Distance: 170mm Rapid Distance: 1432.68mm Estimated Cycle Time: 5m:26s (2.4%) Coolant: Flood	**T7 D7 L7** Type: drill Diameter: 4.76mm Tip Angle: 118° Length: 50.16mm Flutes: 1 Description: 3/16	

Operation 20/21 Description: Drill3 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -37mm Maximum Spindle Speed: 2000rpm Maximum Feedrate: 33mm/min Cutting Distance: 170mm Rapid Distance: 1432.68mm Estimated Cycle Time: 5m:26s (2.4%) Coolant: Flood	**T8** D8 L8 Type: drill Diameter: 6.35mm Tip Angle: 118° Length: 66.04mm Flutes: 1 Description: 1/4	
Operation 21/21 Description: Drill5 Strategy: Drilling WCS: #0 Tolerance: 0.01mm	Maximum Z: 15mm Minimum Z: -8mm Maximum Spindle Speed: 1150rpm Maximum Feedrate: 50mm/min Cutting Distance: 52mm Rapid Distance: 438.68mm Estimated Cycle Time: 1m:8s (0.5%) Coolant: Flood	**T9** D9 L9 Type: flat end mill Diameter: 11.11mm Length: 27.5mm Flutes: 3 Description: 12mm Flat Endmill	


(16.16)
(R5.56)
(35.86)
(2.02)
SECTION A-A
SCALE .75 : 1
A
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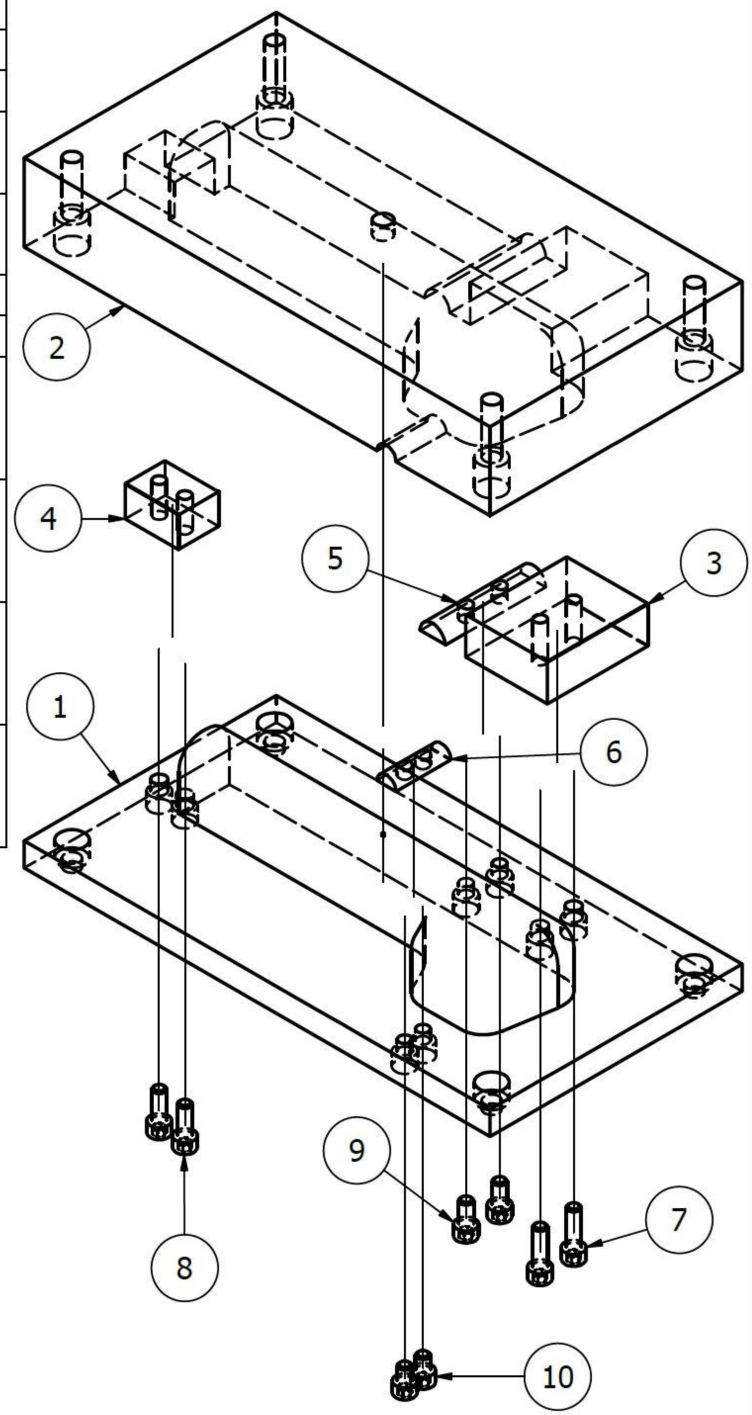
(26.27)
(R10.10)
(46.47)
(2.02)
(R10.10)
(R10.10)
(13.38)
(28.28)
(R4.19)
(17.68)
(161.60)
Designed by: Ing. Gilberto Eduardo Chávez Pérez
UNAM
Facultad de ingeniería
THIRD ANGLE PROJECTION
SCALE 0.75:1
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS (mm)
SURFACE FINISH Ra 27 μm
PART VOLUME: 30 cm³
WALL THICKNESS: 2.02 mm
RIGHT HALF OF THE THERMOMETER CASE
PLASTIC INJECTION PART
Edition
1st
Sheet
1 / 11

MOLD ASSEMBLY: PART LIST		
ITEM	QTY	PART NAME
1	1	Mold core
2	1	Mold cavity
3	1	Large rectangular insert
4	1	Small rectangular insert
5	1	Large circular insert
6	1	Small circular insert
7	2	Socket head cap screw -3/16"-24 UNC 5/8"-Thread length
8	2	Socket head cap screw -3/16"-24 UNC 1/2"-Thread length
9	2	Socket head cap screw -3/16"-24 UNC 3/8 "-Thread length
10	2	Socket head cap screw -3/16"-24-UNC 1/4"-Thread length



THIRD ANGLE PROJECTION

Designed by: Ing. Gilberto Eduardo Chávez Pérez

UNAM
Facultad de ingeniería

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS (mm)
SURFACE FINISH Ra 1.5 μm
MATERIAL: A36 STEEL

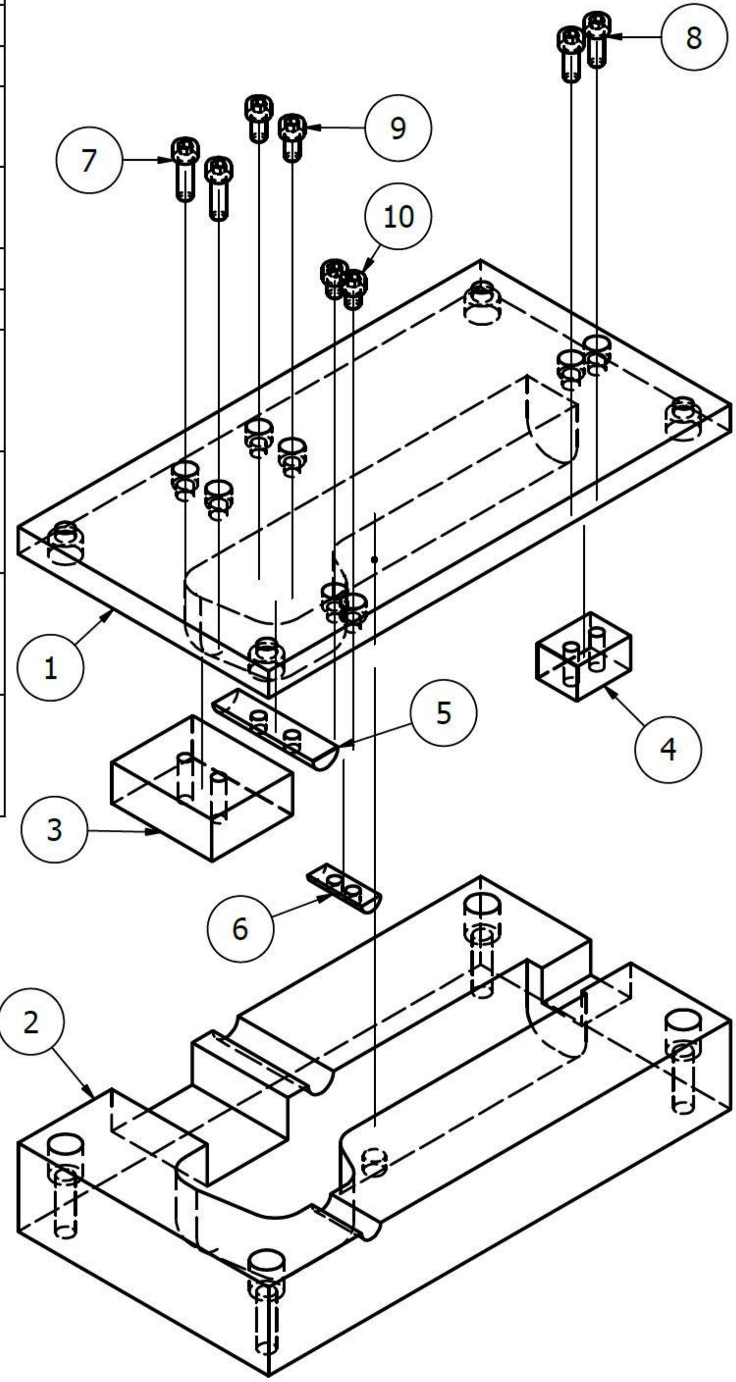
EXPLODED VIEW 1

MOLD ASSEMBLY

Edition 1st

Sheet 2 / 11

MOLD ASSEMBLY: PART LIST		
ITEM	QTY	PART NAME
1	1	Mold core
2	1	Mold cavity
3	1	Large rectangular insert
4	1	Small rectangular insert
5	1	Large circular insert
6	1	Small circular insert
7	2	Socket head cap screw -3/16"-24 UNC 5/8"-Thread length
8	2	Socket head cap screw -3/16"-24 UNC 1/2"-Thread length
9	2	Socket head cap screw -3/16"-24 UNC 3/8 "-Thread length
10	2	Socket head cap screw -3/16"-24-UNC 1/4"-Thread length



THIRD ANGLE PROJECTION

Designed by: Ing. Gilberto Eduardo Chávez Pérez

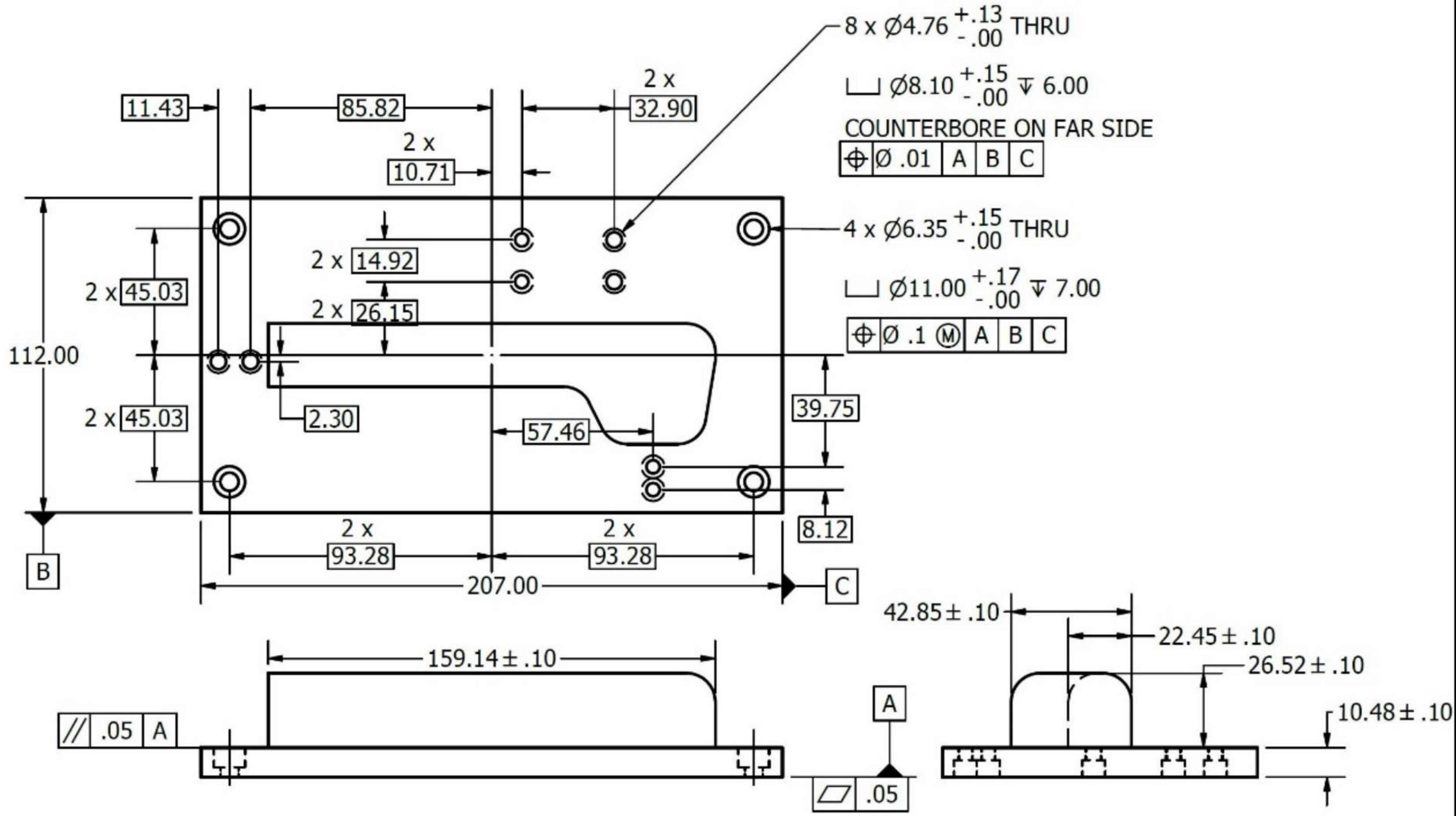
UNAM
Facultad de ingeniería

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS (mm)
SURFACE FINISH Ra 1.5 μm
MATERIAL: A36 STEEL

EXPLODED VIEW 2

MOLD ASSEMBLY

Edition	Sheet
1st	3 / 11



THIRD ANGLE PROJECTION

SCALE 1:2

Designed by: Ing. Gilberto Eduardo Chávez Pérez

UNAM
Facultad de ingeniería

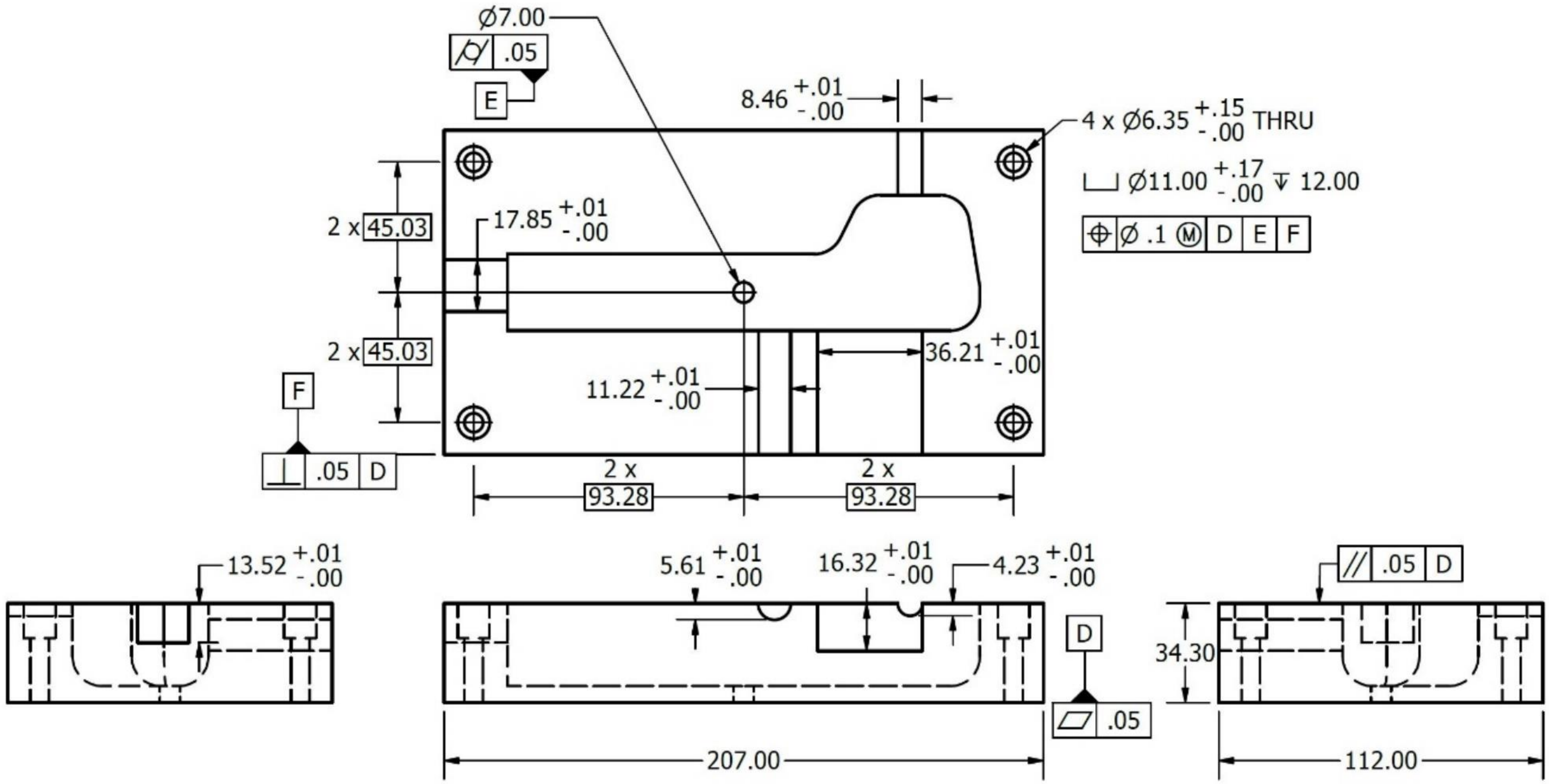
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm)
UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25
SURFACE FINISH Ra 1.5 µm
MATERIAL: A36 STEEL

MOLD CORE

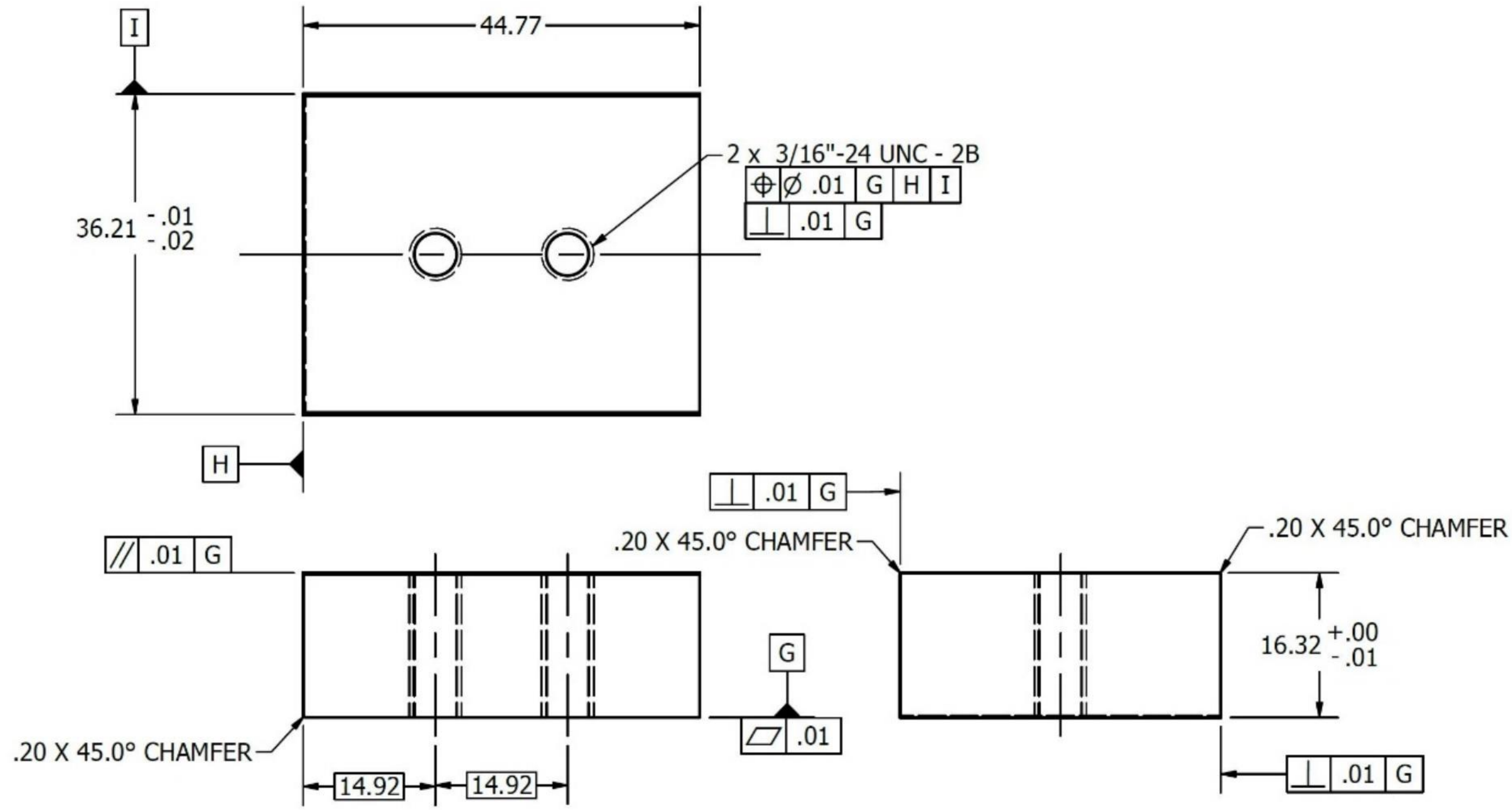
PART 1

Edition 1st

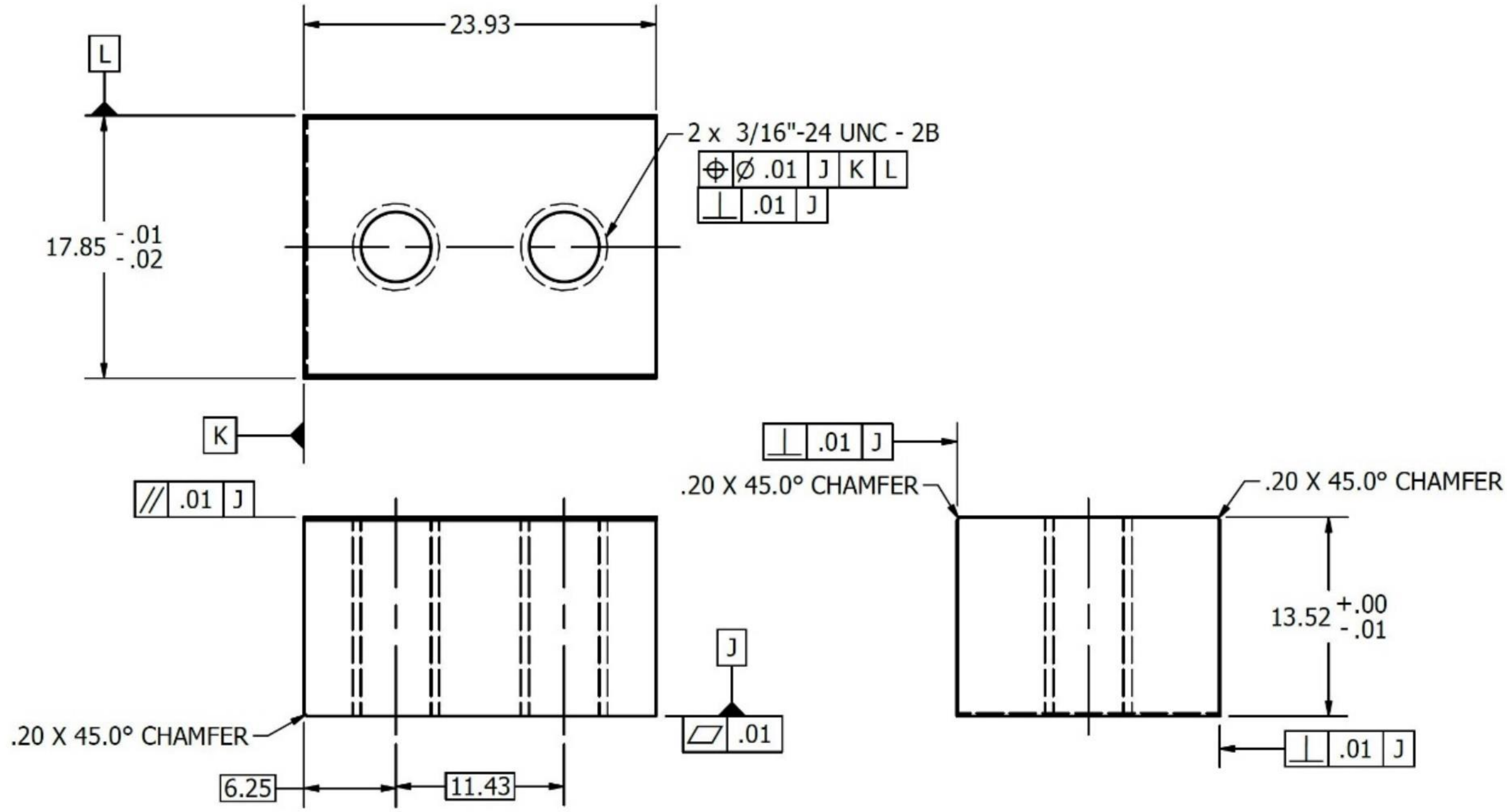
Sheet 4 / 11



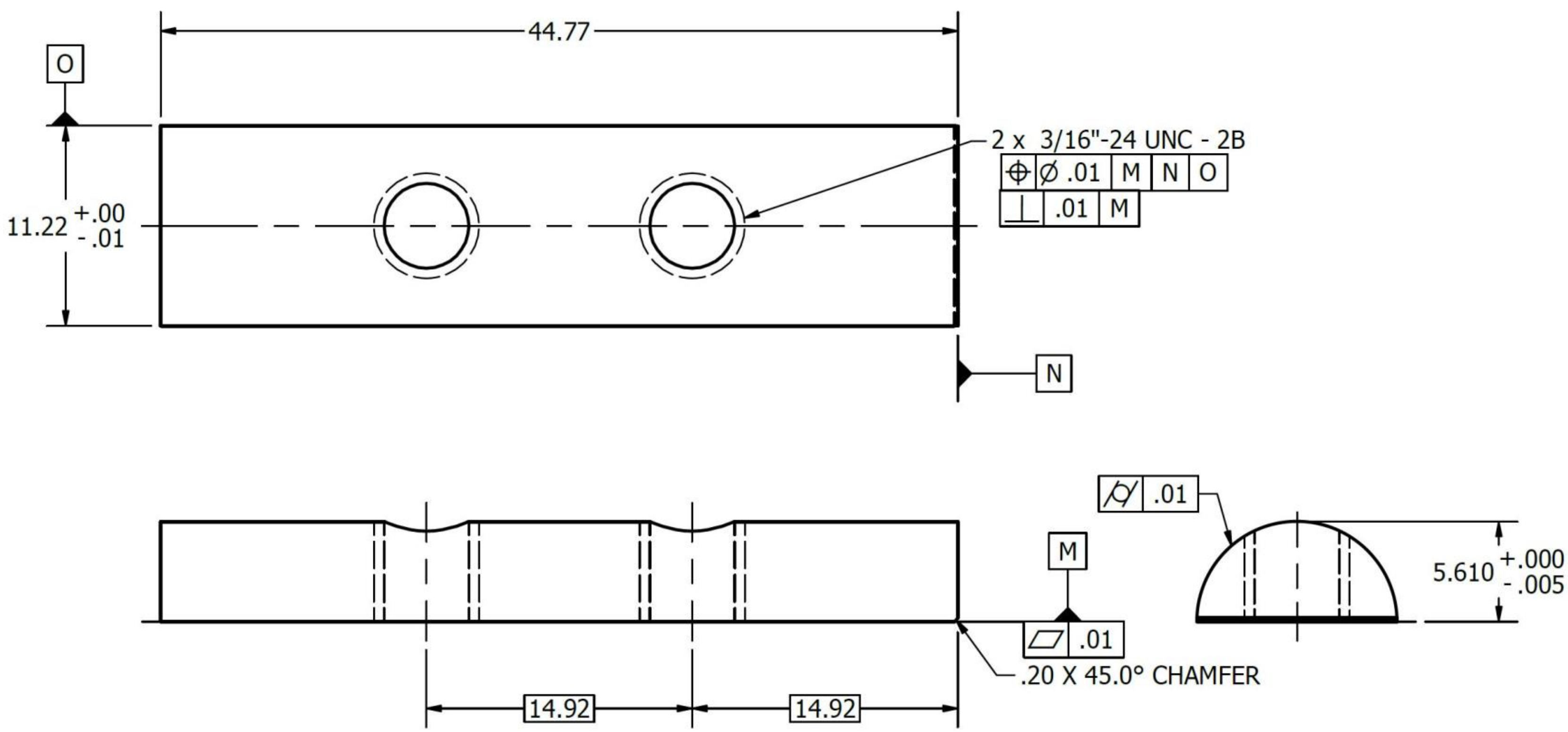
THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez	UNAM Facultad de ingeniería	
SCALE 1:2	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 μm MATERIAL: A36 STEEL	MOLD CAVITY PART 2	Edition 1st Sheet 5 / 11



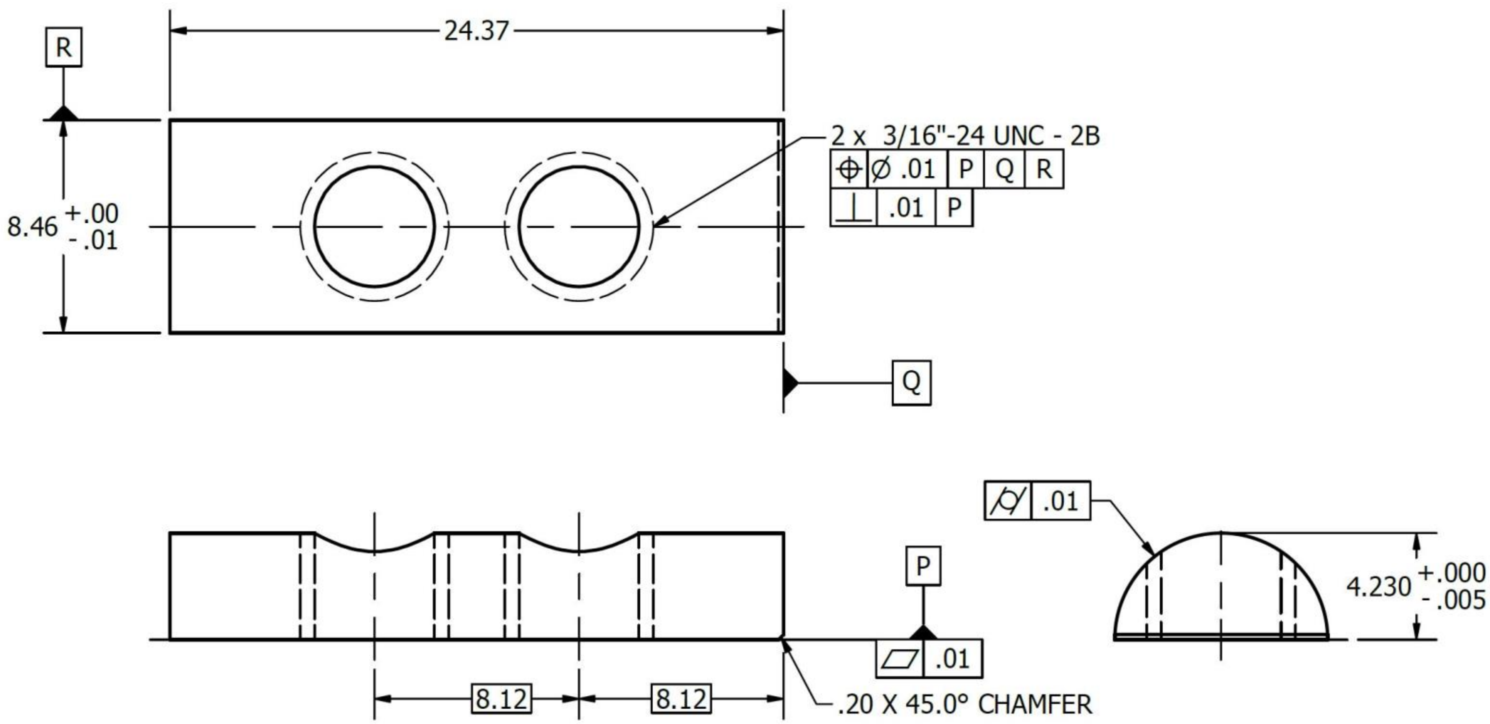
THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez	UNAM Facultad de ingeniería	
SCALE 1.5:1	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 µm MATERIAL: A36 STEEL	LARGE RECTANGULAR INSERT	
		PART 3	Edition 1st / Sheet 6 / 11



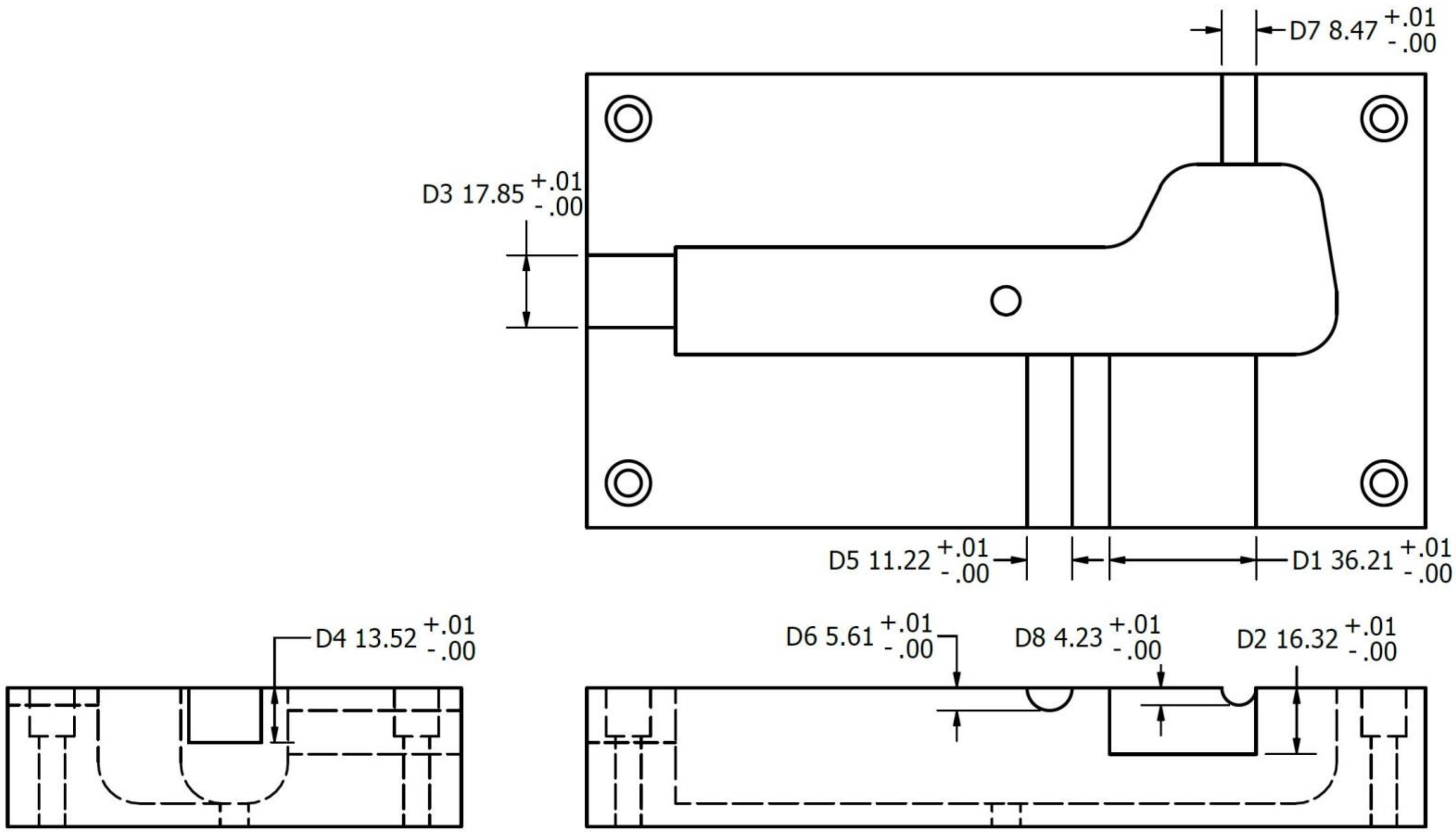
THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez	UNAM Facultad de ingeniería		
SCALE 2.5:1	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 µm MATERIAL: A36 STEEL	SMALL RECTANGULAR INSERT		
		PART 4	Edition 1st	Sheet 7 / 11



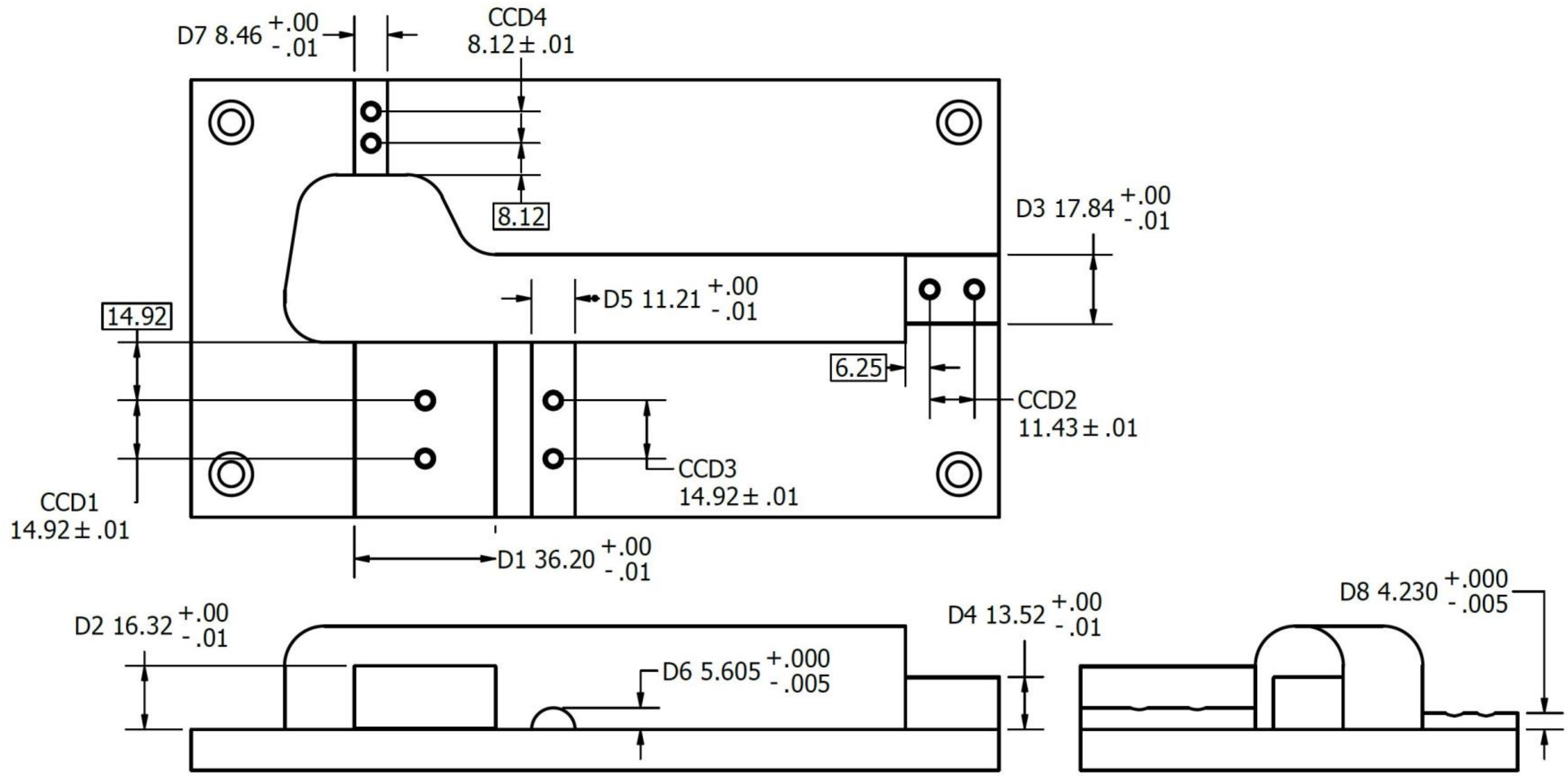
THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez		UNAM Facultad de ingeniería	
SCALE 3:1	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 µm MATERIAL: A36 STEEL	LARGE CIRCULAR INSERT		
		PART 5	Edition 1st	Sheet 8 / 11



THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez	UNAM Facultad de ingeniería
SCALE 4:1	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 μm MATERIAL: A36 STEEL	SMALL CIRCULAR INSERT PART 6 — Edition 1st — Sheet 9 / 11



THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez	UNAM Facultad de ingeniería	
SCALE 1:1.5	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 µm MATERIAL: A36 STEEL	QUALITY CHECKLIST DIMENSIONS MOLD CAVITY	Edition 1st Sheet 10 / 11



THIRD ANGLE PROJECTION	Designed by: Ing. Gilberto Eduardo Chávez Pérez		UNAM Facultad de ingeniería	
SCALE 1:1.5	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS (mm) UNSPECIFIED TOLERANCES ARE ASSUMED TO BE EQUAL TO ±0.25 SURFACE FINISH Ra 1.5 µm MATERIAL: A36 STEEL	QUALITY CHECKLIST DIMENSIONS		
		MOLD CORE ASSEMBLY	Edition 1st	Sheet 11 / 11

Appendix D. Quality criteria checklist

Table 41. Critical dimensions for the proper function of the mold

Quality criteria to verify in the CNC machined mold				
Features of the mold	**Design specification (Nominal value)**	**Obtained measurement**	**Fulfillment of the design specification**	**Features assembled, closed, and sealed correctly**
Cavity dimension D1	36.21 mm	36.17 mm	✗	✓
Cavity dimension D2	16.32 mm	16.33 mm	✓	✓
Cavity dimension D3	17.85 mm	17.85 mm	✓	✓
Cavity dimension D4	13.52 mm	13.53 mm	✓	✓
Cavity dimension D5	11.22 mm	11.23 mm	✓	✓
Cavity dimension D6	5.61 mm	5.62 mm	✓	✓
Cavity dimension D7	8.47 mm	8.53 mm	✗	✓
Cavity dimension D8	4.23 mm	4.23 mm	✓	✓
Core dimension D1	36.20 mm	36.16 mm	✗	✓
Core dimension D2	16.32 mm	16.32 mm	✓	✓
Core dimension D3	17.84 mm	17.84 mm	✓	✓
Core dimension D4	13.52 mm	13.52 mm	✓	✓
Core dimension D5	11.21 mm	11.21 mm	✓	✓
Core dimension D6	5.605 mm	5.62 mm	✗	✓
Core dimension D7	8.46 mm	8.53 mm	✗	✓
Core dimension D8	4.23 mm	4.23 mm	✓	✓

Table 42. Critical dimensions for assemble the mold core and the inserts

Quality criteria to verify in the CNC machined mold			
Features of the part	**Design specification**	**Obtained measurement**	**Fulfillment of the design specification**
Center-to-center distance 1	14.92 mm	14.92 mm	✓
Center-to-center distance 2	11.43 mm	11.43 mm	✓
Center-to-center distance 3	14.92 mm	14.92 mm	✓
Center-to-center distance 4	8.12 mm	8.12 mm	✓

Table 43. Mean surface roughness of the CNC machined mold

Average surface roughness of the mold			
Sample	**Design specification (µm)**	**Mean surface roughness (µm)**	**Fulfillment of the design specification**
A	1.50	0.68	✓
B	1.50	0.38	✓
C	1.50	0.50	✓
D	1.50	0.63	✓
E	1.50	0.43	✓
F	1.50	0.52	✓
G	1.50	0.47	✓
H	1.50	0.49	✓
I	1.50	0.57	✓
J	1.50	0.60	✓
K	1.50	0.30	✓
L	1.50	0.35	✓
M	1.50	0.43	✓
N	1.50	0.26	✓
O	1.50	0.56	✓
P	1.50	1.38	✓
Q	1.50	1.20	✓
R	1.50	0.95	✓
S	1.50	1.29	✓
T	1.50	1.14	✓
U	1.50	1.16	✓
V	1.50	0.12	✓
W	1.50	0.04	✓
X	1.50	0.03	✓
Y	1.50	0.06	✓
Average roughness of the mold = 0.58 ✓			

Table 44. Summary of the quality criteria verified in the plastic part

Quality criteria to verify in the plastic injected part		
Features of the part	**Design specification**	**Outcomes**
Cosmetically acceptable	No sink marks nor voids	✓
Mass	35.40 grams	35.39 grams
Surface roughness	27 µm	0.85 µm

Table 45. Different samples of weight measurements in the plastic part

Part mass verification	
Sample	Registered weight (g)
A	35.40
B	35.39
C	35.40
D	35.36
E	35.36
F	35.36
G	35.40
H	35.40
I	35.41
Mass of the part = 35.39 grams	

Table 46. Different samples of mean surface roughness of the plastic part

Average surface roughness of the part	
Sample	Mean surface roughness (µm)
A	0.78
B	1.00
C	0.85
D	0.81
E	0.84
Average roughness of the part = 0.856	