Applications of Additive Manufacturing in the Shopfloor: The case of the Wire Harness Industry

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Abstract

Injection molding has been the most used industrial process for plastic parts production. However, due to the high investment required, mainly on the injection molding machine and the molds required for each model produced, along with the warehousing costs, low design flexibility and high lead times have made industrial companies look for alternative production methods. To produce small/medium series parts, companies have been investing and developing different methods, with Additive Manufacturing (AM) appearing to be an alternative. Already commonly used to manufacture prototypes and tools, industries now want to explore ways to integrate the 3D Printing technologies in the production process of final speciality parts.

With considerable progress made already in aerospace, automotive and healthcare fields, AM methods are also being explored by wire harness companies for the production of components to the final assembly. Together with the product development department of Yazaki Saltano in Ovar, Portugal, a case study aiming to understand the feasibility of using 3D Printing technologies for manufacturing small/medium series parts as an alternative method to plastic injection molding used nowadays will be carried out. For the study, a comparative evaluation between the various Additive Manufacturing technologies will be developed in order to choose the most suitable method for the manufacturing of three specific plastic parts provided by the company. After that, a cost calculation method for both injection molding and the selected additive manufacturing technology will be designed in order to carry out a cost comparison between the production by each method. Finally, a sensitive analysis will be developed varying to key inputs: number of units produced per year and number of years. Based on the steps mentioned above, conclusions will be drawn.

Keywords: Injection Molding; Additive Manufacturing; 3D Printing; Small/Medium Series Parts

Resumo

A moldagem por injeção tem sido o processo industrial mais utilizado para a produção de peças plásticas. No entanto, devido ao elevado investimento necessário, principalmente na máquina de injeção e nos moldes necessários para cada modelo produzido, juntamente com os custos de armazenagem, a baixa flexibilidade de design e os elevados prazos de entrega fizeram com que as empresas industriais procurassem métodos de produção alternativos. Para produzir peças de pequenas/médias séries, as empresas têm vindo a investir e a desenvolver diferentes métodos, parecendo a Produção Aditiva (AM) ser uma alternativa. Já comummente utilizada para fabricar protótipos e ferramentas, as indústrias querem agora explorar formas de integrar as tecnologias de impressão em 3D no processo de produção de peças de especialidades finais.

Com consideráveis progressos já realizados nos campos aeroespacial, automóvel e da saúde, os métodos AM estão também a ser explorados por empresas de cablagem para a produção de componentes até à montagem final. Em conjunto com o departamento de desenvolvimento de produtos da Yazaki Saltano em Ovar, Portugal, será realizado um estudo de caso com o objetivo de compreender a viabilidade da utilização de tecnologias de impressão 3D para o fabrico de peças de pequenas/médias séries como um método alternativo à moldagem por injeção de plástico utilizada atualmente. Para o estudo, será desenvolvida uma avaliação comparativa entre as várias tecnologias de Fabrico de Aditivos a fim de escolher o método mais adequado para o fabrico de três peças plásticas específicas fornecidas pela empresa. Depois disso, será concebido um método de cálculo de custos tanto para a moldagem por injeção como para a tecnologia de fabrico de aditivos selecionada, a fim de realizar uma comparação de custos entre a produção por cada método. Finalmente, será desenvolvida uma análise sensível variando em função dos principais fatores de produção: número de unidades produzidas por ano e número de anos. Com base nas etapas acima mencionadas, serão tiradas conclusões.

Palavras-chave: Injeção plástica; Manufatura aditiva; Impressão 3D; Componentes de series pequenas

Index

List of Tables

List of Figures

List of Equations

Acronyms

3D – Three Dimensional.

ABS - Acrylonitrile Butadiene Styrene.

AM – Additive Manufacturing.

ASTM - American Society for Testing and Materials.

CAD – Computer-Aided Design.

CAM - Computer-Aided Manufacturing

CNRS - Centre National de la Recherche Scientifique (French National Center for Scientific Research)

DMLS - Direct Metal Laser Sintering.

E/E - Electrical and Electronic.

FDM - Fused Deposition Modelling.

IM – Injection Molding

LENS - Laser Engineered Net Shaping.

LOM - Laminated Object Manufacturing.

MJF – Multi Jet Fusion.

PETG – Polyethylene Terephthalate Glycol.

PLA - Polylactic Acid.

R&D – Research and Development.

RP - Rapid Prototyping.

SBJ - Sand Binder Jetting.

SLA – Stereolithography.

SLM - Selective Laser Melting.

SLS - Selective Laser Sintering.

USA – United States of America.

UV – Ultraviolet.

VW – Volkswagen.

WH – Wire Harness.

Chapter 1

1. Introduction

Additive Manufacturing (AM) or 3D Printing is a technology that took its first steps in 1980 and since then has grown in terms of both hardware/software and applications. There are several different processes, most of them aimed at the production of objects whose raw materials are polymers or metals. This technology is considered as a disruptive technology for how it can change the paradigm of production processes and delivery of new products. According to Dumitrescu & Nase (2016)[1], AM is part of the 4th industrial revolution, mainly known as "Industry 4.0", after the invention of the steam engine at the end of the 18th century, the emergence of new sources of energy as electricity, gas and oil at the end of the 19th century, and the development of nuclear energy and electronics in the second half of the 20th century.

Simultaneously, the wire harness industry has been a main supplier for major transportation industries, especially automotive, and has been growing with the increase of electric components in conventional cars and the growth of the electric car market.[2] The wiring harness assembly is the biggest and heaviest bought-in part in an automotive vehicle and it connects all electrical and electronic (E/E) components, being responsible for the energy and information flow within the car.[3] Their final assembly consists of not only cables, but also extra components, such as connectors, cable conduits, rotary clamps, cover sleeves, and protective tape. Currently, all these plastic or metal components are produced by injection processes.

Depending on their final application, purpose and the type of vehicle where they are inserted, many components in the wire harness process require low production volumes. Each of these small/medium series or short run parts require their own metal mold, which the cost varies greatly with the size and material of the part to be produced.[4] Besides the cost, a mold has the disadvantages of being totally inflexible in design, which in case of any defect or correction causes huge costs, and often being heavy, and therefore not user-friendly. In addition to the mold itself, the injection molding machine is required, entailing initial investment and maintenance costs. Furthermore, the costs of storing the injected parts and molds after they are produced must also be considered, even after the discontinuation of their production, since companies need to guarantee replacement parts to their customers during a certain period.

For that reason, companies have been investing in research and development in order to find alternative ways of producing these same parts at a lower cost, with Additive Manufacturing (AM) being one of the alternatives to produce auxiliary parts, prototypes and even final parts.

3D printing technologies have been gaining ground in the industry, and are already commonly used for prototyping. In general, the 3D Printing processes are split into seven groups: binder jetting, directed energy deposition, material extrusion, materials jetting, powder bed fusion, sheet lamination, and vat photopolymerisation. Each of these processes have their own technologies and work with specific types of materials. However, by still being a growing technology, AM still has some gaps compared to plastic injection, especially in terms of material variety, volume and speed of production. For this reason, for each particular case study it is necessary to conclude the feasibility of replacing one process with the other.

In partnership with Yazaki Corporation, the world leader in the wire harness industry, and with the support of the product development department of Yazaki's factory in Ovar, Portugal, a case study of three small/medium series parts for a vehicle application will be carried out, with the objective of concluding if an investment in 3D printing technology is financially justifiable to replace plastic injection molding in their production. Firstly, it will be required a comparison between the different processes and technologies, considering the characteristics and applications of the components under study as well as the necessary number of units. Selected the most suitable technology, the production costs per batch for both processes – additive manufacturing and plastic injection molding – will be calculated for the conditions of the case study. In order to perform further analysis, it will be developed a Cost Calculator tool to calculate the costs for both methods by inputting the number of units to produce per year and the number of years for the production. Finally, after those analysis, a conclusion will be taken on whether or not the investment in AM technology for the production of the parts in question is justified and under which conditions.

Chapter 2

2 Problem Definition

Chapter 2 describes and defines the problem under study, as well as the case study on which this paper will be based. Section 2.1 starts by introducing the concept of small/medium series parts and the costs associated with producing them through plastic injection processes. Thereafter, section 2.2 suggests the possibility of adopting additive manufacturing technologies as an alternative to plastic injection to produce these parts. Finally, section 2.3 presents the case study from Yazaki Ovar about the production of small/medium series parts by additive manufacturing.

2.1 The Problem of Small/Medium Series Injected Parts

Small/Medium series, or short run, injection parts are parts produced in small/medium batches by injection molding. These short runs are necessary for several purposes: for when accuracy and part performance are critical and so making production quality prototyping is necessary, for highly specialized parts that may be required in smaller quantities, or for standard parts used in final products with low production volumes.[5] A range of industries, including any industry where injection molding can be used for production, require small/medium series parts, and wire harness is no exception. Depending on the business's field and on each particular business unit, the production volume that establishes the difference between small, medium and large batches varies.

Even though these parts are very useful and important in the production process, there are some problems concerning the production of these kind of parts. The first problem is related to initial investment costs on molds and tools - for the injection of any given part, a unique mold is needed. The cost of that component differs based upon key factors, these being the volume, the design complexity, and the final application of the plastic part to be molded.[6] Since these factors are very variable and particular, so will be the price of a mold. While simple plastic injection molds can cost anywhere between \$3,000 and \$6,000, the price for a large, more complex high-production, multi-cavity mold can cost between \$25,000 and \$50,000 or more[6], which makes them normally a high impact cost driver. Nonetheless, the cost per unit produced and the production volume are indirectly proportional, meaning that the more parts manufactured, the lower the cost per part, as the high initial investment costs are diluted, which ultimately makes injection molding a more cost-effective production process for large volume production.[7] The problem, however, is that small/medium series parts are produced in small quantities.

Another problem is related to warehousing costs. Since the products have warranty contracts established by the companies with their customers, it is necessary for the industries to have spare parts and the respective molds stocked during a determined period, even after the model of a certain product is no longer produced. This factor implies several costs, such as the cost of human resources for inventory planning and management, and the cost of storage space, which can add 5% to 15% to the total cost of a product.[7] Additionally, there is a high risk that the spare parts will become obsolete, meaning that their molds, sometimes stored for years, will become useless.[9] Actually, it is estimated that 15% to 25% of inventory is scrapped each year because it is not sold.[7] This risk increases even more with small/medium series parts, since they are specialized parts with lower demand.

2.2 The Possibility of Additive Manufacturing as an Alternative Process to Injection Molding

To address the problems described above, industries have been looking for alternative processes for the production of small/medium series injection parts, as Additive Manufacturing (AM).[10] As first, while in injection molding investiment in tooling is required each time a new part will enter in production, AM has considerably low costs for a part with a new design. Additionally, this disruptive technology has minimal inventory risk by allowing to print as much as demanded, guaranteeing no unsold or obsolete finished parts or molds warehoused. Even in case of waste, in most of AM processes 95% to 98% of the misused material can be recycled in 3D Printing.[1] Moreover, the response time within the supply chain that Additive Manufacturing can provide is considerably shorter than injection molding. All these characteristics make industries to consider AM as a suitable alternative process for tailored small/medium batches.

However, it is also necessary to consider that in terms of available materials, for example, Additive Manufacturing is still limited in relation to injection molding, which sometimes makes it impossible to achieve key characteristics of the parts to be produced, such as fatigue, fracture and heat resistance, among others. Furthermore, this production technology often requires post-processing which can include cleaning the parts, painting, or surface treatments.

When considering AM as an alternative to conventional plastic injection molding for the production of small/medium batch parts, three central issues need to be addressed by companies:

I. Within the concept of Additive Manufacturing, and as detailed later in subsection 3.1.2, there are currently several printing technologies with different characteristics, used in diverse contexts with varied materials. Depending on the size, material and production volume of the final part to be printed, it is necessary to choose which 3D printing technology is most suitable and in which to invest.

II. As mentioned above, while the current plastic injection process remains the most cost-effective for large volume production, the 3D printing process may be more appropriate for small/medium series parts production. The second question is exactly up to which production volume it is more profitable to implement AM rather than injection molding. In other words, what is the break-even point between the two processes (Figure 1 - Break-even point of the production volume.Figure 1).

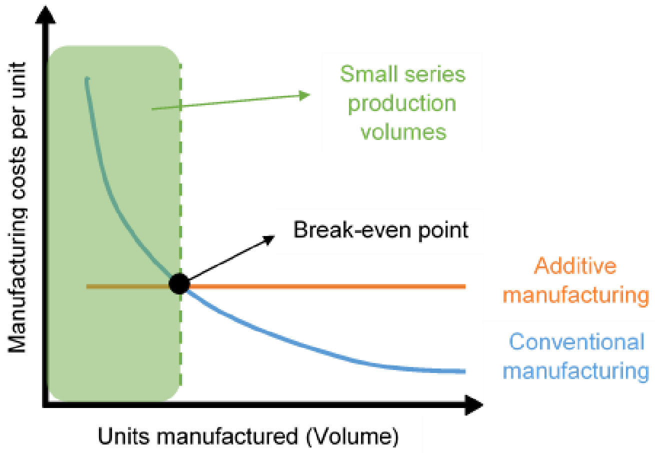

Figure 1 - Break-even point of the production volume.
Adapted from: https://www2.deloitte.com/us/en/insights/deloitte-review/issue-14/dr14-3d-opportunity.html[8]

III. As with any investment, it is of utmost importance to calculate the new technology's payback period, demonstrated in Figure 2, being that the amount of time needed to earn back the cost of the investment.[12] As such, it is important for companies that consider the adoption of 3D technologies to calculate that period in order to assess whether this time is justifiable or not.

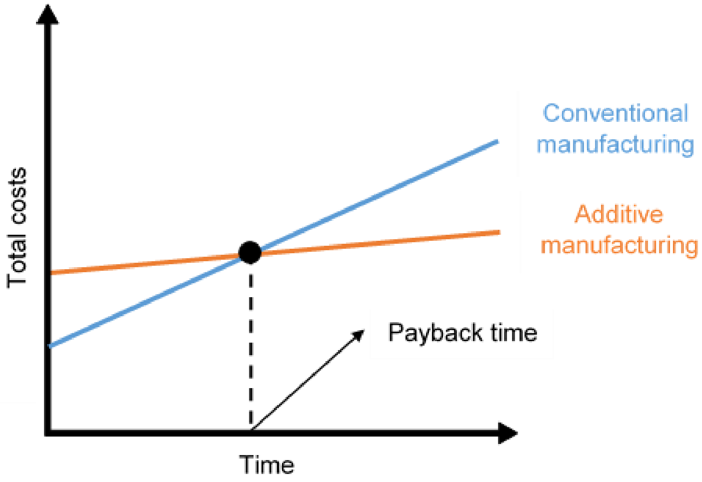

Figure 2 - Payback time of investing in additive manufacturing.
Adapted from: https://www.praxisframework.org/en/library/payback-method[13]

2.3 The Case Study of Yazaki

Within the framework of the problems raised in the previous section, a real case from Yazaki was selected to study the feasibility of adopting 3D printing technology as a replacement for plastic injection processes.

2.3.1 Historical and International Context of the Company

Starting as a small Japanese family business selling wiring harnesses for automobiles, the Yazaki Corporation was officially founded on October 8, 1941 in Tokyo, Japan. After Second World War, the company has grown rapidly and established itself abroad, especially due to the general trend of Japanese automotive companies to move production abroad to avoid trade sanctions in this period.[14]

Nowadays, the corporation offers a diverse range of products in the global automotive and energy system sectors, and has recently began to expand into a third sector, mainly in the areas of nursing care and environment-related businesses, providing in all of them a worldwide integrated business system of research and development, production, sales and local management.[15]

Yazaki has almost 245,000 employees spread over 143 companies present in 45 countries in Asia, Europe, Africa, and America. In 2019, the company achieved total sales of 1.714 billion yen, equivalent to approximately 16 billion dollars, being the currently global leader producer of automotive wiring harnesses.[14][15]

2.3.2 Case Study

In partnership with the Yazaki factory in Ovar, Portugal, a case study was outlined about the possible adoption of Additive Manufacturing processes to replace plastic injection processes for the manufacture of complementary small/medium series parts to the wire harness assembly, which have the function of conducting the wires inside the car where they are inserted in.

For the development of the study in question, three different plastic injected parts were considered. They have different sizes and characteristics so that the study is more comprehensive. These components belong to a high-end commercial car model belonging to a Yazaki customer, whose wiring three-dimensional schematic is shown Figure 3. This model has a lifetime of 7 years.

Figure 3 - Three-dimensional schematic of the wiring of the car model.

Of the various parts that make up this model, the three chosen have a required production of 22.000 parts per year, during the 7 years of this car model lifetime. These components, whose photos and technical drawings cannot be shared for confidentiality reasons, are the following:

a) Big Channel – Tower Shield Base Sub-Assy

The Tower Shield Base Sub-Assy is a big channel that has the function to protect and guide the wiring in the area of the suspension tower. The tooling cost of this part is 70,000€. The material used is polyamide 6.6 glass PA66-I.

b) Medium Channel – EPAS Shield LHD Assy

As the big channel, the medium channel, the EPAS Shield LHD Assy, has a wiring protection and guidance purpose in the area of the suspension tower. This channel has a tooling costs of 45,000€. The material used is PA66-I.

c) Small Clip – 80-Way Connector Clip

The last and smaller part selected for the case study was an 80-Way Connector Clip used to connect to an 80-way connector and fix to the car with a "Fir Tree" clip. The production costs considered for this component are mainly 25,000€ in tooling costs. As the medium channel, the small clip is produced with PA66-I.

Table 1 shows the general information of the parts resumed:

Table 1 - Parts' General Information

	Big Channel	Medium Channel	Small Clip
Technical name	Tower Shield Base Sub-Assy	EPAS Shield LHD Assy	80-Way Connector Clip
Material	PA66-I	PA66-I	PA66-I
Dimensions	400x320x130 mm	320x220x80 mm	42x20x10 mm
Approx. volume (block) [cm3]	16640	5632	8.4
Approx. volume part [cm3]	2329.6	479.2	6.2
Required production [parts/year]	22000	22000	22000
Lifetime [years]	7		

Given the parts and the problems raised in section 2.2, it is the goal of the research project:

I. To compare and select, taking into account the characteristics and purposes of the small/medium series parts being studied and the volume of units required, the most appropriate printing technology to invest in so that it is viable for all the three components;

II. To calculate the production costs per batch for both production processes - AM and plastic injection – and conclude, under the conditions of the case study, in which process should Yazaki invest;

III. To develop a Cost Calculator tool for calculating the costs for both methods by inputting the number of units to be produced per year and the number of years pretended;

IV. To perform a sensitivity analysis in order to conclude, together with the results obtained in the previous lines, whether or not the investment in AM technology for the production of the parts in question is justified and under which conditions.

2.4 Chapter Overview

Small/medium series parts are plastic injected parts produced in small/medium batches. The parts are produced in smaller quantities, because they are used for prototyping, they are specialized parts, or they are applied in low consumption products. By being produced through a plastic injection process, these components require a large initial investment on a specific mold for each part, high warehousing costs, which often does not pay off due to the small production volume needed. For that reason, companies started to look for alternative processes to produce these short run parts.

With a growing evolution in the last years, Additive Manufacturing (AM), or 3D Printing, has become a possible alternative to injection molding, once it doesn’t require molds and provide design flexibility, among others. However, in an industrial context, it is still mainly used only for prototyping and tooling. Due to the interest of the industries to study the possibility of expanding the use of the technology also to final products, companies have been investing in research and development of AM.

In partnership with the world leader in wire harness industry - Yazaki Corporation – and in particular its facilities in Ovar, this research aims to study the feasibility from a financial perspective of producing via a 3D printing technology three plastic components complementary to the final wire harness assembly.

Chapter 3

3 Literature Review

This chapter introduces the reader to the two manufacturing processes in discussion: Injection Molding in section 3.1 and Additive Manufacturing (AM) in section 3.2. For both, a historical background is presented (subsection 3.1.1 and subsection 3.2.1), as well as a detailed explanation on how each process works (subsection 3.1.2 and subsection 3.2.2), taking in consideration that in the case of AM there are several different technologies. Some examples of industries where 3D Printing is already applied today are also described in subsection 3.1.2. Finally, the industry in which the case-study is inserted, the Wire Harness industry, is explained in a step-by-step format.

3.1 Injection Molding

Injection Molding is a manufacturing process for producing plastic parts in large volumes, where the same part is created thousands or millions of times in succession.[16] This process obtains molded products by injecting plastic materials molten by heat into a mold, and then cooling and solidifying them. It is currently the most used in fabrication of plastic parts.[17]

3.1.1 History & Evolution of Injection Molding

The first plastic injection-molding machine was developed by the American inventors and brothers John Wesley Hyatt and Isaiah Hyatt and patented in 1872.[18] After that, several different methods and processes were developed. In 1903, two German scientists, Arthur Eichengrun and Theodore Becker, created soluble forms of cellulose acetate that was significantly less flammable than the previous alternative and suitable to manufacture more complicated parts.[19]

Second World War and the post-war period, during the 1940s, were periods of intense innovation for the plastic industry, due to the high demand for inexpensive, mass-produced materials. In 1943, H. Beck filed a patent that described using a plasticizing screw as an injection molding piston, concept that is still used in today's machines. After that, the American inventor James Watson Hendry built in 1946 the world’s first extrusion screw injection machine, revolutionizing the injection molding process, due to the ability to better control the process itself. The same inventor also develop the first gas-assisted injection molding process, a pivotal innovation that allowed for the creation of long, complex, hollow products.[17][19]

With the development of materials and their mechanical characteristics - increased strength and reduced weight - plastic production had overtaken steel production by the 1970s. Later, in the 1990s, aluminum molds had also become the most trendy manufacturing alternative to steel molds, being a faster, cheaper production solution.[19]

Since then and until today, the machines have increased their efficiency and the materials have reinforced their mechanical characteristics and expanded their applications, but keeping the same concept of injection.

3.1.2 Injection Molding Process

The injection molding machine is divided in two different stages: injection unit and clamping unit, being the mold of the parts to be produced between them.[20] Regarding the manufacturing itself, the process is cyclic and consists of plasticizing stage and injection stage.[17]

During the plasticizing stage, a rotating screw is used for moving the raw material, fed through a hopper, into the screw channels. While is being molted by the heat caused by the screw rotation friction and by the heating units, the raw material moves to the tip of the screw fulfilling a reservoir of the melt at the front end of the screw barrel until the required volume of material is achieved. At that point, the screw rotation stops, and the first stage is finished.[17]

In the injection stage, the empty mold is mechanically approximated from the stationary platen and is closed by a clamp unit. Consequently, the mold is filled with the melted material due to the screw pressure. After that, the cavity pressure is reduced and the part cools down and solidifies. After sufficiently long cooling time, the part finally becomes sufficiently stiff, the mold opens, and the part is ejected.[17]

All the process inside the machine can be graphically understood in Figure 4.

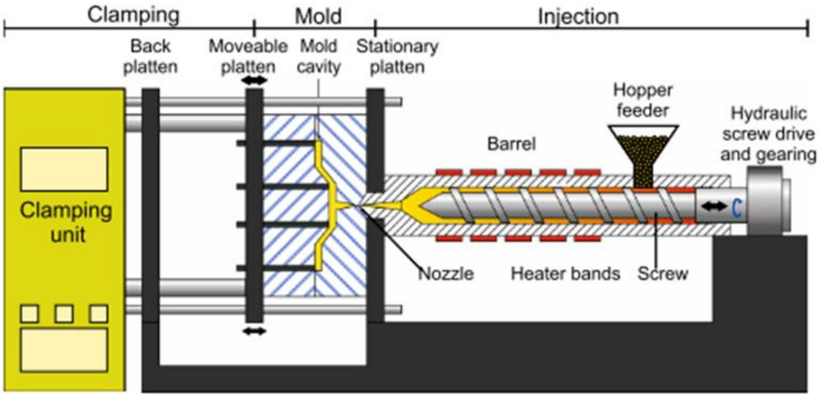

Figure 4 - Injection Molding machine and its mechanical process. Retrieved from: Journal of Intelligent Manufacturing[17]

In the process described above, the mold where is essential. This equipment is a hollow metal block into which the melted plastic is shaped into a specific fixed format. Besides having the cavities that shape the final plastic part, the mold also contains the sprue, the channel that guides molten plastic from the nozzle of the injection molding machine to the entry point for the entire injection mold tool, and runners and gates, which lead to the cavities. A typical mold interior format can be seen in Figure 5. All these extra canals cool after the injection cycle, but are separated from the final part by the machine itself upon the process. The amount of wasted solid plastic in the sprue, runners and gates is commonly finely reground and reused for molding. However, the maximum allowable limit for the ratio of reprocessed materials among the original raw material is about 30% so as not to endanger the properties of the final part.[20]

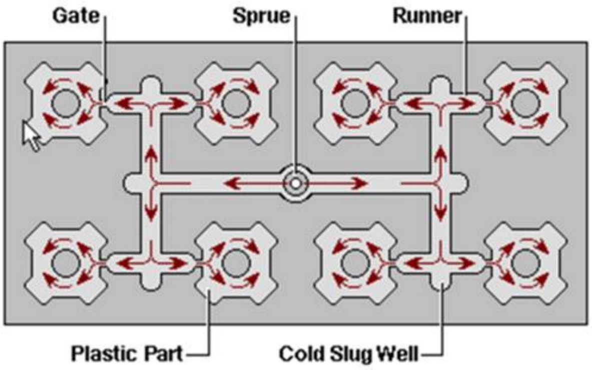

Figure 5 - Mold interior format.
Retrieved from: *https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-injection-molding*[16]

3.2 Additive Manufacturing (AM)

Additive Manufacturing (AM), also known as 3D Printing, is, according to Panda (2016)[21], one of the most promising technologies that have connected digital and physical domains without the need of tooling and human intervention, being used in several areas. Its ability to turn digital models into physical objects allows, for example, designers to design, scan, share, and send digital representations of physical objects just as they can do with images or text online. With developments of material science over the past years, this technology has greatly improved and now used for many more applications such as energy, healthcare, automotive and aerospace.

This is a form of manufacturing that starts from a base and adds materials together on a layer-by-layer basis to form a three-dimensional object from a computer-aided design (CAD) model.[22] In opposition to this innovative technology is the most conventional process - mechanized or subtractive process, which starts from a block of material and cuts it away to form an object.

3.2.1 History & Evolution of AM

The first steps in research and development in 3D Printing field were taken in the 1980s, when Japanese researcher Doctor Hideo Kodama developed a system in which a vat of photopolymer material was exposed to a UV light that solidified the part and built up the model in layers, which at the time it was called Rapid Prototyping (RP) technology.[23] Some years later, in 1986, the American Charles “Chuck” Hull patented the stereolithography (SLA) process, describing it as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed", allowing engineers to create prototypes of their designs in a more time effective manner or designers to create 3D models using digital data, which can then be used to create tangible objects. This was the first 3D Printing patent, which make Hull to be considered nowadays the "father of 3D Printing".[24] After that, several 3D Printing technologies were developed. In 1988, Professor Carl Robert Deckard brought a patent for the Selective Laser Sintering (SLS), and in the same year the American Steven Scott Crump established the Fused Deposition Modelling (FDM).[23][25]

In the 1990s most 3D printing technologies emerged and the first CAD tools were developed. In these years, the evolution of additive manufacturing was fast, since the basics were already stablished. During these year, Selective Laser Melting (SLM), another printing technology, was being developed at the Fraunhofer Institute ILT in Aachen, Germany. Several experiments and tests were also carried out, leading to the first 3D-printed organ implant in humans.[26]

Leveraged on the studies carried out in the previous decade, the 2000's were a period of great innovations in medicine field, where AM also started to get some relevant media visibility. In 2006, the first SLS machine became commercially viable, which opened the door to on-demand manufacturing of industrial parts, which started to trigger in consumers the concept of mass customization, which served as the motto for the following years.[27]

Over the past years since 2010, additive manufacturing has penetrated into various industrial fields, especially in aerospace and automotive industries. At the same time, there has been an increase in accessibility of this technology to all people. The first years of the decade had become the years of 3D printing, mainly due to the FDM patent expiration. This factor opened new possibilities and, with it, AM was becoming a real and affordable prototyping and production technique for businesses. More and more small and big companies were taking advantage of the low prototyping price that 3D printing offers, and started to fully integrate it in their innovation and production processes.[23] Several case studies were also developed, making it possible, for example, to 3D print the first human bone.[28]

For a more detailed description of the History & Evolution of AM, the reader can refer to Appendix A.

3.2.2 AM Processes & Technologies

As it is possible to conclude from 3.1.1, over the years several additive manufacturing processes have been developed using different technologies depending on the application for which they are intended. American Society for Testing and Materials (ASTM)[29] catalogued 3D Printing processes into seven groups: binder jetting, directed energy deposition, material extrusion, materials jetting, powder bed fusion, sheet lamination, and vat photopolymerisation.[30] Each of these processes have some technologies. Both processes and the respective technologies are explained below.

3.2.2.1 Binder Jetting

Binder jetting is an AM process in which an industrial printhead selectively deposits a liquid binding agent onto a thin layer of powder particles.[31] Once a layer has been printed, the powder bed is lowered, and a new layer of powder is spread over the previous one.[32] That way, the layers of the print are bonded together, resulting in a box of powder with binder arranged in the 3D shape of the desired part geometry.[33] This layer-by-layer process, represented in Figure 6, is repeated until the desired object is formed.

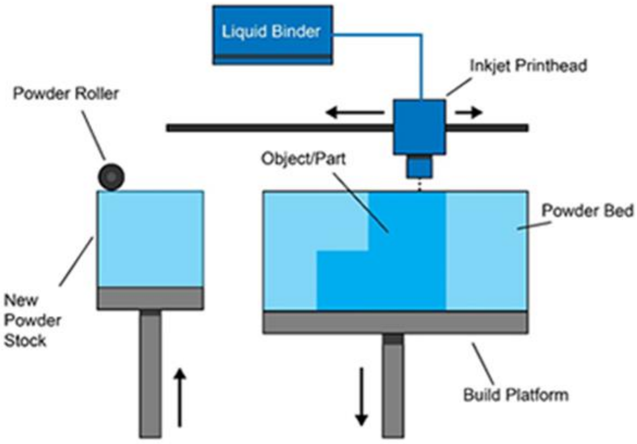

Figure 6 - Injection Molding machine and its mechanical process.
Retrieved from: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/ [34]

A variety of materials, such as metals, sands, polymers, hybrid, and ceramics, can be printed by the binder jetting method. The most common applications are functional metal parts, full-colour models and sand casting.[30]

Comparatively, the binder jetting is a low-cost process that has the ability to produce large, complex geometries. However, it is not the most cost-effective process to produce specifically functional metal parts, by the fact that it needs a secondary process to reach high mechanical properties.[32]

Sand Binder Jetting (SBJ) is part of binder jetting technologies for producing parts from sand, as sandstone or gypsum. When using this type of machines, the printed parts are often exposed to an infiltrate material, which makes it possible to grant the printed material different properties, given the large number of infiltrates available. Moreover, SBJ is also useful for the production of sand cast molds and cores, once the technology is quite easy to integrate into existing manufacturing or foundry processes without disruption.[32]

3.2.2.2 Directed Energy Deposition

Directed energy deposition is a complex printing process commonly used to repair or add additional material to existing components or objects.[30] The particularity of this process is the fact that the nozzle that deposits the material is not fixed to a specific axis and can move in multiple directions. The material, provided in wire or powder form, is deposited from the nozzle onto existing surfaces of the object. Upon the deposition, the material is melted with a laser, electron beam or plasma arc. The process proceeds layer by layer as more material is added, creating or repairing new material features on the existing object.[35] Figure 7 shows a representation of the process.

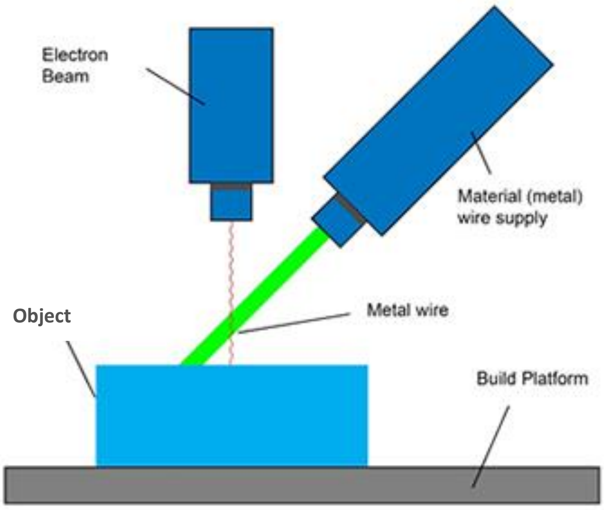

Figure 7 - The directed energy process.
Retrieved from:
https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/ [35]

Directed energy deposition can be used with ceramics, polymers but is typically used with metals and metal-based hybrids, in the form of either wire or powder.[30]

This process, excellent for repair applications, has the advantage of having high degree control of grain structure and printing high quality parts. However, it requires a balance between surface quality and speed, and it is also limited to metals/metal based hybrids printings.

One of the technologies within this method is the Laser Engineered Net Shaping (LENS). LENS has not only the unique capability of producing parts with thin walls and high depth-to-diameter aspect ratios, but also the capability of selectively applying metal to existing parts or repairing worn or broken parts while maintaining the integrity of the parent material.[36]

3.2.2.3 Material Extrusion

Material extrusion is a 3D printing process where a filament of solid thermoplastic material is pushed through a heated nozzle, melting it in the process.[32] First layer is built as nozzle, which only moves on the horizontal axis, deposits material where required onto the cross sectional area of first object slice. Thereafter, the build platform is lowered, and the following layers are added on top of previous layers, until the final object is totally done. Where support or buffering needed, the 3D printer deposits a removable material that acts as scaffolding.[30] The process is exemplified in Figure 8:

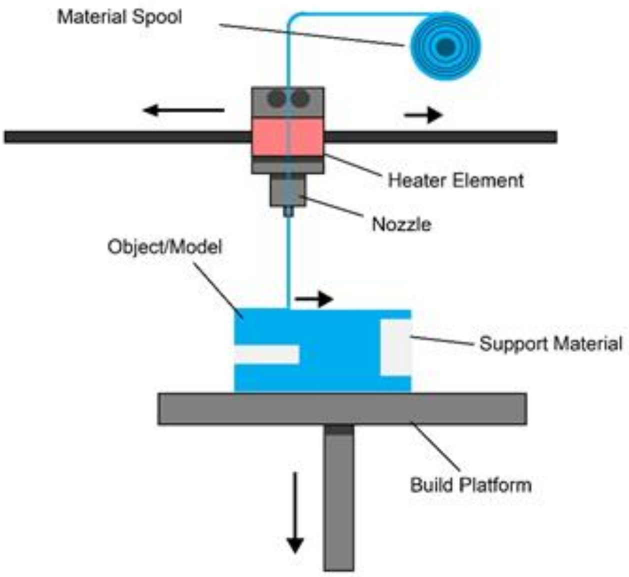

Figure 8 - The material extrusion process.
Retrieved from:
https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/[37]

The material extrusion process uses thermoplastic filaments as printing material, which is added to the machine in spool form as shown in Figure 3. Among the main materials used are PLA, ABS, or PETG.[32] Because it is a simple process that does not require a large investment and it can build fully functional parts of product, material extrusion is widely used on many inexpensive, domestic and hobby 3D printers.[37] Furthermore, this process can be used to print multi-material and multi-colour objects.[30] Nonetheless, it is relatively expensive for visual purposes, and it is still not sustainable for mechanical parts.[32]

Fuse Deposition Modelling (FDM) is the most typical material extrusion technology. FDM is commonly used for testing applications, such as models and prototyping, or auxiliary parts, as jigs and fixtures. This technology offers the relatively best surface completion in addition to full tone. Additionally, there is a wide range of different materials accessible for its utilization.[38]

3.2.2.4 Material Jetting

In material jetting process, droplets of material are deposited from the printhead, which moves only horizontally, onto surface where required and exposed to an ultraviolet (UV) light to solidify. Further layers are then built up as before on top of the previous, as shown in Figure 9. When the printing is finished, post processing, including removal of support material, is required.[39]

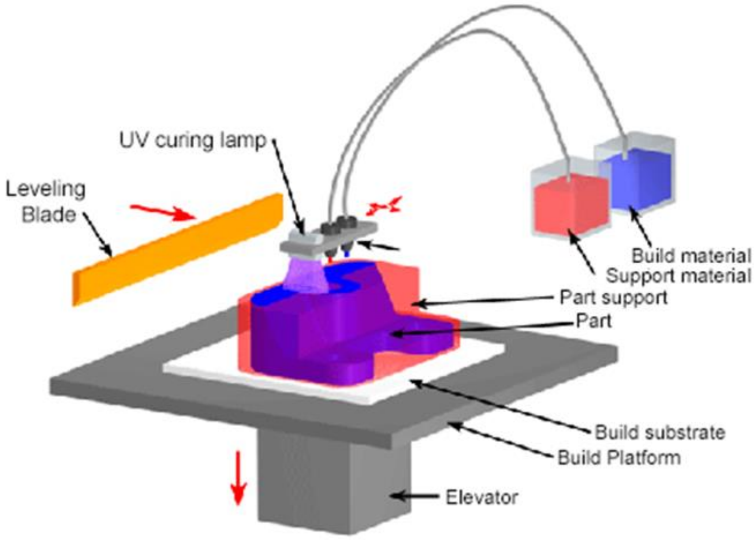

Figure 9 - The material jetting process.
Retrieved from: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/[39]

Due to the fact that material must be deposited in drops, the materials available are mainly photopolymer resins and waxes, although it is possible to print with ceramics, composites, hybrid, and biologicals.[30] This process has also the feature of multi-color and multi-material 3D printing, further adding to the aesthetic quality of both prototypes, molds and end-use parts with very smooth surface finish and high dimensional accuracy. However, because of those characteristics, material jetting's costs of both machines and materials are comparatively high. Additionally, because it requires support material, this process produces material waste, which is expensive given the high cost of resins.[40]

Within this printing method and having the same denomination, Material Jetting (MJ) is one of the fastest and most accurate 3D printing technologies, by its line wise deposition. While the other 3D printing technologies deposit, cure, and sinter material in a pointwise fashion, MJ printers jet resin from multiple print heads along an X-axis carrier, providing a better option for multi-material printing, the possible to produce multiple parts without affecting the build speed, and a smoothness on printed surfaces comparable to injection-molded parts.[40]

3.2.2.5 Powder Bed Fusion

The powder bed fusion 3D printing method resorts to the use of a thermal energy source to selectively induce fusion between powder particles inside a build area to create a solid object.[32] The process starts when a layer of powder material contained in a reservoir is spread over the build platform by a roller or a blade. Through the use of an electron beam or a laser projected against mirrors, the first layer is fused. After the build platform lowers, a second powder layer is disseminated over the first one, and the same process is repeated until the entire model is created, as demonstrated in Figure 10.[41] During post processing, the unfused powder is removed, which can be sometimes reused in another printing depending on the object.

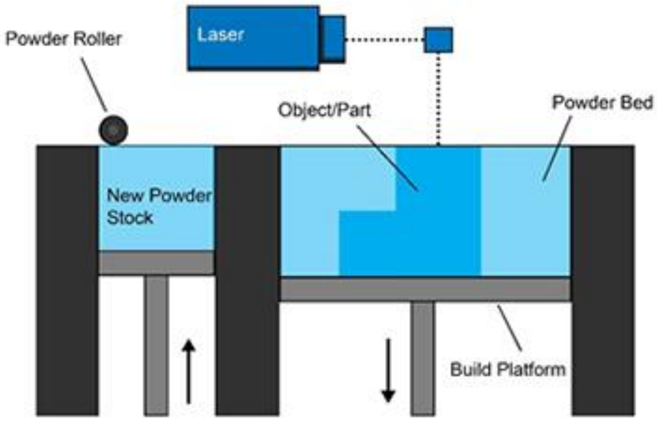

Figure 10 - The powder bed fusion process.
Retrieved from:
https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/[41]

In the above method, the main raw materials used are thermoplastic powder, especially nylon, and metal powder, principally aluminium, stainless steel, and titanium.[42] Using them, this method is very suitable for printing functional parts for several application and complex geometries.[32] The comparative advantages of powder bed fusion compared to other 3D printing processes are the lower price and footprint, which is reduced due to the powder bed's self-supporting structure, and the variety of printing material options. This method is, however, limited in terms of speed and print size, and it requires high power.[43] Also, build rates are limited by the mechanical movement of the printers' mirrors manipulating the laser beam as well as the intensity of the laser beam itself.[33]

Among polymers' powder bed fusion technologies, Selective Laser Sintering (SLS) is the most known for industries application, such as tools and fixtures, fuel tanks, automotive designs, air-ducts and architectural models. Within the same concept, but using metal powder as raw material, there is Direct Metal Laser Sintering (DMLS).

More recently, HP developed the Multi Jet Fusion (MJF) technology. While SLS uses lasers to melt the material together, MJF uses a fusing agent with added heat to create the solid parts.[44] This method allows final parts exhibit quality surface finishes, fine feature resolution, and more consistent mechanical properties when compared to SLS.[45] Additionally, SLS has more waste, but MJF has added cost with the fusing agents. SLS takes into consideration how much space the part takes in the build, whereas MJF is more to do with the amount of material used by the part. This means that MJF is cheaper for less dense parts, and SLS is cheaper for more solid ones.[44] This technology is ideal, among other purposes, for the production of small series' components as a cost-effective alternative to injection molding.[46]

3.2.2.6 Sheet Lamination

Sheet lamination is the 3D printing process in which sheet of materials are bond together to produce a part of object.[30] A mechanism of feed roller unrolls the continuous sheet of material from the spool along the build platform. After the material being coated with adhesive, the laminating roller is heated and passed over the surface of the material, melting the adhesive and pressing it onto the platform. The material is then cut into the wanted form by a computer controlled laser or blade. Thereafter, the platform is automatically slightly lowered, allowing the new sheet of material to be unrolled over the previous layer.[47] As can be seen in Figure 11, the process continues until the final product is fully formed.

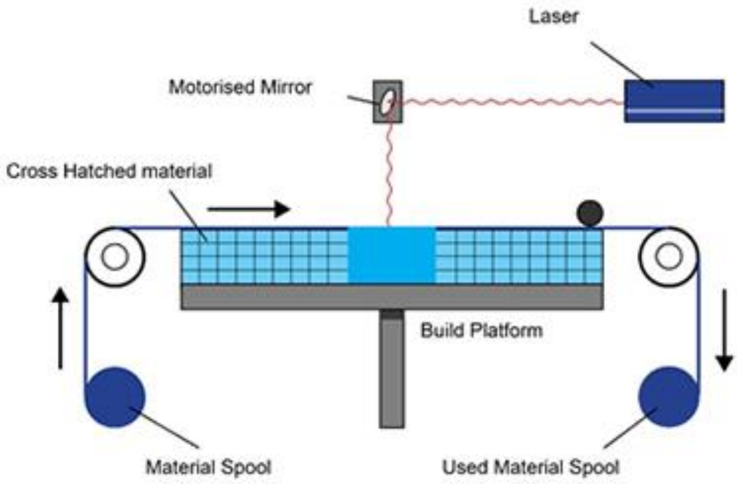

Figure 11 - The sheet lamination process.
Retrieved from:
https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/[48]

Applying the sheet lamination process and depending on the technology within this method, a wide variety of materials can be use, although each material must have the most suitable binding method. The most common sheet lamination material is paper with pre-applied adhesive where heat and pressure are used to activate the adhesive layer. And while, for example, metal sheets are bound using ultrasonic welding, polymers use heat and pressure without the adhesive as it relies on melting the sheets together.[49]

The cost of the sheet lamination method is very low and requires relatively little energy, as the material used is not melted and the excess can be recycled. Additionally, it is easier to build large models, since no enclosed chamber is needed. However, the strength and integrity of parts is not guaranteed, being dependent on the adhesive used. Moreover, post processing, including sanding, painting or varnishing, is required.[22][47]

An example of 3D printing technology that uses this process is Laminated Object Manufacturing (LOM). Using paper sheets as raw material, LOM is capable to manufacture complicated geometrical parts with lower cost of fabrication and less operational time.[30] However, is only used to make scaled models and conceptual prototypes that can be tested for design or form, due to the lack of bonding strength.[49]

3.2.2.7 Vat Photopolymerisation

The vat photolymerisation 3D printing process uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer.[50] A movable platform is submerged in a vat containing a photopolymer resin and a laser beam is focused on the horizontal plane (X-Y axis) across the top surface of the resin. The pre-programmed design's first layer is marked onto the surface of the liquid polymer by the laser beam, which causes the resin hardness precisely where it hits the surface.[47] Consequently, the build platform is lowered by the layer thickness, a blade is used to provide a smooth resin base over it, and the next layer is then traced over the previous one.[50] The process, illustrated in Figure 12, goes on until the entire object is printed and the platform is elevated out of the vat for removal. During it, important parameters as the time of laser exposure, wavelength, and the amount of power supply must be controlled.[30]

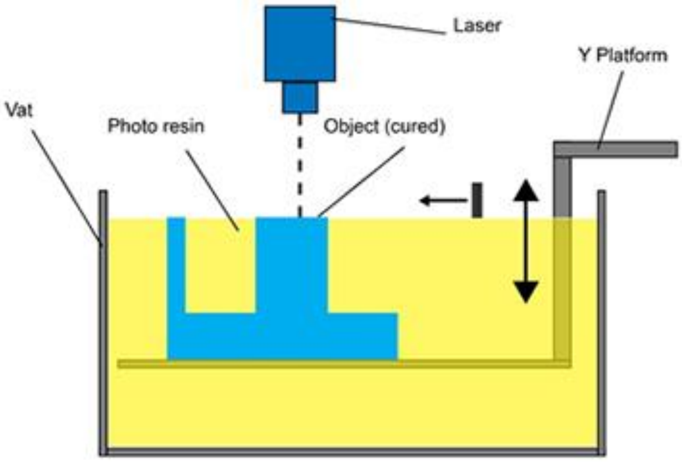

Figure 12 - The vat photopolymerisation process.
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https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation/[50]

Due to its particular characteristics, vat photopolymerisation process can only use polymers for printing, being this one of its main limitations. Additionally, as the process uses liquid to form objects, there is no structural support from the material during the build phase.[50] This means support structures are often needed. Post processes, including a chemical bath and a hardening treatment to the object, are also required, which makes this method very expensive.[47] Despite that, vat photopolymerisation is one of the most accurate 3D printing processes with excellent surface finish and details. Moreover, parts can be printed in a very short period and in large sizes.

Within this method, the fundamental difference between the different technologies is the light source they use to cure the resin. Stereolithography (SLA), for example, uses a point laser.[32] This technology, invented by Chuck Hull in 1986, holds the historical distinction of being the world's first 3D printing technique, as described above in subsection 3.1.1. Due to its high level and accurate finishes, SLA is commonly used in injection mold-like polymer prototypes, jewelry, and dental applications.[38]

Each process is best suited to a different type of material. The following diagram shows the separation of processes between polymers, metals and others.

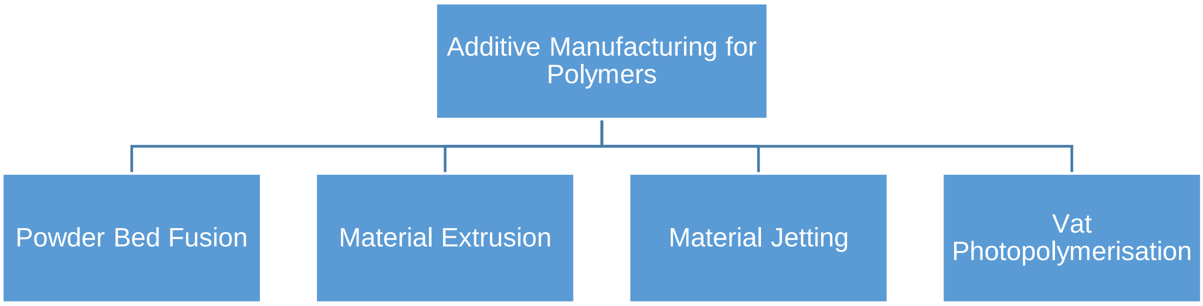


Figure 13 - AM Processes for Polymers.
Adapted from: Formnext AM Field Guide [51]

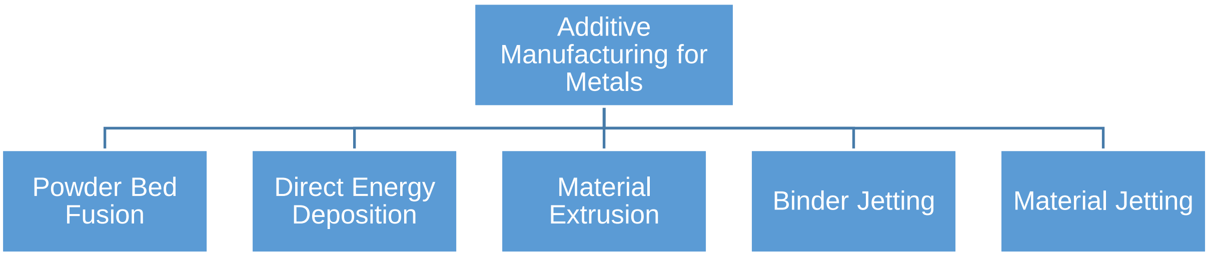


Figure 14 - AM Processes for Metals.
Adapted from: Formnext AM Field Guide [51]

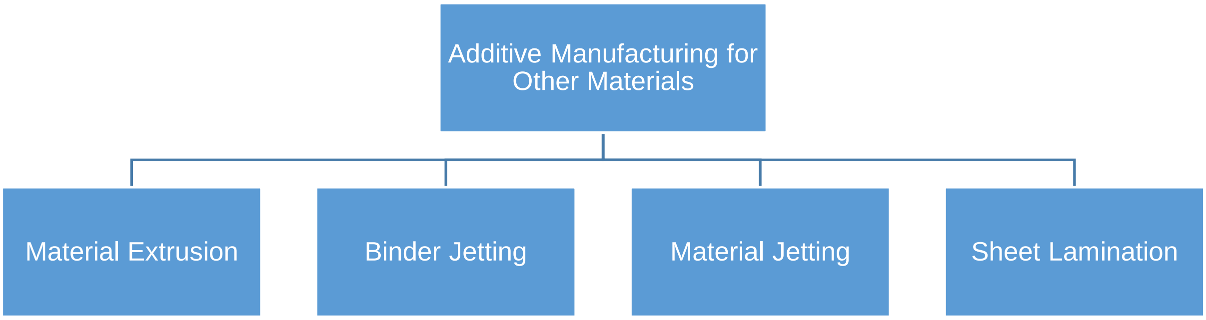


Figure 15 - AM Processes for Other Materials.
Adapted from: Formnext AM Field Guide [51]

3.2.3 AM Adoption in Industrial Environment

As mentioned, there are currently several fields where 3D Printing applications have been developed and are gaining relevance. This section presents the major industrial areas where this reality is growing: aerospace, automotive and healthcare industries.

3.2.3.1 Aerospace Industry

Aerospace industry is considered the one that has the highest rate of adoption of 3D printing technologies. According to Aerospace 3D Printing Market's Global Forecast to 2022 (2017)[52], this market is projected to grow beyond $3 billion by 2022, mainly due to the growing demand for lightweight 3D printed parts for aircraft engines. This is a fundamental factor for the aircraft design, since reducing its weight significantly decreases its carbon dioxide emissions, fuel consumption and payload.

However, it is not only the weight of the parts that is relevant. The special geometries of jet engine parts, for example, are generally made using traditional subtractive machining methods removing material from a block of metal. But these processes cannot handle structures with sophisticated internal substructures, while it is estimated that more than 75 percent of jet engine parts are suitable for AM application, due to its capability to handle very complex and irregular shapes.[53] Moreover, being an additive process the production of parts layer by layer, 3D printing has a much higher material efficiency, producing less waste.

Through its ability to combine different materials with different mechanical properties into a single structure, AM can also reduce the number of total engine parts needed, which can significantly simplify the assembly and maintenance by reducing the amount of time and labour force needed on those processes. The average lifespan of an aircraft can range between 20 and 30 years, making maintenance an important and expensive process in this industry. Wherefore the reduction of parts to be evaluated or the capability of restoration and repair of turbine blades and other high-end equipment through the integration of AM has high impacts on costs.[54]

Airbus, one of the biggest companies in aerospace industry, started in 2018 to produce and to install 3D-printed spacer panels on its commercial A320 aircraft using FDM technique, which enabled the company to produce components with higher complex features and to reduce the spacer panels' total weight in 15 percent in comparison to the former traditional methods. Also Boeing equipped is Boeing 777x with two GE9X engines, world's largest jet engines by GE Aviation, incorporating more than 300 printed parts, reducing the engine's weight, lowering fuel consumption by 12 percent and the operating costs by 10 percent, making Boeing 777x the most efficient twin-engine jet in the world.[52]

3.2.3.2 Automotive Industry

Another growing user of additive manufacturing is the automotive industry. In 2019 global automotive AM revenues reached $1.4 billion, and the tendency only looks set to increase, as revenues relating to

AM in automotive part production are expected to reach $5.8 billion by 2025.[55] Several automotive companies are not only increasingly finding applications of 3D printing for their productive process, but also beginning to find innovate end-use applications for 3D printing.

Each new automobile starts off as a prototype before it heads into production, and instead of fabricating each piece individually, engineers can now use 3D metal printing to create a fully functional prototype directly from their digital design. This ability to produce prototypes quickly also gives designers a great flexibility when testing multiple design options, enabling them to make quick design changes and modifications in a fraction of the time.

For use in manufacturing and assembly processes, tooling equipment is a vital element of the production process. Through the use of 3D printing techniques like FDM and SLS, automotive companies are able to produce tooling aids at a fraction of the cost, increasing considerably efficiency on the factory floor. For instance, Volkswagen Autoeuropa used to use third-party suppliers to manufacture their tools, a process that used to take several weeks and extra costs, especially when multiple designs or assemblies were required. However, ads of 2014, the VW plant in Portugal invested in seven Ultimaker 3D printers, starting to manufacture in-house 93% of tools previously made externally. Within two years, their assembly tooling cost savings rose from 70% to 95%, and it enabled Volkswagen Autoeuropa to test solutions without having to contact suppliers, reducing the time taken by an average of eight weeks.[56]

The same way, AM has the potential to transform the conventional manufacture and distribution of spare parts through on-demand manufacturing, printing them locally and at the time of need, reducing drastically inventory costs and delivery times to the end customer. The famous German car manufacturer Porsche is already taking advantage of 3D printing in this field. In 2018, the company announced the use of 3D printing to produce spare parts for its rare and classic cars, combining SLM technology for metal components and SLS for plastics, providing its car collectors' a wide range of high-quality rare parts, which was not previously feasible due to the relatively low demand, coupled with short production runs.[54]

By the use of AM, automotive manufacturers can print latticed parts made from aluminium alloys as strong and as safe as their solid aluminium counterparts while reducing weight by up to 80%. By being lighter, vehicles produced will also use less fuel, increasing fuel economy and reducing the amount of carbon dioxide and monoxide released by the exhaust system. More than that, it also reduces waste and the overall production cost of the vehicle, making the purchase of a vehicle much more affordable for the average driver.[57]

Customization is another of AM's great advantages in this industry. This technology offers automakers a cost-effective and flexible way to produce customised parts for both the interior and exterior parts of a vehicle. Rolls-Royce, for example, is working on creating fully bespoke vehicles with the use of 3D printing, giving their clients the option to create a unique vehicle where they can design everything from the frame and body to the interior entertainment console, totally changing the luxury and customised car industry concept.[57]

3.2.3.3 Healthcare Industry

The healthcare industry is one of the fastest-growing adopters of additive manufacturing. According to Kholgh Eshkalak et al. (2020)[58], the global medical AM market size was valued at $1.34 billion in 2020 and is estimated to register a rapid compound annual growth rate of 21.8%.

As evidenced above, 3D printing provides a great customization capability, a characteristic that is also taken advantage of by this industry, especially to create totally personalised patient-specific devices such as prosthetics, implants or orthopaedic devices. In this type of equipment, it is of utmost importance to get a perfect fit to create a functional and comfortable prosthesis for the patient, as the devices and their sockets are subjected to rigorous use. While traditional technologies are extremely expensive and time-consuming, 3D printing, on the other hand, can produce small/medium runs of custom parts at no extra cost and without any setup time or tooling.[59]

Likewise, by combining intraoral scanning and 3D printing, it is now possible in dental labs to create dental products like crowns, bridges and bite splints that perfectly match a patient's anatomy. With the increased accessibility of digital technologies, such as desktop 3D printing systems, 3D scanners and materials, traditional processes used to create dental impressions are gradually being replaced.[60]

AM can also be used to create artificial living tissues that can mimic natural tissue characteristics. Named as bioprinting, this technology is nowadays used for research and testing, but it is seen with great potential to be used in regenerative medicine in the near future. An example is the case of a mountaineer that received a hip implant featuring a 3D-printed acetabular cup after a climbing accident. Thanks to the technology used, it was possible to produce a cup similar to the porous structure of natural bone, improving osseointegration, which made the patient to be able to walk and climb again just two and a half months after the implantation. By 2027 are estimated to be produced over 4 million 3D-printed implants.[54]

Having already more applications than those described above, the medical and dental sector is estimated to represent 11% of the overall additive manufacturing market.[61] The healthcare industry, with its need for customizable, biocompatible and sterilizable plastic and metal components, is one of the most promising fields for 3D printing application.[59]

3.3 Wire Harness (WH) Industry

Wire Harness (WH), or cable harness, is an assembly of wires, cables and connectors that transmit electric power and signals. The wire harness assembly maximizes efficiency by binding wires together in a safe and secure routing pattern by durable materials as for example rubber, vinyl or electrical tape. With transportation industry, including automobiles, buses, trucks and planes, as the main consumer, these wires are used to connect electronic components, control units, sensors and actuators.[2][62]

As more and more technological components are developed and integrated into automobiles nowadays, the number of wires and total weight has steadily risen, which makes the WH industry to grow as well.

According to the article *Shedding Pounds In Automotive Electronics* [63] and to put into perspective, while in 1948 the average family car contained only about 55 wires, amounting to total length of around 46 meters, today's luxury cars contain between 1500 and 2000 copper wires, with an aggregated cable length of over 1610 meters. Due to that reason, it is of extreme importance to assemble the cables and wires into a cable harness not only to better secure them against the adverse effects of vibrations, abrasions, and moisture, but also to optimize space and decrease the risk of a short and electrical fires. Moreover, since the multiple wires are now assembled in one single harness, installation time is decreased and the process can be easily standardized.[62]

3.3.1 Production Process of Wire Harness

Manufacturing the wire harness is a process that requires several steps that vary according to the final assembly implementation purpose and application. The sequence of steps generally adopted follows the sequence represented in Figure 16. It is started with cable and harness design. Subsequently, a prototype of the designed product is made. After that, pre-assembly processes are required before the final assembly is performed. Finally, the final product is tested, and then packed to be delivered. In this section a more detailed explanation of the steps listed here is presented.

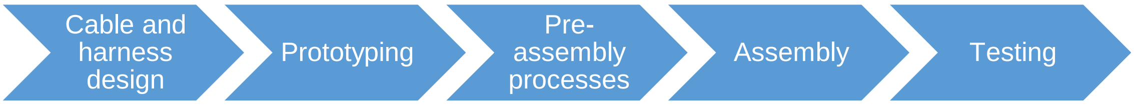


Figure 16 - Steps of wire harness production process.

3.3.1.1 Cable and Harness Design

The production process of WH starts with a pre-planned design. As described by Trommnau et al. (2019), the basic function of a wiring harness is to ensure reliable and error-free electrical connection between electronic components over its lifetime which is usually about 15 to 20 years. In order to achieve such requirements, the harness layout design, the selection of the most suitable cable and insulation materials, and the choice of harness components must be rigorously planned taking into account any necessary custom features for the wire harness intended application.[64][65]

First, a wiring diagram or a circuit diagram, as shown in Figure 17, is produced showing the various parts of the device requiring transport of electric signal. In this initial representation, all connections between electronic components, necessary voltages and currents as well as resulting wire diameters are studied and listed.

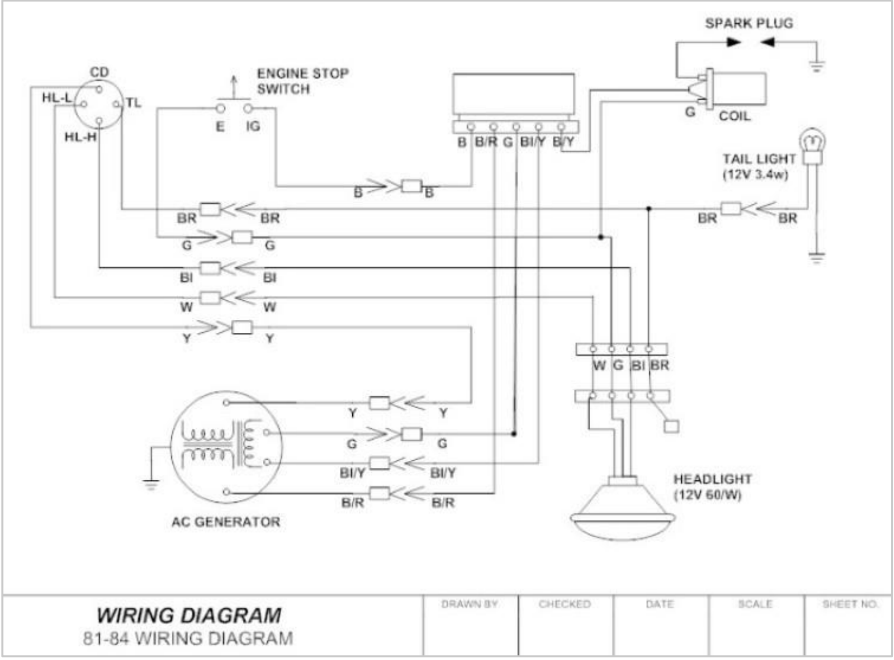


Figure 17 - Example of a wiring diagram.
Retrieved from: https://www.edrawmax.com/wiring-diagram/[66]

Thereafter, a 3D layout is designed in the CAD software, like the one in Figure 18, taking into account several factors such as relative movements of components, installation spaces, sharp edges, temperature ranges, media resistance, and installation requirements. After considering these factors, it is possible to adjust the previously defined layout in order to avoid as much as possible wear and damage on the final product when it is exposed to the working conditions.[2]

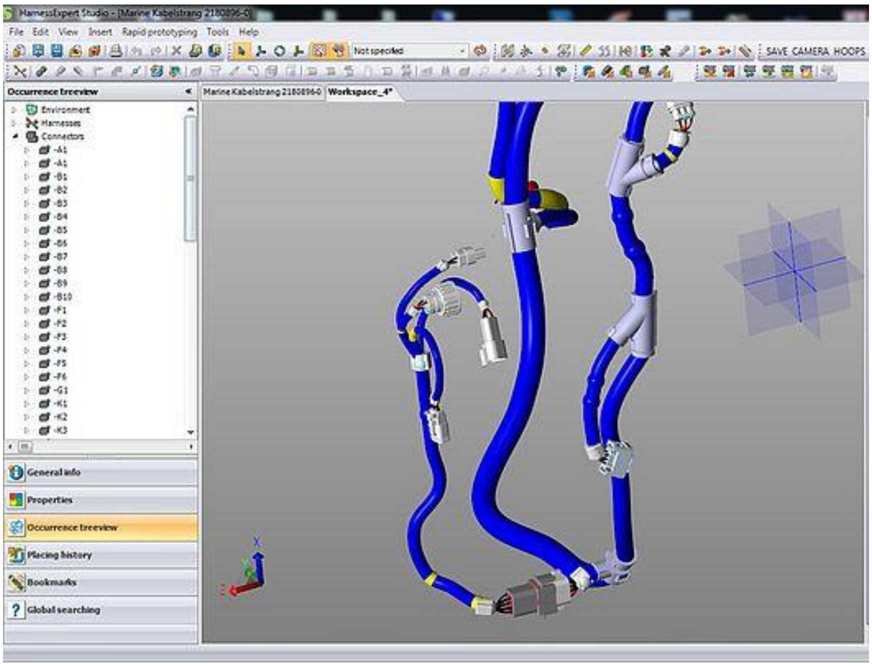


Figure 18 - Wire harness 3D CAD layout in Harness Expert 3D/2D software.
Retrieved from: https://www.ien.eu/article/wire-harness-software/[67]

Based on the wiring diagram as well as the 3D CAD layout, engineers create a detailed 2D full sized drawing that is later mapped onto to the pin board in which the final assembly will be performed (Figure 19). In it are showed all of the components and their locations and the testing units for each and every outlet.[62]

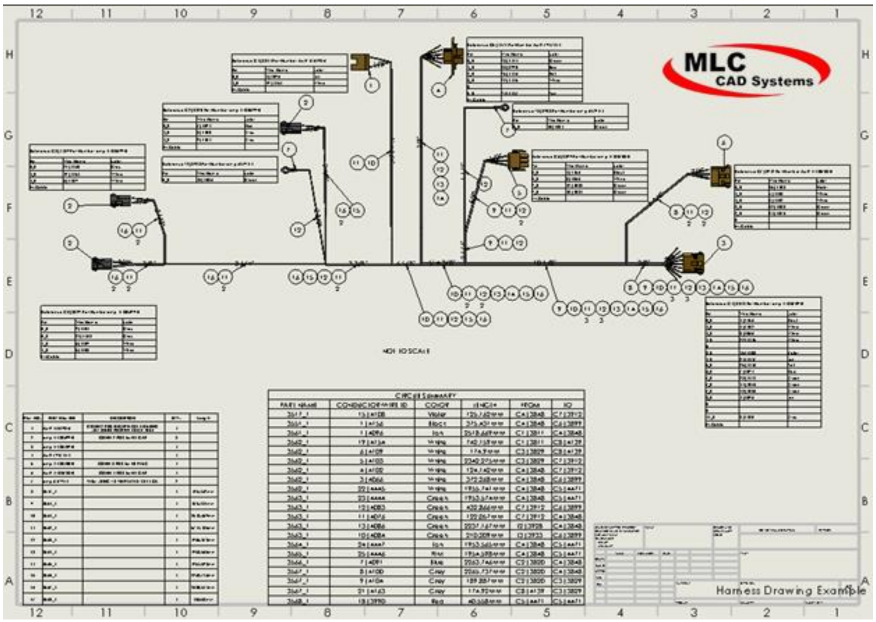


Figure 19 - 2D detailed assembly draw.
Retrieved from: https://blog.matric.com/what-to-know-about-electronic-cable-harness-assembly[68]

3.3.1.2 Prototyping

Prototyping is a common practice in the electronics manufacturing industry. It allows engineers and product designers to create a test version of the final product. They can then test the harness in its intended application before beginning the first production run, ensuring optimal performance, and, in case of need, any kinks that weren't ironed out in the design phase can be worked out, leading designers to come up with more efficient layouts or refine their blueprints.[64][68]

3.3.1.3 Pre-Assembly Processes

Before the final assembly of all the cables, there are certain tasks that need to be performed.
This step in the production process is initiated with the cutting of the wires. It is performed by an automatic wire-cutting machine that cuts wires with different cross-sections into predefined lengths.[3] Once it is done, the cable isolation is stripped back to reveal the core, in which single wire seals and terminals are then attached to the ends of the wires. Some automation is available for this step, including crimping and soldering the wire into their proper connections. If needed, the wires are also inserted into a connector housing, allowing the mating of male and female bundles of wires.[65][68]

3.3.1.4 Assembly

The final assembly is the core process and most labour-intensive part of the wire harness manufacturing. The prepared wires and their connectors are gathered up and crafted into the harness utilizing an assembly board, as the one shown in Figure 20, to meet the design specifications.

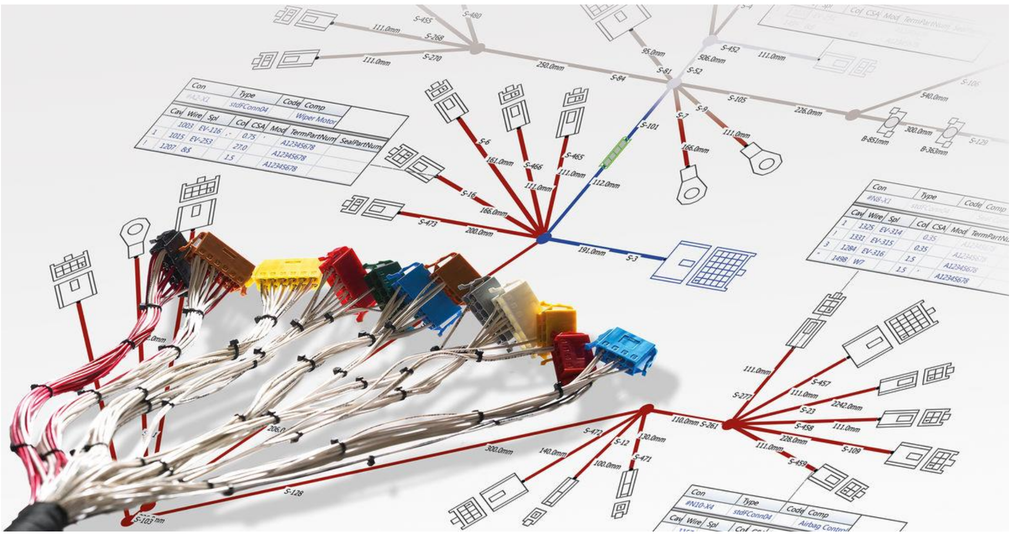


Figure 20 - Wire harness assembly board.
Retrieved from: https://www.edrawmax.com/wiring-diagram/[69]

Machined connector holders, represented as the white blocks in Figure 21Figure 21, are used to attach the connectors to the assembly table.

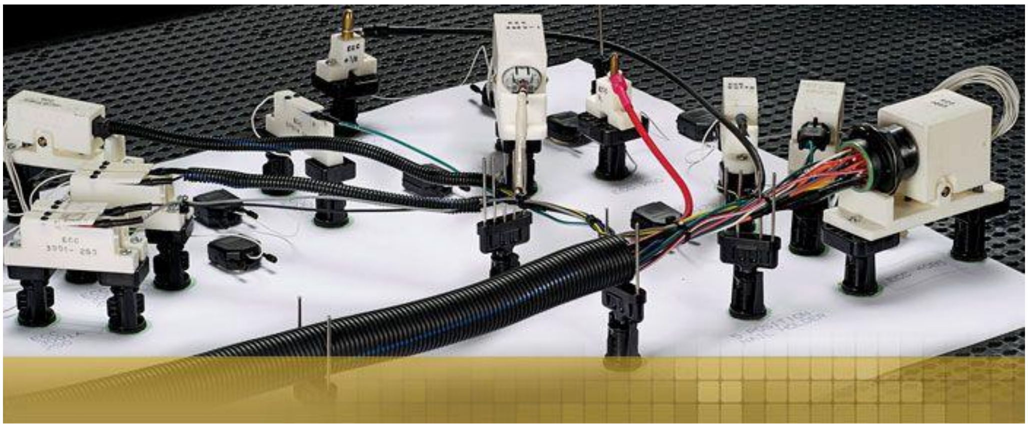


Figure 21 - Connector holders in assembly board.
Retrieved from: https://www.panduit.com/en/landing-pages/harness-board-system-and-fixture.html[70]

Firstly, it is necessary to route the wires through sleeves following the designed layout represented on the assembly board and to apply fabric tape to fix them. Terminals are then crimped onto wires, which are subsequently bundled with adhesive tape. Finally, the cable components are fitted with any form of insulation, such as suitable protective sleeves, conduit, and protective yarn.[71] During the process, wire channels, cable ties and fixations are also installed.[2][68] The final assembly finally looks like the one represented in Figure 22:

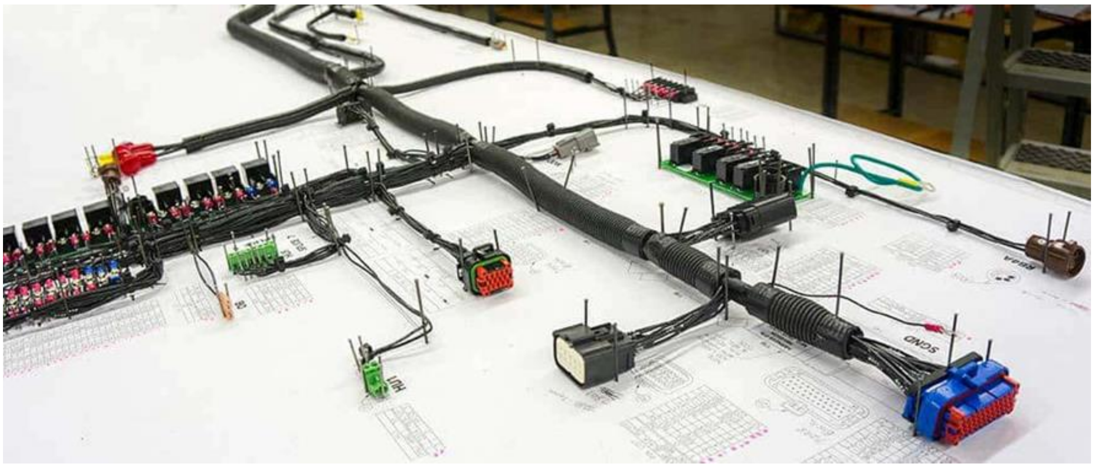


Figure 22 - Wire harness after assembly process.
Retrieved from: https://www.lacroproducts.com/custom-cable-services/[72]

These processes are mainly hand manufactured, due to its complexity and delicacy, specifically routing cables or wires through sleeves and fastening strands.[3] It is also necessary to do quality control by ensuring the distances and routes of the harnesses match the design specifications.[64]

3.3.1.5 Testing

After the assembly process, an electrical functionality and safety test of the entire wire harness is mandatory, subjecting the it to the conditions it will face in real-world operation.[64] To do so, it is necessary the aid of a test board, like the one shown in Figure 23, pre-programmed with a circuit diagram data similar to the required electrical characteristics.[62] To avoid damaging the product, connectors are not allowed to be plugged in during this process, which requires that the test board be equipped with special brackets touching the terminals in the connector housings without using the plug mechanism.

Figure 23 - Wire harness test board.
Retrieved from: https://www.fpc.cz/wire-harness-testing[73]

In order to be approved and labelled by the Quality Assurance and Control Teams to go forward to the customer, each wire harness must perform 100% reliably during testing.[62][64] In case an error is detected, a documented rework process has to be performed. This process sometimes has a high degree of complexity, because, for example, the replacement of a single wire requires the removal of a large amount of tape or other attachments. Also for the replacement of a crimped terminal of the plug, special tools are required to open the securing lock.[2] After the rework process, in case it is needed, another 100% function and completeness test of the reworked wire harness is mandatory.

If the tests verify that the product is fully functional, the final wire harness, similar to the one in Figure 24, is packaged and stored in a warehouse, to be later shipped to the customer.

Figure 24 - Final wire harness.
Retrieved from: https://www.tenkateracingproducts.com/mectronik-wire-harness-kit-yzf-r6-17-008-h2590-10.html[74]

3.4 Chapter Overview

During the 20th century, plastic injection molding, a cyclic manufacturing process using a worm screw, has been developed and established as one of the main and most used industrial processes in all areas for the production of plastic parts. This manufacture method requires, among other component, an injection molding machine and a mold for each single part to be produced, making the process only worthwhile for large volume production.

On the other hand, since the early 80's Additive Manufacturing was born and has been developed and branched out into many different technologies. Today it is already an effective method for many different applications, such as prototyping, tooling and other auxiliary parts to production processes, as well as for final parts, especially in the aerospace, automotive, and healthcare industries.

One of the industries that require a huge amount of plastic injected components is the wire harness industry. Growing due to the constant increase of electrical components, especially in transportation, such as automobiles and airplanes, the wire harness industry needs plastic components to support the cables in the final applications. It already uses 3D printing for prototyping and auxiliary parts to the assembly process, but it shows a high margin to also apply this technology to the production of final components.

Chapter 4

4 Research Methodology

As described in section 2.3, this case study requires several steps in its development.
Firstly, in section 4.1, it will be chosen the most suitable 3D Printing technology to produce the parts pre-defined above by comparing the various types of AM technologies detailed in subsection 3.1.2. After that, a cost comparison for the production of each of the three parts by both plastic injection and AM will be carried out in section 4.2. This will be done by considering both variable costs and fixed costs from each step of the production process.

4.1 AM Technology Choice

To initiate the case resolution, the most suitable AM technology for the parts production must be selected according to several criteria.

4.1.1 Technologies Considered for Comparison

The first consideration to take is the group or type of material from the parts under study. Since the three components – small clip, medium channel, big channel - are made out of polymers, more specifically polyamide (PA66-I), the AM processes that can be used are limited to four, as showed above in Figure 13: powder bed fusion, material extrusion, material jetting, or vat photopolymerization.
Each of these processes has different printing technologies associated with it. In subsection 3.2.2 only the most developed technology for each process was considered, with the exception of powder bed fusion to which two alternatives were presented. Hence, these will be the technologies considered for the context of this problem:

- Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF) in powder bed fusion
- Fuse Deposition Modelling (FDM) in material extrusion
- Material Jetting (MJ) in material jetting
- Stereolithography (SLA) in vat photopolymerization

4.1.2 Criteria for Comparison

In the decision-making process for any business investment, it is first necessary to define the decision criteria, that is, those variables or characteristics that are important to the organization taking in consideration before making the choice and which will be used to evaluate the suitability of each alternative recommended.[75]

In the case study in hands, decision criteria are the variables that will be weighed to evaluate and compare the 3D printing production technologies considered for the small/medium series parts production. Taking that in consideration, the following variables are defined:

a) Suitability

Each printing technology is best suited for a particular purpose. Several factors such as the printing process, the mechanical and chemical characteristics achieved in the final product, or the quality and detail of the print are what distinguish the AM technologies from one another and makes them suitable for different purposes. For the case study being developed, it is particularly important the possibility of complex geometries production and in large batches. Characteristics such as multi-material or multi-color printings are not relevant, since each monochrome part contains only one type of polymer.

b) Mechanical properties

Since the parts will be applied in a vehicle, they will be exposed to high temperatures and pressures. Therefore, it is essential that the technology to be used can provide high consistency levels in the final product, to avoid breaks in the material.

c) Printable volume per batch

By varying the technology, the number of parts that can be printed simultaneously also varies. Conciliating the available printing volume on the platform, the placement of the parts in this available volume by the slicer software or even the redesign of the parts in CAD software if necessary, it is possible to achieve considerable production batches. Considering that industrial production volumes need to be achieved in this study, it is very important that the technology's printable volume is as high as possible.

As this variable also depends on the specific printer model chosen, the evaluation was done in average terms within the range of printers of each technology.

d) Support structure

As 3D printed parts are built layer by layer, a previous layer to build upon is required. Depending on the specific 3D Printing technology and the complexity of the 3D model, this can mean that a 3D print requires support structures.[76] The use of this extra material implies increasing material costs, adding more post-processing work, and the possibility of model's surface damage when being removed.[77] For these reasons, technologies that require support structures are undesirable for this study.

e) Surface finish

Surface finish is an often overlooked quality of 3D printed parts. Compared to machined injection mold components, 3D printed tooling appears rougher as different aspects of the 3D printing process (layering, pixelation, etc.) introduce artifacts that increase the surface roughness of the printed parts. Surface finish is a key quality to evaluate when utilizing 3D printing, as a high surface finish will not only make the molded parts more aesthetically pleasing, but it will also prolong the life of the features in the printed tool and reduce the need for post-treatment.[78] Therefore, the highest surface finish quality is preferable, even though a post processing might be required.

f) Post processing

Parts manufactured with 3D printing technologies usually require some degree of post-production treatment. This refers to any process or task that needs to be performed on a printed part, or any technique used to further enhance the object. The options for post-processing 3D printed parts include removing support or excess material, washing and curing or hardening, sanding or polishing a model to painting or coloring. Post-processing can be costly, especially when it is done by hand. Manual post-processing is labor intensive and is not scalable, becoming unsustainable in large series production.[79] For these reasons, the need for post processing is undesired.

g) Technology cost

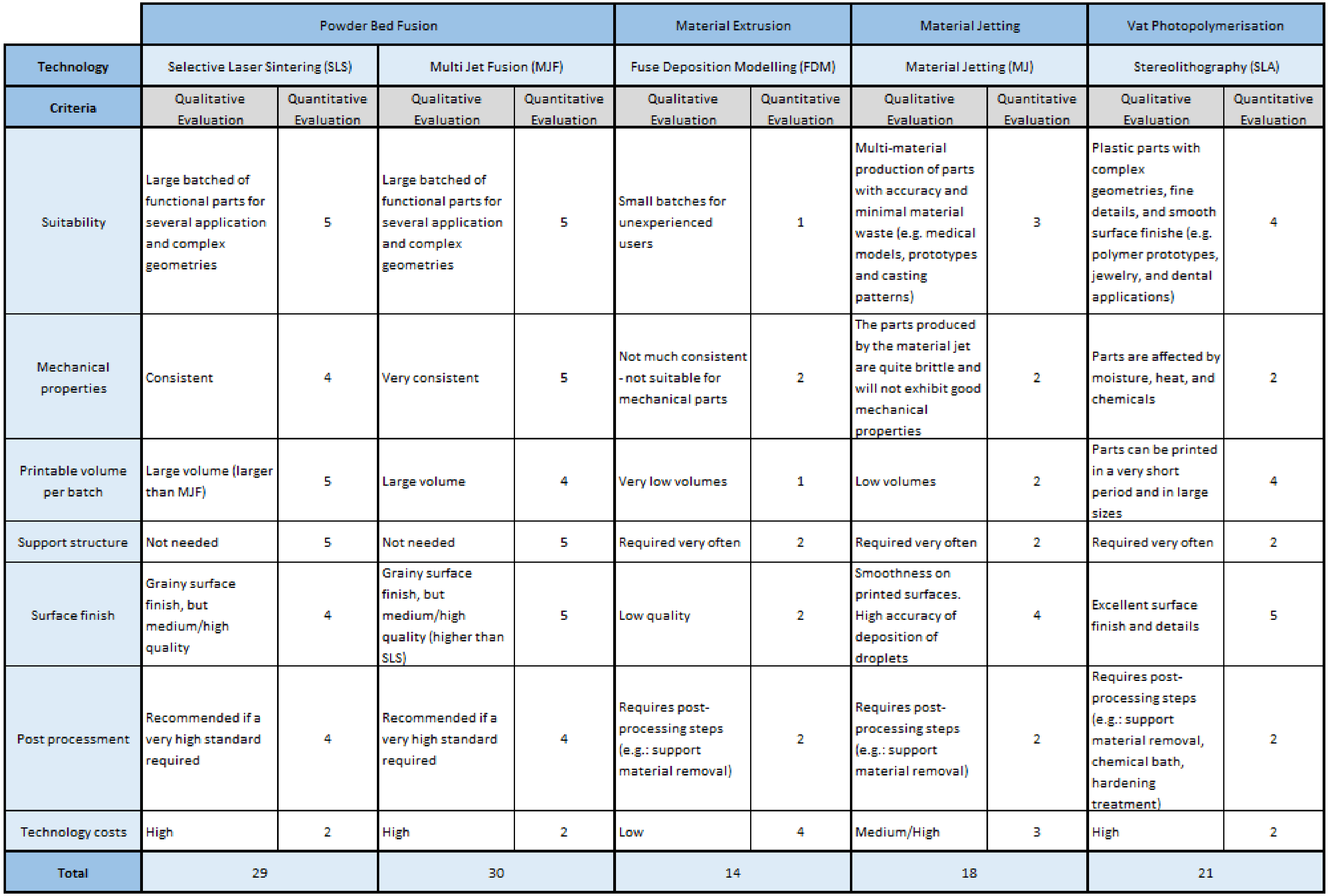
With the case study being a cost evaluation and the possibility of an investment, the printing technology cost is a key consideration. The cost is a very variable factor depending on the printer model chosen within the technology, the units to be produced, the quality required, the material used, etc. However, it is possible to make an average cost comparison, taking into account the only the technology.

4.1.3 AM Technologies’ Comparison

Given the criteria defined above, the comparison between the five 3D printing technologies considered for this study is carried out in Table 2. This comparison is made according to two types of evaluation:

- Qualitative evaluation - based on the information researched and the findings described in subsection 3.2.2.
- Quantitative evaluation – a scale of integers from 1 to 5 reflecting the qualitative evaluation. This assignment takes into account the level of desirability of each criterion for the case study, with rating 1 being totally unwanted and rating 5 being totally desired.

Table 2 - AM Technologies' Comparison Table.



	Powder Bed Fusion				Material Extrusion		Material Jetting		Vat Photopolymerisation	
Technology	Selective Laser Sintering (SLS)		Multi Jet Fusion (MJF)		Fuse Deposition Modelling (FDM)		Material Jetting (MJ)		Stereolithography (SLA)	
Criteria	Qualitative Evaluation	Quantitative Evaluation	Qualitative Evaluation	Quantitative Evaluation	Qualitative Evaluation	Quantitative Evaluation	Qualitative Evaluation	Quantitative Evaluation	Qualitative Evaluation	Quantitative Evaluation
Suitability	Large batched of functional parts for several application and complex geometries	5	Large batched of functional parts for several application and complex geometries	5	Small batches for unexperienced users	1	Multi-material production of parts with accuracy and minimal material waste (e.g. medical models, prototypes and casting patterns)	3	Plastic parts with complex geometries, fine details, and smooth surface finishe (e.g. polymer prototypes, jewelry, and dental applications)	4
Mechanical properties	Consistent	4	Very consistent	5	Not much consistent - not suitable for mechanical parts	2	The parts produced by the material jet are quite brittle and will not exhibit good mechanical properties	2	Parts are affected by moisture, heat, and chemicals	2
Printable volume per batch	Large volume (larger than MJF)	5	Large volume	4	Very low volumes	1	Low volumes	2	Parts can be printed in a very short period and in large sizes	4
Support structure	Not needed	5	Not needed	5	Required very often	2	Required very often	2	Required very often	2
Surface finish	Grainy surface finish, but medium/high quality	4	Grainy surface finish, but medium/high quality (higher than SLS)	5	Low quality	2	Smoothness on printed surfaces. High accuracy of deposition of droplets	4	Excellent surface finish and details	5
Post processment	Recommended if a very high standard required	4	Recommended if a very high standard required	4	Requires post-processing steps (e.g.: support material removal)	2	Requires post-processing steps (e.g.: support material removal)	2	Requires post-processing steps (e.g.: support material removal, chemical bath, hardening treatment)	2
Technology costs	High	2	High	2	Low	4	Medium/High	3	High	2
Total	29		30		14		18		21	

After assigning the weights of each technology to each criterion, a total value resulting from the sum of these values indicates which option is best suited to the context of the problem, with a maximum score of 35.

As it is possible to confirm in the table above, the powder bed fusion is clearly the most suitable process. Within this, Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF) options are very evenly matched, with total scores of 29/35 and 30/35, respectively. However, only one technology can be chosen, so a more in-depth comparison between the two is needed.

4.1.4 Selective Laser Sintering (SLS) vs Multi Jet Fusion (MJF)

Although they both belong to the Powder Bed Fusion family, Selective Laser Sintering and Multi Jet Fusion contain some differences that make them distinct technologies.

The main divergence is in the printing process, more specifically in the heat source. In both processes, a thin layer of powder is first spread over the build platform. After this first step, in SLS a CO2 laser scans each cross-section, sintering the powder. The platform then moves downwards one layer and the process repeats until the job is complete.[80] However, in MJF a carriage with inkjet nozzles passes over the bed, depositing fusing agent on the powder, while a detailing agent that inhibits sintering is printed near the edge of the part. A high-power infrared energy source then passes over the build bed and sinters the areas where the fusing agent was dispensed while leaving the rest of the powder unaltered.[81]

After both processes are completed, the printed parts are encapsulated in powder and need to cool down before they can be removed.

These differences in the printing process make the two technologies slightly different in some critical factors:

- Processing time

SLS and MJF have the same print time for the production of one part. However, Multi Jet Fusion printers have a removable build platform that allows the printed part to be cooled outside of the machine, shortening the global lead time, since the setting up and cooling times will decrease.[82]

- Material recycling and reuse

The same MJF's removable build platforms helps with powder removal, making it possible to recycle and reuse 80-85% of the powder, while in SLS the powder is only 50% recyclable.[81]

- Dimensional accuracy

Both technologies offer high dimensional accuracy when compared to other AM technologies. Nonetheless, Multi Jet Fusion parts have a finer feature resolution of approximately 0.508 mm compared to 0.762 mm from SLS.[83] One of the reasons for this is the detailing agent used in MJF printers, which increases the precision.[82] This will allow not only to print smaller features and sharper edges, but also to have a smoother surface finish in general.

- Materials and Colors

Having been developed much earlier than MJF, SLS provides a broader range of material options with multiple nylons and a wide variety of colors in which the parts can be dyed.[83] Currently, fusing agent used in MJF is black to enhance the absorption of infrared rays. For that reason, MJF parts usually have a greyish appearance and are usually dyed black.[81]
In this case study, the three parts under study will be located inside the car, so their color will be black. For this reason, this is not a critical criterion.

- Maximum part size

SLS printing technology has a larger maximum printable volume - up to 600 x 350 x 560 mm – when compared to MJF - up to 400 x 284 x 380 mm. On the other hand, as stated above, MJF printers can print small features, due to their finer resolution.[81]

- Cost per batch

The production costs of single parts in MJF and SLS are approximately the same. However, MJF printers are more time-efficient in overall processing time, which means they can support larger quantities in a shorter period.[82] Thus, Multi Jet Fusion parts become cheaper at scale.

The comparison between Selective Laser Sintering and Multi Jet Fusion according to the six criteria above is summarized in Table 3:

Table 3 - Selective Laser Sintering vs Multi Jet Fusion.

	Selective Laser Sintering (SLS)	Multi Jet Fusion (MJF)
Processing time	Takes longer than MJF	Takes shorter than SLS, due to its removable build platform
Material recycling and reuse	50%	80%-85%
Dimensional accuracy	0.762 mm	0.508 mm
Materials and Colors	Provides a broader range of material options and a wide variety of colors	Light grey appearance, and can be dyed in black
Maximum part size	600 x 350 x 560 mm	380 x 284 x 380 mm
Cost per batch	More expensive at scale	Cheaper at scale, due to shorter overall processing time
Total Score	2	4

4.1.5 Comparison Conclusions

American Society for Testing and Materials (ASTM)[29] catalogued 3D Printing processes into seven groups: binder jetting, directed energy deposition, material extrusion, materials jetting, powder bed fusion, sheet lamination, and vat photopolymerization.[30] As the various processes have different characteristics and purposes, they are best suited to work with different types of materials. Since the three parts under study only use polymers in their composition, it is possible to narrow the study only to the technologies that use this type of raw material, being them Selective Laser Sintering (SLS), Multi Jet Fusion (MJF), Fuse Deposition Modelling (FDM) and Material Jetting (MJ). In a second step, seven criteria for a comparative analysis between the different options were defined, and qualitatively and quantitatively evaluated according to each technology perspective. As a result, SLS and MJF present the highest total values. It can then be concluded that these are the two best options to develop the intended purposes.

However, the goal of section 4.1 is to choose only the most suitable AM technology. For this reason, a more in-depth comparison between SLS and MJF has been performed. Despite the fact that SLS provides a broader range of material options and a wide variety of colors, as well as a maximum printable size, Multi Jet Fusion printer has a lower overall processing time and cost per batch, provides higher dimensional accuracy and reduces material waste.

Because it has the most and more critical criteria in its favor, Multi Jet Fusion (MJF) technology is the chosen to carry out this case study.

4.2 Manufacturing Costs Theoretical Demonstration & Calculation

Having chosen the most suitable printing technology for the case, it is time to proceed to the theoretical demonstration and the calculation of the variable and fixed costs involved in the manufacturing of the three parts by injection molding and additive manufacturing.

4.2.1 Manufacturing Costs by Injection Molding

For the manufacturing of parts by plastic injection molding, the process is divided into two activities: machine setup and part production.

The machine setup consists in the removal of a previous mold from the machine, introduction and fixing of the mold of the parts in the injection machine, safety and dimensional control, and locking of the machine. The setup process is entirely manual, so it requires a full-time operator during the process.

The production of the parts includes the entire injection process from the introduction of the raw material to the obtaining of the final part and the waste of material. Despite being automatic, this process also requires the presence of an operator for safety control and to stop the injection if necessary. However, this operator does not need to be 100% allocated to the task during the process, since this control is not continuous.

Both setup costs and production costs are subdivided into variable costs and fixed costs. While variable costs include the necessary material, labor and energy costs, fixed costs include the costs of the machine, the molds of the parts (commonly named tooling costs), machine maintenance and the building associated with the footprint of the injection molding machine. For this case study, and as it happens at Yazaki, the injection machine is not 100% allocated to the production of the three parts, meaning that is not dedicated – the machine can be used also for the production of other parts when the required production is met.

After these costs have been defined and explained in theory, they will be obtained for each of the three study pieces of the project: Big Channel, Medium Channel and Small Clip.

4.2.1.1 Theoretical Demonstration - Injection Machine Setup Costs

The calculation starts with the setup costs of the injection molding machine, which, as mentioned above, include variable costs and fixed costs.

Variable Costs

In this situation, the variable costs are equal to the labor cost of the operator, since there are no materials or energy costs associated with the task, since the machine is stopped. The operator, who is required to work 100% of his time during the entire setup process, has labor cost per hour that needs to be considered during the time of the setup process, as contemplated on equation 1.

Table 4 - Variables for the calculation of IM variable setup costs.

Variable	Description	Units
$t_{setup_{inj}}$	Injection machine setup time	hours (h)
C_{labor}	Labor cost per hour	€/h
$C_{labor_{setup}}$	Labor cost per setup	€
$C_{Variable_{setup}}$	Injection machine variable costs per setup	€

$$C_{variable_{setup}} = C_{labor_{setup}} = t_{setup_{inj}} * C_{labor} \qquad (1)$$

Fixed Costs

For the setup process, no molds are needed, and machine maintenance and building costs are not considered since the machine is turned off and not producing. Therefore, the only fixed costs for the setup are the costs of the injection molding machine - although the machine is not in use, it is unavailable for injection, due to the setup operations.

To obtain the cost of the injection molding machine for the setup process (equation 2) it is necessary to consider the cost of the machine per hour taking into account the project's lifetime and the total annual usage time of the machine (equation 3). As written above, the injection molding machine is not fully allocated to the project, so its cost will be given by the hourly cost of the machine times the hours required for setup to produce the number of parts requested.

Table 5 - Variables for the calculation of IM fixed setup costs.

Variable	Description	Units
WD_{year}	Number of working days per year	days/year
WH_{day}	Number of working hours per day	h/day
UT_{day}	Uptime - Available operation time	h/year
$t_{setup_{inj}}$	Injection machine setup time	h
p_{inj}	Price of the injection machine	€
$t_{lifetime}$	Project's lifetime	years
$C_{inj_{setup}}$	Injection machine cost per setup	€
$C_{fixed_{prod}}$	Injection machine fixed costs per setup	€

$$C_{fixed_{setup}} = C_{inj_{setup}} = (\frac{p_{inj}}{t_{lifetime} * UT_{day}} * t_{setup_{inj}}) * \%t_{dedicated} \qquad (2)$$

$$UT = WD_{year} * WH_{day} \qquad (3)$$

Total Setup Costs

The total costs for a single setup are the variable costs added to the fixed costs. In this situation they are the sum of the labor cost and the injection machine cost per setup (equation 4).

$$C_{setup_{inj}} = C_{variable_{setup}} + C_{fixed_{setup}} = C_{labor_{setup}} + C_{inj_{setup}} \qquad (4)$$

4.2.1.2 Theoretical Demonstration - Injection Machine Production Costs

As above, the injection machine's production costs are divided into variable and fixed costs.

Variable Costs

During production, the injection molding machine is already running, so in addition to labor costs, material and energy costs must also be considered.

Starting by the labor costs: as already stated, it is necessary an operator allocated to the production for safety control. However, this collaborator does not need to be 100% allocated to the task during the process, being able to perform other tasks simultaneously. Therefore, it is necessary to consider an operator occupancy rate for this process, as seen in equation 5. But first, the production time per batch needs to be calculated (equation 6) based on the units per batch, time per injection (the takt time) and units per injection, since a mold can have several cavities, and therefore produce several parts per injection.

Table 6 - Variables for the calculation of labor production costs.

Variable	Description	Units
$t_{prod_{inj}}$	Injection machine production time per batch	hours (h)
C_{labor}	Labor cost per hour	€/h
$r_{occupancy}$	Operator occupancy rate	%
$C_{labor_{batch}}$	Labor cost per batch	€

$$C_{labor_{batch}} = t_{prod_{inj}} * C_{labor} * r_{occupancy} \tag{5}$$

$$t_{prod_{inj}} = \frac{N_{batch}}{N_{inj}} * \frac{t_{inj}}{3600} \tag{6}$$

Now for the material costs: these are calculated by considering the price per kilogram of the quantity of raw material used in the production of a batch (equation 7). Before, the weight of raw material per unit necessary is estimated based on its density in kilogram per cubic centimeters (equation 8).

Table 7 - Variables for the calculation of raw material IM production costs.

Variable	Description	Units
$t_{prod_{inj}}$	Price of raw material per kg	€/kg
V_{unit}	Volume of the part	cm^3
$\rho_{raw\ mat}$	Desity of raw material per cm3	kg/cm3
$w_{raw\ mat_{unit}}$	Weight of raw material required per unit	kg
$w_{raw\ mat_{batch}}$	Weight of raw material required per batch	kg
$C_{raw\ mat_{batch}}$	Cost of raw material per batch	€

$$C_{raw\ mat_{batch}} = p_{raw\ mat} * w_{raw\ mat_{batch}} \tag{7}$$

$$w_{raw\ mat_{unit}} = V_{unit} * p_{raw\ mat} \tag{8}$$

Finally the energy costs, which are the costs associated to the energy expended by the injection machine during the production of a batch taking into account its power and the price of electricity per kWh (equation 9).

Table 8 - Variables for the calculation of IM energy production costs.

Variable	Description	Units
$t_{prod_{inj}}$	Injection machine production time per batch	h
P_{inj}	Injection machine power	kW
p_{energy}	Price of energy per kWh	€/kWh
$C_{inj\ energy_{batch}}$	Injection machine energy cost per batch	€
$C_{Variable_{prod}}$	Injection machine variable costs per batch	€

$$C_{inj\,energy_{batch}} = t_{prod_{inj}} * P_{inj} * p_{energy} \tag{9}$$

In short, the variable costs per batch of plastic injection molding production are the sum of labor costs, material costs, and energy costs (equation 10).

$$C_{variable_{prod}} = C_{labor_{batch}} + C_{raw\,mat_{batch}} + C_{inj\,energy_{batch}} \tag{10}$$

Fixed Costs

In contrast to setup process, during production the injection molding machine is turned on and in use. This means that the fixed costs, in addition to the cost of the machine itself, also include the machine maintenance costs, building costs and the costs of the molds of the part being produced (tooling costs). As in setup process, to obtain the cost of the injection molding machine (not totally dedicated) per bath produced, it is necessary to consider the cost of the machine per hour - taking into account the project's lifetime and the total annual usage time of the machine (equation 3) – times the hours needed for the production of the parts required (equation 11).

Table 9 - Variables for the calculation of injection machine costs per batch.

Variable	Description	Units
WD_{year}	Number of working days per year	days/year
WH_{day}	Number of working hours per day	h/day
UT_{day}	Uptime - Available operation time	h/year
$t_{prod_{inj}}$	Injection machine production time per batch	h
p_{inj}	Price of the injection machine	€
$t_{lifetime}$	Project's lifetime	years
$C_{inj_{batch}}$	Injection machine cost per batch	€

$$UT = WD_{year} * WH_{day} \tag{3}$$

$$C_{inj_{batch}} = (\frac{p_{inj}}{t_{lifetime} * UT_{day}} * t_{prod_{inj}}) * \%t_{dedicated} \tag{11}$$

Associated with the injection molding machine are the maintenance costs. It involves regular servicing of equipment, routine checks, repair work, and replacement of worn or nonfunctional parts. For this exercise, it will be used an estimation method to calculate these costs based on a percentage of the total machine cost (equation 12).

$$C_{maint_{batch}} = C_{inj_{batch}} * \%_{maint} \tag{12}$$

The building cost per batch (equation 13) is calculated taking into account the cost of the area occupied by the injection machine based on the building price per square meter (equation 14) during the batch production time. It should be noted that the area occupied by the machine includes a safety margin around the machine that cannot be occupied.

Table 10 - Variables for the calculation of building costs per batch by IM.

Variable	Description	Units
$p_{building_{m2}}$	Price of the building per m^2	€/m^2
A_{inj}	Injection machine occupied area	m^2
$p_{building_{inj}}$	Price of building occupied by injection machine	€
$t_{prod_{inj}}$	Injection machine production time per batch	h
UT_{day}	Uptime - Available operation time	h/year
$t_{lifetime}$	Project's lifetime	years
$C_{building_{batch}}$	Building cost per batch	€

$$C_{building_{batch}} = \frac{p_{building_{inj}}}{t_{lifetime} * UT_{day}} * t_{prod_{inj}} \qquad (13)$$

$$p_{building_{inj}} = p_{building_{m2}} * A_{inj} \qquad (14)$$

Unlike the injection machine, which can be used to produce other parts, each mold can only produce one type of part, since its shape is not moldable or adaptable to another design. Therefore, the cost of the molds is allocated entirely to the parts to be produced. Its calculation (equation 15) is based on the mold cost distributed over the number of batches that are needed to produce the desired quantity of parts (equation 16).

Table 11 - Variables for the calculation of tooling costs per batch.

Variable	Description	Units
$Units_{year}$	Required production per year	units
N_{batch}	Number of units per batch	units
$N_{batches_{inj}}$	Number batches required by IM per year	units
$C_{tool_{total}}$	Tooling costs for the total production	€
$t_{lifetime}$	Project's lifetime	years
$C_{tool_{batch}}$	Tooling cost per batch	€
$C_{fixed_{prod}}$	Injection machine fixed costs per batch	€

$$C_{tool_{batch}} = \frac{C_{tool_{total}}}{t_{lifetime} * N_{batches_{inj}}} \qquad (15)$$

$$N_{batches_{inj}} = \frac{Units_{year}}{N_{batch}} \qquad (16)$$

In short, the fixed costs per batch of plastic injection molding production are the sum of injection molding machine, machine maintenance, building and tooling costs per batch (equation 17).

$$C_{fixed_{prod}} = C_{inj_{batch}} + C_{maint_{batch}} + C_{building_{batch}} + C_{tool_{batch}} \tag{17}$$

Total Production Costs

The costs for the production of a batch are the variable costs added to the fixed costs, as showed below (equation 18).

$$C_{prod_{inj}} = C_{variable_{prod}} + C_{fixed_{prod}} \tag{18}$$

Total Injection Machine Costs per Batch

The total costs to produce a batch by injection molding are given by the setup costs plus the production costs (equation 19).

$$C_{inj_{batch}} = C_{setup_{inj}} + C_{prod_{inj}} \tag{19}$$

4.2.1.3 Calculation - Injection Machine Setup Costs

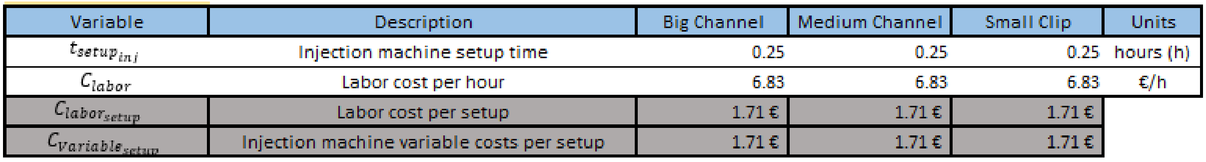
After the theoretical demonstration of the variable and fixed cost calculation formulas for the setup and production processes of the plastic injection molding machine, the next step is the calculation of the variables to obtain these costs. Since they only involve labor and injection machine costs, the setup costs will be the same for the three parts of the project - Big Channel, Medium Channel and Small Clip.

Variable Costs

As shown above, the variable setup costs equal the labor costs of this process. In order to calculate them, it is necessary to identify the injection machine setup time and labor cost per hour.

For internal estimations and calculations, Yazaki has established an estimated value of 15 minutes for the entire setup process, or 0.25 hours. Moreover, the labor cost per hour can be calculated based on the average operator's gross salary in Portugal, which is around 1110€ per month, equivalent to 6.83€ per hour.

Table 12 - Variable costs per injection machine setup.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{setup_{inj}}$	Injection machine setup time	0.25	0.25	0.25	hours (h)
C_{labor}	Labor cost per hour	6.83	6.83	6.83	€/h
$C_{labor_{setup}}$	Labor cost per setup	1.71 €	1.71 €	1.71 €	
$C_{variable_{setup}}$	Injection machine variable costs per setup	1.71 €	1.71 €	1.71 €	

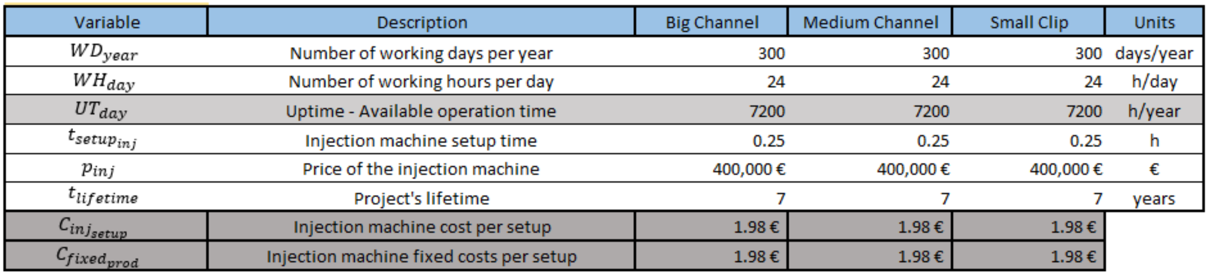
Fixed Costs

On the other hand, the fixed setup costs equal the costs of the injection molding machine.

At Yazaki the factory is in operation 24 hours a day, with the workers divided into three shifts. This allows an injection molding machine to be operational for about 300 days during a year, while the remaining days of downtime are dedicated to maintenance and repair work.

Given the intensity and recurrence of use, it is expected, according to Yazaki employees, that a company plastic injection molding machine, with proper maintenance, will last between 10 and 15 years. For calculation purposes, the expected injection machine lifetime will be 12 years. According to the company, these machines have a price tag of around 400,000€.

Table 13 - Fixed costs per injection machine setup.

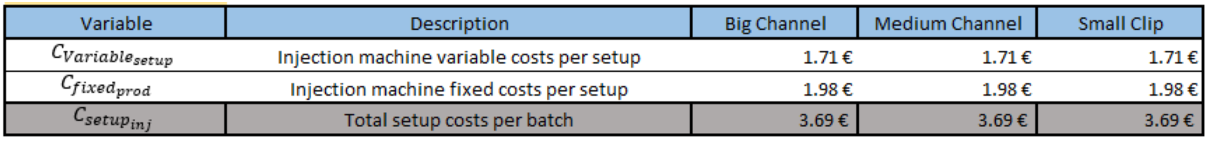


Variable	Description	Big Channel	Medium Channel	Small Clip	Units
WD_{year}	Number of working days per year	300	300	300	days/year
WH_{day}	Number of working hours per day	24	24	24	h/day
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{setup_{inj}}$	Injection machine setup time	0.25	0.25	0.25	h
p_{inj}	Price of the injection machine	400,000 €	400,000 €	400,000 €	€
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{inj_{setup}}$	Injection machine cost per setup	1.98 €	1.98 €	1.98 €	
$C_{fixed_{prod}}$	Injection machine fixed costs per setup	1.98 €	1.98 €	1.98 €	

Total Setup Costs

The total costs for a single setup are the variable costs added to the fixed costs. In this situation they are the sum of the labor cost and the injection machine cost per setup, as seen above.

Table 14 - Total setup costs per batch.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{setup}}$	Injection machine variable costs per setup	1.71 €	1.71 €	1.71 €
$C_{fixed_{prod}}$	Injection machine fixed costs per setup	1.98 €	1.98 €	1.98 €
$C_{setup_{inj}}$	Total setup costs per batch	3.69 €	3.69 €	3.69 €

4.2.1.4 Calculation - Production Costs

In the same way, the production costs are calculated. However, some costs will depend on the characteristics of the part to be produced and capacity of production, so the cost values will vary between the 3 parts.

There are some assumptions that have to be highlighted for the injection molding process. As mentioned before, the mold is unique for each part and can only be used for the production of a single model. Therefore, each of the three parts in the case study have its own mold, and the cost of the mold, the number of units it can mold simultaneously, and the time it takes to mold them in each injection will vary. For the case study, it is dimensioned, for the three parts, that a production batch by injection molding process is equivalent to 500 units.

Table 15 - General information on injection molding process.

		Big Channel	Medium Channel	Small Clip
Tooling costs [€/total production]	$[C_{tool_{total}}]$	70,000 €	45,000 €	25,000 €
N. units per mold [units]	$[N_{inj}]$	1	1	8
Time per injection [seconds]	$[t_{inj}]$	12	8	10
N. units per batch [units]	$[N_{batch}]$	500	500	500

Once defined the number of units per batch, it is useful to calculate the times required to produce the batches for the conditions of each part. Using equation 6 defined above, and the data provided, the respective times are obtained:

$$t_{prod_{inj}} = \frac{N_{batch}}{N_{inj}} * \frac{t_{inj}}{3600} \tag{6}$$

Table 16 - Injection machine production time per batch.

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	hours (h)

Variable Costs

The variable costs of production are given by labor cost, raw material cost, and energy cost.

Given the production time per batch and assuming an operator occupancy rate of 33%, the labor costs per batch are the following:

Table 17 - Labor cost per batch.

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	hours (h)
C_{labor}	Labor cost per hour	6.83	6.83	6.83	€/h
$r_{occupancy}$	Operator occupancy rate	33%	33%	33%	%
$C_{labor_{batch}}$	Labor cost per batch	3.76 €	2.50 €	0.39 €	

To calculate the cost of raw material, it is first necessary to understand the cost per kg of raw material. According to the reference plastic raw materials' German data base Plasticker, the average price of PA66 is currently 1.73€/kg, that being the reference price to use. Knowing that the density of PA66 plastic, the raw material of the 3 pieces, is 1.14 g/cm^3, the breakdown of raw material costs follows:

Table 18 - Cost of raw material per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$p_{raw\ mat}$	Price of raw material per kg	1.73	1.73	1.73	€/kg
V_{unit}	Volume of the part	2329.6	479.2	6.2	cm^3
$\rho_{raw\ mat}$	Desity of raw material per cm3	0.00114	0.00114	0.00114	kg/cm3
$w_{raw\ mat_{unit}}$	Weight of raw material required per unit	2.66	0.55	0.007	kg
$w_{raw\ mat_{batch}}$	Weight of raw material required per batch	1327.87	273.14	3.53	kg
$C_{raw\ mat_{batch}}$	Cost of raw material per batch	2,297.22 €	472.54 €	6.11 €	

Given that the injection machine used in the company has a power of 33kW, and based on the EDP electricity price in Portugal of 0.182 €/kWh, it is possible to calculate the energy costs per batch:

Table 19 - Injection machine energy cost per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	h
P_{inj}	Injection machine power	33	33	33	kW
p_{energy}	Price of energy per kWh	0.182	0.182	0.182	€/kWh
$C_{inj\ energy_{batch}}$	Injection machine energy cost per batch	9.98 €	6.66 €	1.04 €	

Once the labor, raw material and energy costs have been calculated, it is then possible to obtain injection machine variable costs per batch:

Table 20 - Injection machine variable costs per batch

Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{prod}}$	Injection machine variable costs per batch	2,310.96 €	481.70 €	7.54 €

Fixed Costs

Fixed costs, which, as concluded above, include the injection machine, maintenance, building and tooling costs per batch, are now considered and calculated.

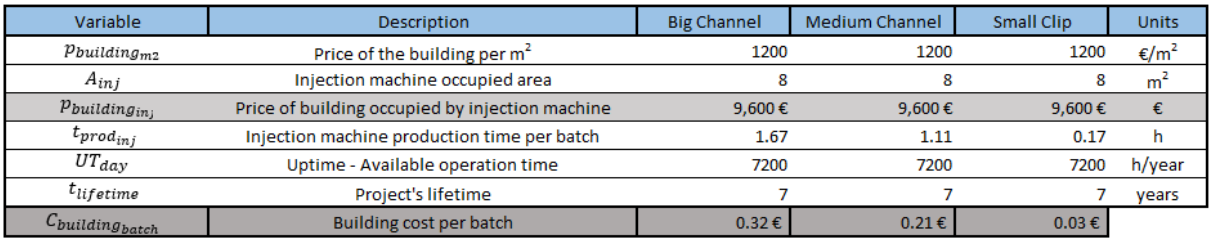
Assuming a maintenance percentage of 3%, it is possible to immediately get the injection machine costs and the maintenance costs per batch:

Table 21 - Injection machine cost and maintenance cost per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
WD_{year}	Number of working days per year	300	300	300	days/year
WH_{day}	Number of working hours per day	24	24	24	h/day
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	h
p_{inj}	Price of the injection machine	400,000 €	400,000 €	400,000 €	€
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{inj_{batch}}$	Injection machine cost per batch	13.23 €	8.82 €	1.38 €	
$\%_{maint}$	Estimated Maintenance Percentage	3%	3%	3%	%
$C_{maint_{batch}}$	Maintenance cost per batch	0.40 €	0.26 €	0.04 €	

Taking into account that an injection molding machine occupies an area of approximately 8 m^2, and assuming that at the Ovar plant, Yazaki's location in Portugal, the cost of the building is set at 1200€/m^2, follows the breakdown of the building costs per batch for each part:

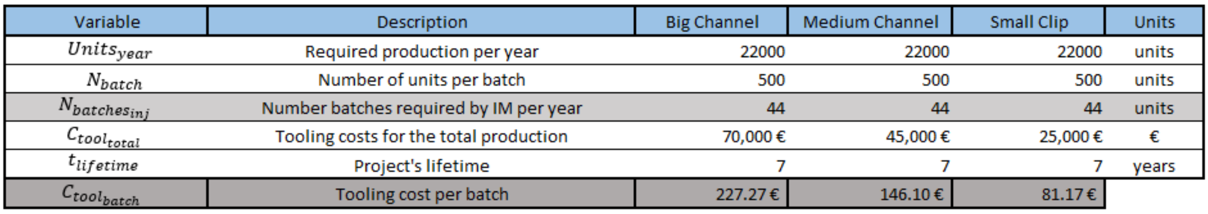
Table 22 - Building cost per batch



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$p_{building_{m2}}$	Price of the building per m^2	1200	1200	1200	€/m^2
A_{inj}	Injection machine occupied area	8	8	8	m^2
$p_{building_{inj}}$	Price of building occupied by injection machine	9,600 €	9,600 €	9,600 €	€
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	h
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{building_{batch}}$	Building cost per batch	0.32 €	0.21 €	0.03 €	

Finally, the tooling cost per batch, by first calculating the number of batches required per year:

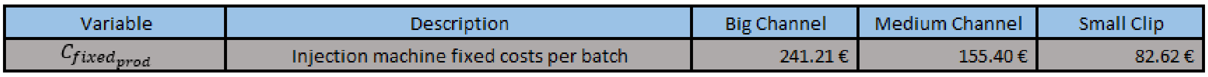
Table 23 - Tooling cost per batch



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$Units_{year}$	Required production per year	22000	22000	22000	units
N_{batch}	Number of units per batch	500	500	500	units
$N_{batches_{inj}}$	Number batches required by IM per year	44	44	44	units
$C_{tool_{total}}$	Tooling costs for the total production	70,000 €	45,000 €	25,000 €	€
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{tool_{batch}}$	Tooling cost per batch	227.27 €	146.10 €	81.17 €	

With the above calculations obtained, it is then possible to calculate the injection machine fixed costs per batch:

Table 24 - Injection machine fixed costs per batch

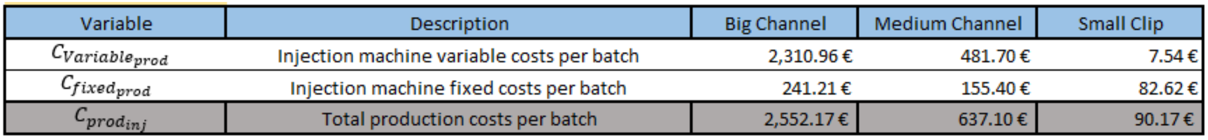


Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{fixed_{prod}}$	Injection machine fixed costs per batch	241.21 €	155.40 €	82.62 €

Total Production Costs

The total costs for a single setup are the variable costs added to the fixed costs. In this situation they are the sum of the labor cost and the injection machine cost per setup.

Table 25 - Total production costs per batch

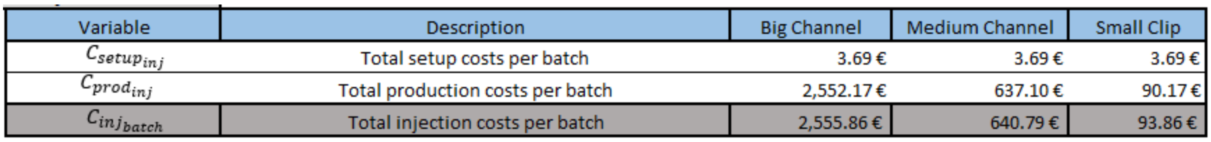


Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{prod}}$	Injection machine variable costs per batch	2,310.96 €	481.70 €	7.54 €
$C_{fixed_{prod}}$	Injection machine fixed costs per batch	241.21 €	155.40 €	82.62 €
$C_{prod_{inj}}$	Total production costs per batch	2,552.17 €	637.10 €	90.17 €

Total Injection Machine Costs per Batch

Finally, by adding the setup costs with the production costs, it is possible to obtain the total injection costs per batch for each of the three parts under study:

Table 26 - Total production costs per batch



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{setup_{inj}}$	Total setup costs per batch	3.69 €	3.69 €	3.69 €
$C_{prod_{inj}}$	Total production costs per batch	2,552.17 €	637.10 €	90.17 €
$C_{inj_{batch}}$	Total injection costs per batch	2,555.86 €	640.79 €	93.86 €

4.2.2 Manufacturing Costs by Additive Manufacturing

It is time to look for the manufacturing of parts by additive manufacturing. As concluded in section 4.1, Multi Jet Fusion (MJF) is the most suitable technology to use in this case study. Recalling the production process of this technology, it all starts when a thin layer of powder is first spread over the build platform. After that, a carriage with inkjet nozzles passes over the bed, depositing fusing agent on the powder, while a detailing agent that inhibits sintering is printed near the edge of the part. A high-power infrared energy source then passes over the build bed and sinters the areas where the fusing agent was dispensed while leaving the rest of the powder unaltered. When it is concluded, the printed parts are encapsulated in powder and need to cool down before they can be removed.

Just like the injection molding process, the additive manufacturing process is divided into different activities: setting up the 3D printer, printing the parts, cleaning and removing the parts after production, and post processing process.

The setup process consists of cleaning the machine, supplying the raw materials needed for printing, dimensional control and calibration of the platform, among other preparation processes to ensure the success of the printing process. This printing process, as described above, is fully automatic, so there is no need for an operator to be present during the process. However, other variable costs (raw material, energy), and also fixed costs (printer, building, maintenance) are considered. After the process is finished it is necessary to remove and clean the freshly produced parts, clean off the excess raw material, and do a first quality check, all of which are manual tasks. Finally, post-processing treatment may be necessary in some cases to, for example, colorize or reinforce the parts. However, for the purposes of the case study, this last step will not be considered.

As with the injection molding process, the steps in the printing process also include fixed and variable costs, as detailed below. After these costs have been defined and explained in theory, they will be obtained for each of the three study pieces of the project: Big Channel, Medium Channel and Small Clip.

For this case study, and as in injection molding, it is being considered that the MJF printer is not 100% allocated to the production of the three parts only, meaning that is not dedicated – the printer can be used also for the production of other parts when the required production is met.

4.2.2.1 Theoretical Demonstration – Additive Manufacturing Setup Costs

The calculation starts with the setup costs of the MJF printer, which, as mentioned above, include variable costs and fixed costs.

Variable Costs

As in injection molding process, the variable costs for the setup of the MJF printer are equal to the labor cost of the operator, since there are no materials or energy costs associated with the task because the machine is stopped. The operator, who is required to work 100% of his time during the entire setup process, has labor cost per hour that needs to be considered during the time of the setup process, as contemplated on equation .

Table 27 - Variables for the calculation of MJF variable setup costs.

Variable	Description	Units
$t_{setup_{MJF}}$	MJF printer setup time	hours (h)
C_{labor}	Labor cost per hour	€/h
$C_{labor_{setup}}$	Labor cost per setup	€
$C_{Variable_{setup}}$	MJF variable costs per setup	€

$$C_{variable_{setup}} = C_{labor_{setup}} = t_{setup_{MJF}} * C_{labor} \qquad (20)$$

Fixed Costs

For the printer setup process, the only fixed costs to be considered are the MJF printer ones – once again, although the printer is not in use, it is unavailable for printing, due to the setup activities.

To obtain the cost of the MJF printer for the setup process (equation 21), the process is the same as injection machine, by considering the cost of the printer per hour taking into account the project's lifetime and the total annual usage time (equation 3). As considered for the case study, the injection molding machine is not fully allocated to the project, so its cost will be given by its hourly cost times the hours required for setup the printer.

Table 28 - Variables for the calculation of IM fixed setup costs.

Variable	Description	Units
WD_{year}	Number of working days per year	days/year
WH_{day}	Number of working hours per day	h/day
UT_{day}	Uptime - Available operation time	h/year
$t_{setup_{MJF}}$	MJF printer setup time	h
p_{MJF}	Price of the MJF printer	€
$t_{lifetime}$	Project's lifetime	years
$C_{MJF_{setup}}$	MJF printer cost per setup	€
$C_{fixed_{setup}}$	MJF printer fixed costs per setup	€

$$C_{fixed_{setup}} = C_{MJF_{setup}} = \frac{p_{MJF}}{t_{lifetime} * UT_{day}} * t_{setup_{MJF}} \qquad (21)$$

$$UT = WD_{year} * WH_{day} \qquad (3)$$

Total Setup Costs

The total costs for a single setup are the variable costs added to the fixed costs. In this situation they are the sum of the labor cost and the MJF printer cost per setup (equation 22).

$$C_{setup_{MJF}} = C_{variable_{setup}} + C_{fixed_{setup}} = C_{labor_{setup}} + C_{MJF_{setup}} \tag{22}$$

4.2.2.2 Theoretical Demonstration – Additive Manufacturing Printing Costs

The additive manufacturing printing costs are divided into variable costs - raw material and energy costs - and fixed costs - printer, building and maintenance costs.

Variable Costs

As already stated, during the printing process of the parts, the 3D printers are totally autonomous, not requiring any operator for safety control or performance of any task, meaning that it does not exist labor costs during production. On the other hand, there are the raw material and energy costs to be considered.

The raw material in the Multi Jet Fusion process includes not only the powdered material of the part in production, but also the fusing and detailing agents that solidify the part and perfect its surface (equation 23).

Table 29 - Variables for the calculation of raw material MJF production costs.

Variable	Description	Units
N_{batch}	Number of units per batch	units
$w_{powder_{unit}}$	Weight of powder required per unit	kg
p_{powder}	Price of powder per kg	€/kg
$w_{agents_{unit}}$	Weight of agents per unit	kg
p_{agents}	Price of agents per kg	€/kg
$C_{raw\ mat_{batch}}$	Cost of raw material per batch	€

$$C_{raw\ mat_{batch}} = N_{batch} * \left(w_{powder_{unit}} * p_{powder} + w_{agents_{unit}} * p_{agents}\right) \tag{23}$$

For the energy costs, the calculation method is the same as for injection molding based on the price of energy per kWh (equation 24).

Table 30 - Variables for the calculation of MJF energy production costs.

Variable	Description	Units
$t_{prod_{MJF}}$	MJF printer production time per batch	h
P_{inj}	Injection machine power	kW
p_{energy}	Price of energy per kWh	€/kWh
$C_{MLF\ energy_{batch}}$	MJF printer energy cost per batch	€

$$C_{MJF\,energy_{batch}} = t_{prod_{MJF}} * P_{inj} * p_{energy} \tag{24}$$

By adding up the raw material costs and the energy costs per batch, it is then possible to obtain the MJF printer variable costs per batch:

$$C_{variable_{print}} = C_{raw\,mat_{batch}} + C_{MJF\,energy_{batch}} \tag{25}$$

Fixed Costs

Focusing now on fixed costs, these encompass the cost of the MJF printer, maintenance costs, and building costs.

The printer cost is calculated in the same way as before taking into account the production time per batch (equation 26). It is also considered a percentage of the total machine cost as the maintenance cost (equation 27).

Table 31 - Variables for the calculation of MJF printer per batch.

Variable	Description	Units
WD_{year}	Number of working days per year	days/year
WH_{day}	Number of working hours per day	h/day
UT_{day}	Uptime - Available operation time	h/year
$t_{prod_{MJF}}$	MJF printer production time per batch	h
p_{MJF}	Price of the MJF printer	€
$t_{lifetime}$	Project's lifetime	years
$C_{MJF_{batch}}$	MJF printer cost per batch	€

$$C_{MJF_{batch}} = \frac{p_{MJF}}{t_{lifetime} * UT_{day}} * t_{prod_{MJF}} \tag{26}$$

$$UT = WD_{year} * WH_{day} \tag{3}$$

$$C_{maint_{batch}} = C_{MJF_{batch}} * \%_{maint} \tag{27}$$

The building cost per batch (equation 28) is again calculated taking into account the cost of the area occupied by the printer (including a safety margin) based on the building price per square meter (equation 29) during the batch production time.

Table 32 - Variables for the calculation of building costs of MJF per batch.

Variable	Description	Units
$p_{building_{m2}}$	Price of the building per m^2	€/m^2
A_{MJF}	MJF printer occupied area	m^2
$p_{building_{MJ}}$	Price of building occupied by injection machine	€
$t_{prod_{MJF}}$	MJF printer production time per batch	h
UT_{day}	Uptime - Available operation time	h/year
$t_{lifetime}$	Project's lifetime	years
$C_{building_{batch}}$	Building cost per batch	€

$$C_{building_{batch}} = \frac{p_{building_{MJF}}}{t_{lifetime} * UT_{day}} * t_{prod_{MJF}} \tag{28}$$

$$p_{building_{MJF}} = p_{building_{m2}} * A_{MJF} \tag{29}$$

The fixed costs per batch of a MJF production are then the sum of MJF printer, machine maintenance and building costs per batch (equation 30).

$$C_{fixed_{prod}} = C_{MJF_{batch}} + C_{maint_{batch}} + C_{building_{batch}} \tag{30}$$

Total Printing Costs

The costs for the production of a batch by MJF are the variable costs added to the fixed costs, as showed below (equation 31).

$$C_{prod_{MJF}} = C_{variable_{prod}} + C_{fixed_{prod}} \tag{31}$$

4.2.2.3 Theoretical Demonstration – Additive Manufacturing After-Printing Costs

After the setup is done and the parts are printed, it is necessary to remove them from the machine, clean the excess powder from them, and make a first quality check of the parts. All these tasks are performed manually by a worker, who needs to be on the machine 100% of the time. Therefore, at the cost level this step only includes the labor cost of the employee for the time he needs to perform all the tasks. These are variable costs, since the more units that are printed, the longer the task will take. As stated above, post-processing costs will not be accounted for in the case study, so these represent the last costs of the entire printing process.

Variable Costs

The tasks of removing and cleaning the parts were considered as a whole. In order to calculate the cost of these tasks (equation 33), it is first necessary to understand how long these activities take per batch by considering the time for one unit (equation 32).

Table 33 - Variables for the calculation of labor cost for removing & cleaning per batch.

Variable	Description	Units
$t_{clean_{unit}}$	Removing & cleaning time per unit	hours (h)
N_{batch}	Number of units per batch	units
$t_{clean_{MJF}}$	Removing & cleaning time per batch	h
C_{labor}	Labor cost per hour	€/h
$C_{labor_{clean}}$	Labor cost for removing & cleaning per batch	€

$$t_{clean_{MJF}} = t_{clean_{unit}} * N_{batch} \tag{32}$$

$$C_{labor_{clean}} = t_{clean_{MJF}} * C_{labor} \tag{33}$$

In regards to the quality check task, it is only done for a certain percentage of randomly chosen units of a batch, but being mandatory for at least one unit per batch (equation 35). For the case study, it is considered that the quality check's duration equals a predetermined percentage of the time of removing and cleaning (equation 34). The labor cost for this activity (equation 37) is calculated by its duration per batch (equation36) times the labor cost per hour.

Table 34 - Variables for the calculation of labor cost for quality check per batch.

Variable	Description	Units
$t_{clean_{unit}}$	Removing & cleaning time per unit	hours (h)
$r_{check_{time}}$	Rate check time vs remo/clean time	% time
$t_{check_{unit}}$	Quality check time per unit	hours (h)
N_{batch}	Number of units per batch	units
$r_{check_{units}}$	Rate check units per batch	% units
N_{check}	Number of units checked per batch	units
$t_{check_{MJF}}$	Quality check time per batch	h
C_{labor}	Labor cost per hour	€/h
$C_{labor_{check}}$	Labor cost for quality check per batch	€

$$t_{check_{unit}} = t_{clean_{unit}} * r_{check_{time}} \tag{34}$$

$$N_{check} = N_{batch} * r_{check_{units}} \tag{35}$$

$$t_{check_{MJF}} = t_{check_{unit}} * N_{check} \tag{36}$$

$$C_{labor_{check}} = t_{check_{MJF}} * C_{labor} \tag{37}$$

Total After Printing Costs

The total after printing costs are then equal to the variable after printing costs, which are the sum of the labor cost for removing & cleaning per batch and the labor cost for quality check per batch (equation 38).

$$C_{after_{MJF}} = C_{Variable_{after}} = C_{labor_{clean}} + C_{labor_{check}} \tag{38}$$

Total Additive Manufacturing Costs per Batch

Finally, by adding the setup costs with the printing costs and the after printing costs, it is possible to obtain the total AM printing costs per batch for each of the three parts under study (equation):

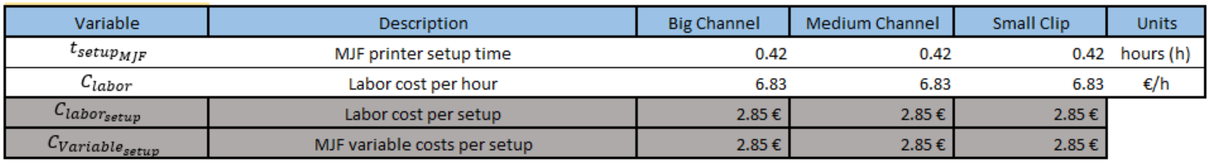
$$C_{MJF_{batch}} = C_{setup_{MJF}} + C_{prod_{MJF}} + C_{after_{MJF}} \tag{39}$$

4.2.2.4 Calculation – Additive Manufacturing Setup Costs

After the theoretical demonstration of MJF's printing variable and fixed costs, now follows the calculation of these same costs.

The setup costs, and similarly to the setup costs of injection molding, they only involve labor and the printer costs, and so the setup costs will be the same for the three parts of the project - Big Channel, Medium Channel and Small Clip. Together with Yazaki specialists, it was established a printer setup time of 25 minutes, while the labor cost per hour has already been defined in subsection 4.2.1 - 6.83€ per hour. With this data, it is possible to conclude the MJF variable cost per setup already:

Table 35 - MJF variable costs per setup



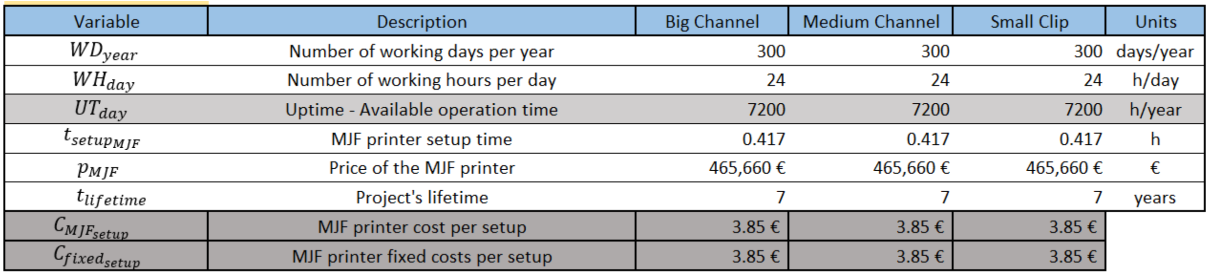
Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{setup_{MJF}}$	MJF printer setup time	0.42	0.42	0.42	hours (h)
C_{labor}	Labor cost per hour	6.83	6.83	6.83	€/h
$C_{labor_{setup}}$	Labor cost per setup	2.85 €	2.85 €	2.85 €	
$C_{Variable_{setup}}$	MJF variable costs per setup	2.85 €	2.85 €	2.85 €	

As seen before, Yazaki facilities operate 24 hours a day, with the workers divided into three shifts. This allows the printer to work for an entire day. For the case study, it is again considered that the MJF device has the capacity to work 300 days per year, while maintenance and calibration activities are performed on the remaining days.

Since the first MJF printer was launched to the market, HP, the company that owns this technology, has already made several changes and improvements to its printers, which resulted in different machines with different features for different purposes. More recently, this company launched the 5200 Series 3D Printing solutions, which comprises three printer models: Jet Fusion 5200, Jet Fusion 5210 and Jet Fusion 5210 Pro. The last two models not only offer better economic value than the 5200 for larger volume production, but are also more conducive for industrial applications because they enable manufacturers to see the status of the machine from distance. Therefore, the model selected will be the Jet Fusion 5210 Pro, because it is the most recent and the most suitable for industrial purposes.

Although it is only possible to get a price quotation after contacting the selling company, the reference additive manufacturing website Formlabs claims that, for the 5200 Series 3D printers, the price will be around $500,000, equivalent to 465,660€ (currency from May 2022 – 0.9313). Considering the same 12 years lifetime for the MJF printer as for the injection machine and it is possible to obtain the machine costs, which also represent the fixed setup costs:

Table 36 - MJF fixed costs per setup

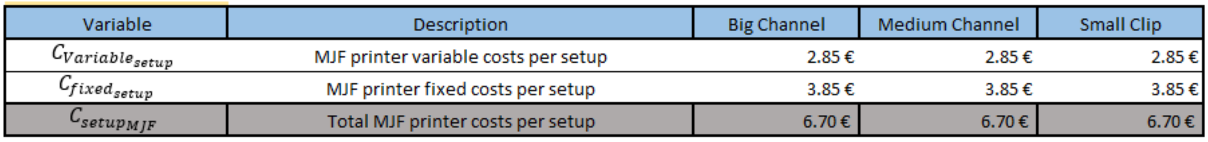


Variable	Description	Big Channel	Medium Channel	Small Clip	Units
WD_{year}	Number of working days per year	300	300	300	days/year
WH_{day}	Number of working hours per day	24	24	24	h/day
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{setup_{MJF}}$	MJF printer setup time	0.417	0.417	0.417	h
p_{MJF}	Price of the MJF printer	465,660 €	465,660 €	465,660 €	€
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{MJF_{setup}}$	MJF printer cost per setup	3.85 €	3.85 €	3.85 €	
$C_{fixed_{setup}}$	MJF printer fixed costs per setup	3.85 €	3.85 €	3.85 €	

Total Setup Costs

The total costs for a single setup are the variable costs added to the fixed costs. In this situation they are the sum of the labor cost and the injection machine cost per setup.

Table 37 - Total MJF printer costs per setup



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{setup}}$	MJF printer variable costs per setup	2.85 €	2.85 €	2.85 €
$C_{fixed_{setup}}$	MJF printer fixed costs per setup	3.85 €	3.85 €	3.85 €
$C_{setup_{MJF}}$	Total MJF printer costs per setup	6.70 €	6.70 €	6.70 €

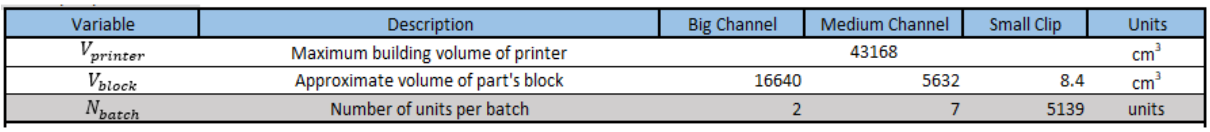
4.2.2.5 Calculation – Additive Manufacturing Printing Costs

Before proceeding to the printing costs, it is first important to understand the number of parts that can be produced per batch on the Jet Fusion 5210 Pro. Unlike the case of injection molding, where a batch was defined as 500 units because there is no physical limitation to the number of parts produced in a row (not simultaneously), in the case of additive manufacturing the number of parts to produce simultaneously is conditioned by the dimensions of the printer, being necessary, after each batch, to proceed to a new setup process for the next production to refill, for example, the raw materials. Due to this fact and also to become lighter and therefore consume less raw material, parts are often redesigned and optimized in CAD programs, making it possible to print more units at once. It is necessary to make the disclaimer that, for the purposes of the case study, this redesign was not carried out.

According to HP's data, the maximum building size of the Jet Fusion 5210 Pro printer model is 400×284×380 mm, which represents a volume of 43168 cm^3. Considering that: 1) the volume of printer's bay is greater than the volume of each of the parts, and 2) none of the parts has any dimension on axes greater than the maximum axial dimensions of the printer, it is possible to estimate the number of units of each part per production batch (values rounded down so as not to exceed any printer's limits) through the volume of the part block (equation):

$$N_{batch} = Round\ to\ unit\ down\ \left[\frac{V_{printer}}{V_{block}}\right] \tag{40}$$

Table 38 - Number of units per batch of MJF.



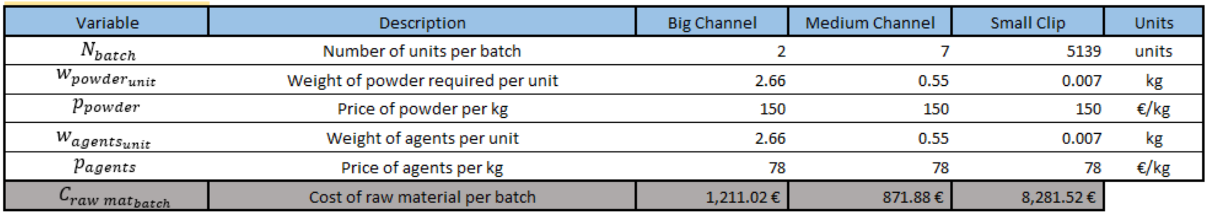
Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$V_{printer}$	Maximum building volume of printer	43168			cm^3
V_{block}	Approximate volume of part's block	16640	5632	8.4	cm^3
N_{batch}	Number of units per batch	2	7	5139	units

Variable Costs

As already stated, during the printing process of the parts, the 3D printers are totally autonomous avoiding labor costs. However, raw material and energy costs need to be considered.

As seen before, for MJF printing process, the raw materials are the powdered material of the part in production and the fusing and detailing agents. Assuming a required weight of powder and weight of agents per unit equal to the weight of raw material needed for injection molding, and discarding the waste of material during the printing process, it is possible to calculate the cost of raw materials used per batch, if we consider a price of powder of 150€ per kg and a price of agents of 78€ per kg (estimated prices provided by Yazaki):

Table 39 - Cost of raw materials per batch by MJF



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
N_{batch}	Number of units per batch	2	7	5139	units
$w_{powder_{unit}}$	Weight of powder required per unit	2.66	0.55	0.007	kg
p_{powder}	Price of powder per kg	150	150	150	€/kg
$w_{agents_{unit}}$	Weight of agents per unit	2.66	0.55	0.007	kg
p_{agents}	Price of agents per kg	78	78	78	€/kg
$C_{raw\ mat_{batch}}$	Cost of raw material per batch	1,211.02 €	871.88 €	8,281.52 €	

It is important to take into account that in AM situation, the batches between the different parts do not represent the same number of units, and therefore the costs are not directly comparable.

Turning now to energy costs. For the electricity price, it is considered the same EDP's standard of 0.1815 €/kWh. To obtain an accurate MJF printer production time per batch, it would be necessary to use a CAM (computer-aided manufacturing) software. Since this resource was not used, the values were estimated together with Yazaki. For the estimation, it was taken into account that a batch of Small Clips, due to the fact that is composed by more units, will take longer, while the Big Channel, because it has fewer units per batch, will take less time - the powder layer is spread evenly regardless of the units printed, but the fusing and detailing agents only focus on the surface that will originate parts, so the more units, the more time it takes. Additionally, the Jet Fusion 5210 Pro has a power of 0.6 kW, according to HP's data. The results of the calculations can be seen below:

Table 40 - MJF printer energy cost per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{prod_{MJF}}$	MJF printer production time per batch	12	14	26	h
P_{inj}	Injection machine power	0.6	0.6	0.6	kW
p_{energy}	Price of energy per kWh	0.182	0.182	0.182	€/kWh
$C_{MLF\ energy_{batch}}$	MJF printer energy cost per batch	1.31 €	1.52 €	2.83 €	

By adding up the raw material costs and the energy costs per batch, it is then possible to obtain the MJF printer variable costs per batch.

Table 41 - MJF printer variable costs per batch

Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{print}}$	MJF printer variable costs per batch	1,212.33 €	873.40 €	8,284.35 €

Fixed Costs

MJF's fixed costs are the cost of the MJF printer, maintenance costs and building costs.

The printer cost per batch calculations follows the same rationale as for the fixed setup costs, now using the printing time instead of the setup time. Assuming the same 3% maintenance percentage, it is also obtained the maintenance costs:

Table 42 - MJF printer cost and maintenance cost per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
WD_{year}	Number of working days per year	300	300	300	days/year
WH_{day}	Number of working hours per day	24	24	24	h/day
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{prod_{MJF}}$	MJF printer production time per batch	12	14	26	h
p_{MJF}	Price of the MJF printer	465,660 €	465,660 €	465,660 €	€
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{MJF_{batch}}$	MJF printer cost per batch	110.87 €	129.35 €	240.22 €	
$\%_{maint}$	Estimated Maintenance Percentage	3%	3%	3%	%
$C_{maint_{batch}}$	Maintenance cost per batch	3.33 €	3.88 €	7.21 €	

The HP Jet Fusion 5210 Pro printer, selected for this case study, occupies an area of 3 m^2. For the same rate of 1200€/m^2, the building costs are calculated in the same way as in the case of plastic injection, as can be seen below:

Table 43 – MJF building cost per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$p_{building_{m2}}$	Price of the building per m^2	1200	1200	1200	€/m^2
A_{MJF}	MJF printer occupied area	3	3	3	m^2
$p_{building_{MJ}}$	Price of building occupied by injection machine	3,600 €	3,600 €	3,600 €	€
$t_{prod_{MJF}}$	MJF printer production time per batch	12	14	26	h
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{lifetime}$	Project's lifetime	7	7	7	years
$C_{building_{batch}}$	Building cost per batch	0.86 €	1.00 €	1.86 €	

To obtain the fixed costs per production batch in MJF, the printer costs, maintenance costs and building costs are added:

Table 44 - MJF printer fixed costs per batch

Variable	Description	Big Channel	Medium Channel	Small Clip
$p_{building_{m2}}$	MJF printer fixed costs per batch	115.05 €	134.23 €	249.29 €

Total Printing Costs

The total printing costs are now calculates adding the variable costs to the fixed costs:

Table 45 - Total printing costs per batch

Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{prod}}$	MJF printer variable costs per batch	1,212.33 €	873.40 €	8,284.35 €
$C_{fixed_{prod}}$	MJF printer fixed costs per batch	115.05 €	134.23 €	249.29 €
$C_{prod_{MJF}}$	Total printing costs per batch	1,327.38 €	1,007.63 €	8,533.64 €

4.2.2.6 Calculation – Additive Manufacturing After-Printing Costs

Finally, the after-printing costs which consist only of variable costs: the labor costs associated with the removal and cleaning of the parts (considered as a whole for calculation) and the quality check process.

Variable Costs

To perform the calculations, it is first necessary to understand how long these activities take per batch. Taking into account that it takes longer to remove and clean a larger part than a smaller one, removal and cleaning times per unit of 30 minutes for the Big Channel, 17 minutes for the Medium Channel and 6 minutes for the Small Clip were assumed, recalculated in hours when presented in

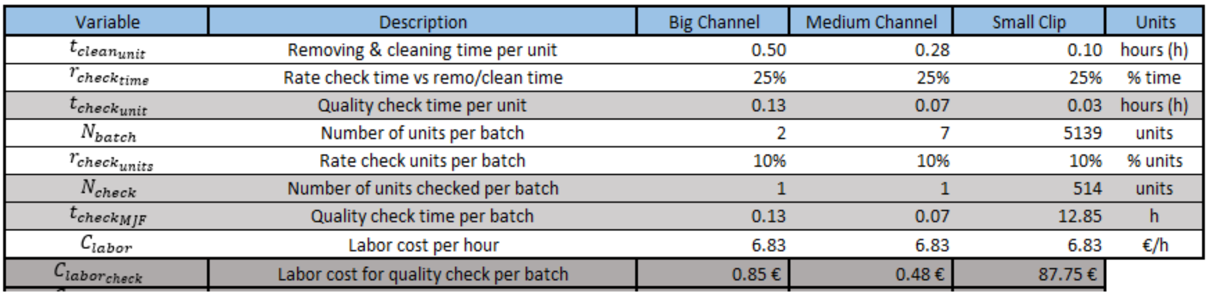
Table 46.

Table 46 - Labor cost for removing & cleaning per batch

Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{clean_{unit}}$	Removing & cleaning time per unit	0.50	0.28	0.10	hours (h)
N_{batch}	Number of units per batch	2	7	5139	units
$t_{clean_{MJF}}$	Removing & cleaning time per batch	1.00	1.98	513.90	h
C_{labor}	Labor cost per hour	6.83	6.83	6.83	€/h
$C_{labor_{clean}}$	Labor cost for removing & cleaning per batch	6.83 €	13.55 €	3,509.94 €	

That leaves the quality check task. For this case, it was considered that a quality check is required for 10% of the units produced in a batch, being mandatory to analyze at least 1 unit per batch. Estimating that the quality check takes 25% of the time of removing and cleaning, the costs were calculated:

Table 47 - Labor cost for quality check per batch

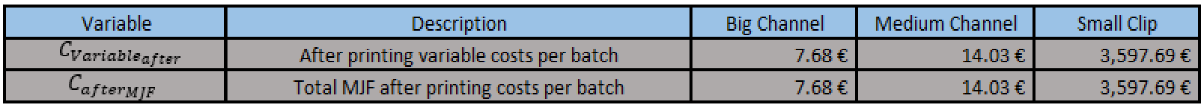


Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$t_{clean_{unit}}$	Removing & cleaning time per unit	0.50	0.28	0.10	hours (h)
$r_{check_{time}}$	Rate check time vs remo/clean time	25%	25%	25%	% time
$t_{check_{unit}}$	Quality check time per unit	0.13	0.07	0.03	hours (h)
N_{batch}	Number of units per batch	2	7	5139	units
$r_{check_{units}}$	Rate check units per batch	10%	10%	10%	% units
N_{check}	Number of units checked per batch	1	1	514	units
$t_{check_{MJF}}$	Quality check time per batch	0.13	0.07	12.85	h
C_{labor}	Labor cost per hour	6.83	6.83	6.83	€/h
$C_{labor_{check}}$	Labor cost for quality check per batch	0.85 €	0.48 €	87.75 €	

Total After Printing Costs

The total after printing costs are, as seen, equal to the variable after printing costs - the sum of the labor cost for removing & cleaning per batch and the labor cost for quality check per batch:

Table 48 - Total MJF after printing costs per batch

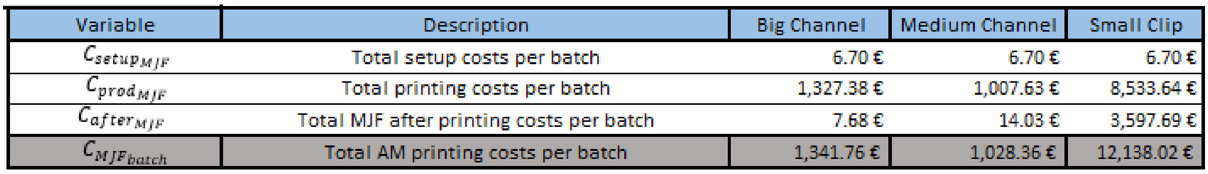


Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{Variable_{after}}$	After printing variable costs per batch	7.68 €	14.03 €	3,597.69 €
$C_{after_{MJF}}$	Total MJF after printing costs per batch	7.68 €	14.03 €	3,597.69 €

Total MJF Costs per Batch

Finally, by adding the setup costs with the printing costs and after-printing costs, it is possible to obtain the total MJF costs per batch for each of the three parts under study:

Table 49 - Total MJF Costs per Batch.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{setup_{MJF}}$	Total setup costs per batch	6.70 €	6.70 €	6.70 €
$C_{prod_{MJF}}$	Total printing costs per batch	1,327.38 €	1,007.63 €	8,533.64 €
$C_{after_{MJF}}$	Total MJF after printing costs per batch	7.68 €	14.03 €	3,597.69 €
$C_{MJF_{batch}}$	Total AM printing costs per batch	1,341.76 €	1,028.36 €	12,138.02 €

4.3 Chapter Overview

The development of the case study is subdivided into two parts: the first one where the most suitable additive manufacturing technology was selected to print the parts to be worked on throughout the case study, and the second one where the theoretical demonstration and the calculation of the manufacturing costs of the three parts when produced by plastic injection and when produced by additive manufacturing were performed.

In subsection 3.2.2 the main additive manufacturing processes were described and, for each one, the most developed technology was presented. These technologies were considered for the context of the problem:

- Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF) in powder bed fusion
- Fuse Deposition Modelling (FDM) in material extrusion
- Material Jetting (MJ) in material jetting
- Stereolithography (SLA) in vat photopolymerization

For the selection of the most suitable technology for the case study, comparison criteria were defined, namely suitability, mechanical properties, printable volume per batch, support structure, surface finish, post processing, technology costs. All seven criteria were evaluated qualitatively, based on the information researched and the findings, and quantitatively, using a scale of integers from 1 to 5 reflecting the qualitative evaluation. From that, it was possible to conclude that powder bed fusion was clearly the most suitable process, but within this, Selective Laser Sintering (SLS) and Multi Jet Fusion (MJF) options were still very evenly matched. It was necessary to make a direct comparison between the two technologies based on some critical factors: processing time, material recycling and reuse, dimensional accuracy, material and colors, maximum part size, and cost per batch. After evaluation, Multi Jet Fusion (MJF) technology was the chosen to carry out this case study for the fact that it has the most and more critical criteria in its favor.

Having chosen the most suitable printing technology for the case, the theoretical demonstration and the calculation of the variable and fixed costs involved in the manufacturing of the three parts by injection molding and additive manufacturing were performed.

The manufacturing of parts by plastic injection molding was split into machine setup and part production. The machine setup consists in the removal of a previous mold from the machine, introduction and fixing of the mold of the parts in the injection machine, safety and dimensional control, and locking of the machine. The setup process is entirely manual, so it requires a full-time operator during the process. Following, the production of the parts includes the entire injection process from the introduction of the raw material to the obtaining of the final part and the waste of material. Despite being automatic, this process also requires the presence of an operator for safety control and to stop the injection if necessary. However, this operator does not need to be 100% allocated to the task during the process, since this control is not continuous. Both setup costs and production costs are subdivided into variable costs and fixed costs. While variable costs include the necessary material, labor and energy costs, fixed costs include the costs of the machine, the molds of the parts (commonly named tooling costs), machine maintenance and building associated with the footprint of the injection molding machine.

Also the additive manufacturing process by Multi Jet Fusion, selected technology, is divided into different activities: setting up the 3D printer, printing the parts, cleaning and removing the parts after production, and post processing process. The setup process consists of cleaning the machine, supplying the raw materials needed for printing, dimensional control of the platform, among other preparation processes to ensure the success of the printing process. This printing process is fully automatic, so there is no need for an operator to be present during the process. However, other variable costs (raw material, energy), and also fixed costs (printer, building, maintenance) are considered. After the process is finished it is necessary to remove and clean the freshly produced parts, clean off the excess raw material, and do a first quality check, all of which are manual tasks. Finally, post-processing treatment may be necessary in some cases to, for example, colorize or reinforce the parts.

For each of the manufacturing methods all of the costs per batch considered above have been demonstrated and calculated. It is important to point out that while for the injection molding process, batches of 500 units for each of the three parts were considered, for the Multi Jet Fusion AM process, batches of 2, 7 and 5139 units were considered for the Big Channel, Medium Channel and Small Clip, respectively.

Chapter 5

5 Results Discussion & Conclusions

Chapter 5 concludes the case study and draws the main conclusions.

An overview of the case study is first given in subsection 5.1. Then, in subsection 5.2, the main results obtained in the Cost Calculator pointed out. Subsection 5.3 concludes the case study giving the final recommendations considering the conditions of the case study. Then, the Cost Calculator tool is introduced and briefly described in 5.4. In Subsection 5.5, a sensitivity analysis is presented and the final conclusions and opportunities are pointed. The section, and the document, is finally concluded with subsection 5.6 that contains the main limitations of the work and the model used for cost calculation.

5.1 Case Study Overview

With the development of additive manufacturing technologies in recent years, several industries have been studying the possibility to adopt these new methods for industrial applications. One of the industries that has invested the most in this area has been that of the Wire Harness, particularly the world's leading company - Yazaki Corporation. Having almost 245,000 employees spread over 143 companies in 45 countries, Yazaki has been investing in Additive Manufacturing for the production of components to the final wire harness assembly that supply automotive factories. However, this is still a developing technology, which means that especially in terms of range of materials, production speed and volume, AM is still a limited method. For that reason, each particular case requires a feasibility study concerning the replacement of the injection molding process by this disruptive one.

Together with the product development department of Yazaki's facilities in Ovar, Portugal, the research project to be developed intends to analyze the possible adoption of AM for the production of three specific small/medium series parts provided by the company. The development of the case study involves making an analysis:

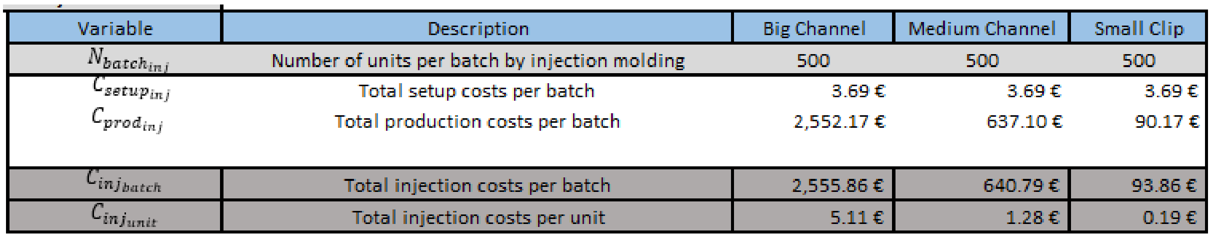
- A comparative analysis between the various different 3D Printing technologies in order to select the most appropriate one for the specific parts under study;
- A comparative cost analysis between injection molding and additive manufacturing.

Through this analysis, it is expected to conclude which is the most suitable method to produce under the conditions of the case study.

5.2 Results Discussion

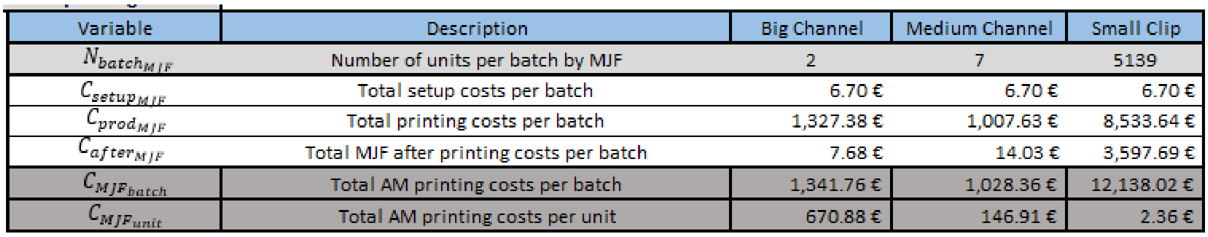
Yazaki established the need to have a production of 22000 units per year over 7 years. Therefore, these were the main inputs to obtain the results shown in Table 50 and Table 51. From those values, it is possible to draw some conclusions.

Table 50 - Total injection molding costs.



Variable	Description	Big Channel	Medium Channel	Small Clip
$N_{batch_{inj}}$	Number of units per batch by injection molding	500	500	500
$C_{setup_{inj}}$	Total setup costs per batch	3.69 €	3.69 €	3.69 €
$C_{prod_{inj}}$	Total production costs per batch	2,552.17 €	637.10 €	90.17 €
$C_{inj_{batch}}$	Total injection costs per batch	2,555.86 €	640.79 €	93.86 €
$C_{inj_{unit}}$	Total injection costs per unit	5.11 €	1.28 €	0.19 €

Table 51 - Total MJF costs.

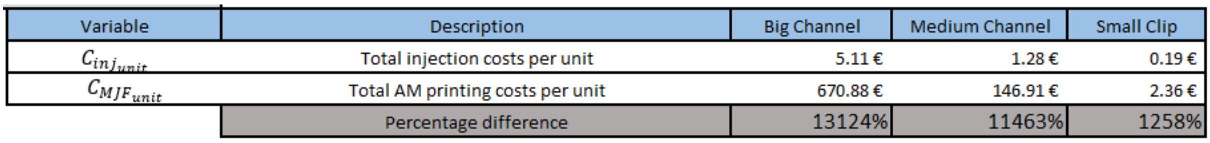


Variable	Description	Big Channel	Medium Channel	Small Clip
$N_{batch_{MJF}}$	Number of units per batch by MJF	2	7	5139
$C_{setup_{MJF}}$	Total setup costs per batch	6.70 €	6.70 €	6.70 €
$C_{prod_{MJF}}$	Total printing costs per batch	1,327.38 €	1,007.63 €	8,533.64 €
$C_{after_{MJF}}$	Total MJF after printing costs per batch	7.68 €	14.03 €	3,597.69 €
$C_{MJF_{batch}}$	Total AM printing costs per batch	1,341.76 €	1,028.36 €	12,138.02 €
$C_{MJF_{unit}}$	Total AM printing costs per unit	670.88 €	146.91 €	2.36 €

- **Costs per unit**

The total costs per batch are not comparable with each other because, as seen earlier, the number of units produced per batch differs between the two methods, and even within AM due to size limitations. However, by dividing the total costs by the number of units per batch, it is possible to get the costs per unit. From this analysis, it is then possible to conclude that, for any of the three parts to be produced, the total cost per MJF greatly exceeds the total cost per injection molding: 13124% for the Big Channel, 11463% for the Medium Channel, and 1258% for the Small Clip.

Table 52 - Costs per unit.



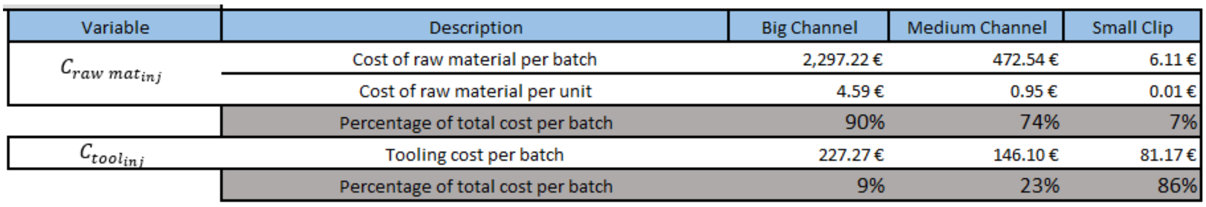
Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{inj_{unit}}$	Total injection costs per unit	5.11 €	1.28 €	0.19 €
$C_{MJF_{unit}}$	Total AM printing costs per unit	670.88 €	146.91 €	2.36 €
	Percentage difference	13124%	11463%	1258%

- **Cost drivers**

In both processes and under the conditions considered for the case study, it is clear that the main cost driver for both Big and Medium Channels by injection molding or by MJF is the cost of the raw material, since it represents the major part of their production costs - 90% for Big Channel; 74% and 85% for Medium Channel, respectively. per batch for both processes. However, if the comparison is made based on cost per unit, the costs on MJF are much higher. This proves the fact that the costs of raw material on Additive Manufacturing, and in this particular case on MJF, are a main limitation.

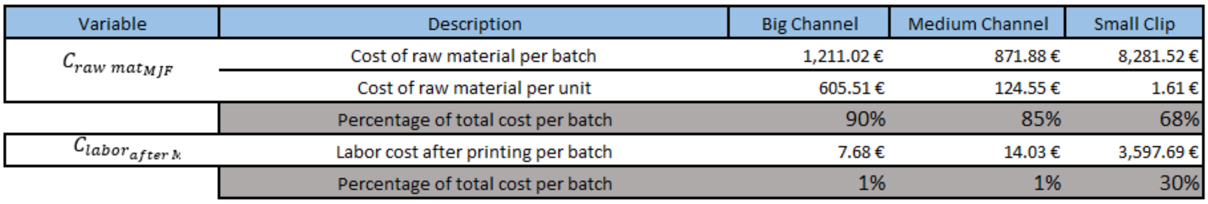
The Small Clip, since it is smaller, it requires less material do be produced when compared with the bigger parts. By injection molding, this cost represents only 7% of the costs, while the tooling costs represent 86%. On MJF, even though the part requires considerably less weight of raw material, the high price per kilogram makes the raw material still to be the main cost. However, it is important to highlight the impactful footprint of the after printing costs on the Small Clip (30% of the total costs). Since the batches by MJF allow to produce may parts at once (5139 units per batch), it requires a lot of labor work on removing the parts, cleaning and doing the quality check.

Table 53 - Cost drivers by injection molding.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{raw\ mat_{inj}}$	Cost of raw material per batch	2,297.22 €	472.54 €	6.11 €
	Cost of raw material per unit	4.59 €	0.95 €	0.01 €
	Percentage of total cost per batch	90%	74%	7%
$C_{tool_{inj}}$	Tooling cost per batch	227.27 €	146.10 €	81.17 €
	Percentage of total cost per batch	9%	23%	86%

Table 54 - Cost drivers by MJF.

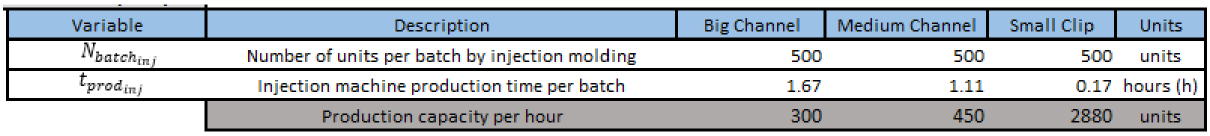


Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{raw\ mat_{MJF}}$	Cost of raw material per batch	1,211.02 €	871.88 €	8,281.52 €
	Cost of raw material per unit	605.51 €	124.55 €	1.61 €
	Percentage of total cost per batch	90%	85%	68%
$C_{labor_{after\ M}}$	Labor cost after printing per batch	7.68 €	14.03 €	3,597.69 €
	Percentage of total cost per batch	1%	1%	30%

- **Production capacity**

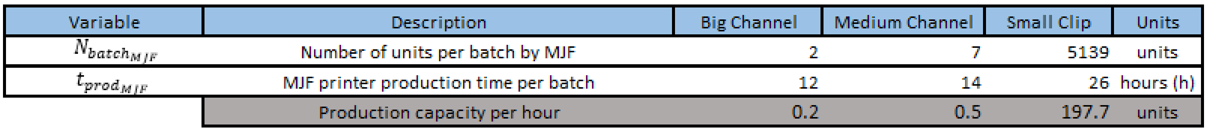
The limited capacity to produce in large quantities in MJF is a determining limitation of this technology, and also a key factor in the final results. The MJF process is not only limited in terms of the dimensionality of the print (reflected in the reduced number of parts per batch for bigger parts), but is also a very time consuming process when compared to injection molding. While in one hour, the injection machine produces 300 Big Channels or 450 Medium Channels, MJF can’t even produce 1 unit of both. Even in the Small Clips where 5139 units can be produced per batch of MJF, injection molding has an hourly production capacity 1457% bigger.

Table 55 - Production capacity per hour by injection molding.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$N_{batch_{inj}}$	Number of units per batch by injection molding	500	500	500	units
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	hours (h)
	Production capacity per hour	300	450	2880	units

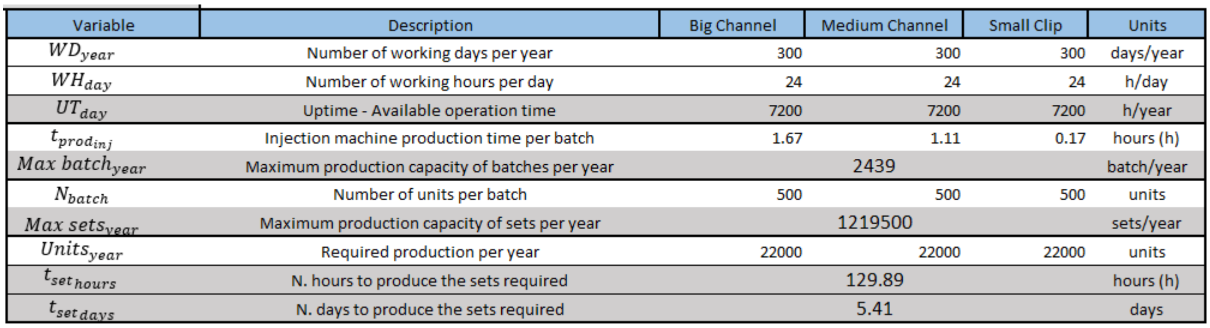
Table 56 - Production capacity per hour by MJF.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$N_{batch_{MJF}}$	Number of units per batch by MJF	2	7	5139	units
$t_{prod_{MJF}}$	MJF printer production time per batch	12	14	26	hours (h)
	Production capacity per hour	0.2	0.5	197.7	units

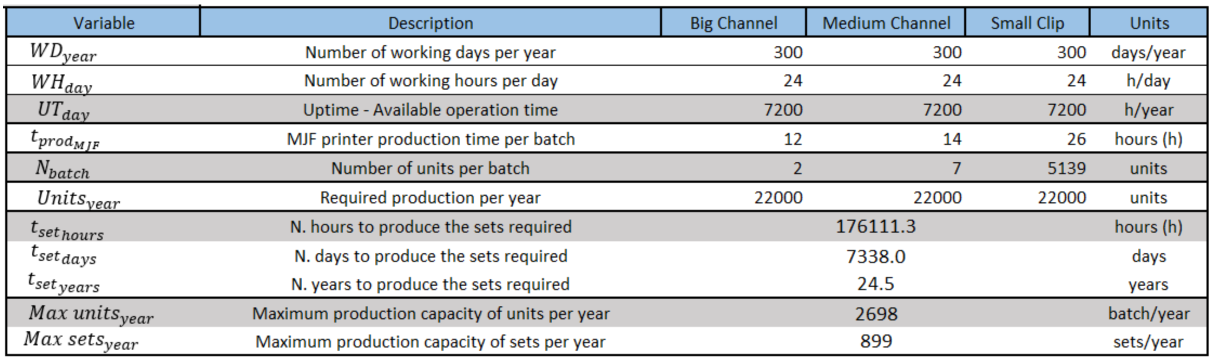
If the analysis is done from an annual point of view, it is seen that the injection machine has a production capacity of 2439 batches per year, which makes 1219500 complete sets (a set is a group of 1 Big Channel + 1 Medium Channel + 1 Small Clip). On the other hand, using this process, the required production per year of 22000 units of each of the three parts would be achieved in less than 6 days. However, when looking for MJF, it would be needed 7338 days, or 24.5 years, to complete the same number of sets, making this solution impossible from the start to meet the annual production requirements of the case study. MJF, under the conditions established, has a maximum production capacity of 899 sets per year.

Table 57 - Production capacity per year by injection molding.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
WD_{year}	Number of working days per year	300	300	300	days/year
WH_{day}	Number of working hours per day	24	24	24	h/day
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{prod_{inj}}$	Injection machine production time per batch	1.67	1.11	0.17	hours (h)
$Max\ batch_{year}$	Maximum production capacity of batches per year		2439		batch/year
N_{batch}	Number of units per batch	500	500	500	units
$Max\ sets_{year}$	Maximum production capacity of sets per year		1219500		sets/year
$Units_{year}$	Required production per year	22000	22000	22000	units
$t_{set_{hours}}$	N. hours to produce the sets required		129.89		hours (h)
$t_{set_{days}}$	N. days to produce the sets required		5.41		days

Table 58 - Production capacity per year by MJF.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
WD_{year}	Number of working days per year	300	300	300	days/year
WH_{day}	Number of working hours per day	24	24	24	h/day
UT_{day}	Uptime - Available operation time	7200	7200	7200	h/year
$t_{prod_{MJF}}$	MJF printer production time per batch	12	14	26	hours (h)
N_{batch}	Number of units per batch	2	7	5139	units
$Units_{year}$	Required production per year	22000	22000	22000	units
$t_{set_{hours}}$	N. hours to produce the sets required		176111.3		hours (h)
$t_{set_{days}}$	N. days to produce the sets required		7338.0		days
$t_{set_{years}}$	N. years to produce the sets required		24.5		years
$Max\ units_{year}$	Maximum production capacity of units per year		2698		batch/year
$Max\ sets_{year}$	Maximum production capacity of sets per year		899		sets/year

5.3 Case Study Conclusions

Under the conditions pretended by Yazaki to produce 22000 sets per year over 7 years, the company should rule out Additive Manufacturing, represented in this case study by Multi Jet Fusion technology, as an alternative process to injection molding for mass production, due to not only lack of production capacity but also by having higher costs. It is, however, necessary to remember that Additive Manufacturing is a recent technology still in a development stage, which means that this decision may be true today, but not in the future.

5.4 Cost Calculator

A calculation tool was developed in order to obtain all the manufacturing costs for both processes - plastic injection molding and additive manufacturing - for each and for the total of the three parts based on 2 inputs: units to be produced per year for each of the three parts (Big Channel, Medium Channel, Small Channel), i.e. the number of sets required, and the project lifetime in years. If one or both variables change, all costs are recalculated accordingly. In addition to cost breakdown, the Cost Calculator also presents a sensitivity analysis of the total costs according to the variation of the two input variables from a range of 1 to 900 units per year and 4 to 10 years lifetime. This analysis is made for each one of the three parts produced by each process plus an analysis for the totals of producing the sets inputted by IM or by MJF, which gives a total of 8 analysis. The final costs for all the above options are supported by a heat map for more direct interpretation of the results, which compares the costs of each individual part by both processes and the total costs by both processes. Finally, the Cost Calculator shows the distribution of costs for both processes taking into account the inputs, allowing to visually identify the main cost drivers of each method. A complete explanation on how this tool works and which data provides can be found in Appendix B.

It is relevant to note that for a more comparable cost study, the costs of both production machines - injection machine and MJF printer – on the Cost Calculator were considered to be fully dedicated to the production of the input parts during the defined years. This means that the total cost of both machines is 100% supported by the parts produced by them.

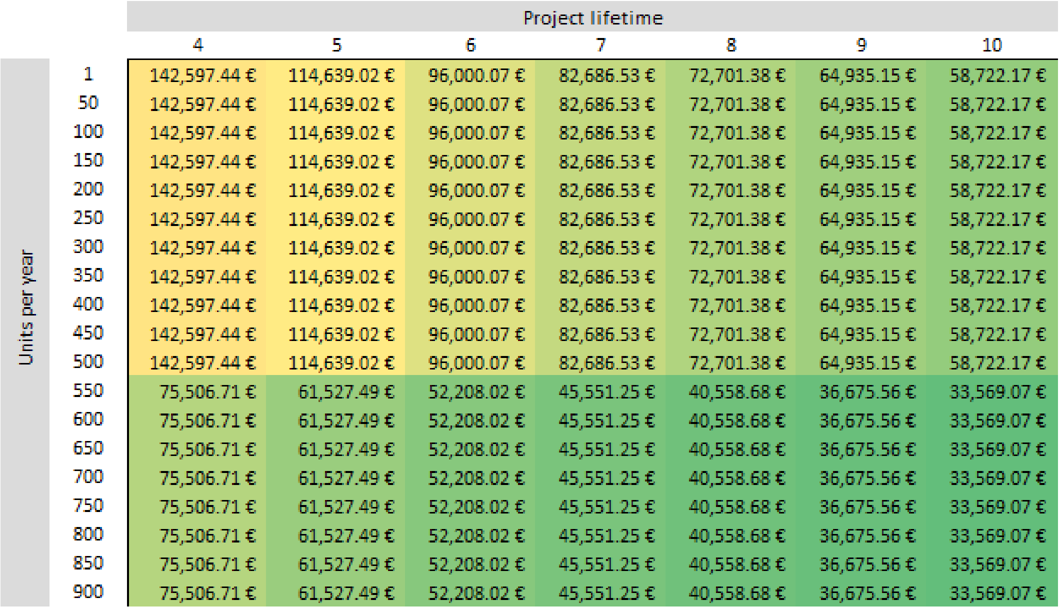
5.5 Sensitivity Analysis

5.5.1 Sensitivity Analysis Introduction

With the help of Cost Calculator developed, it was possible to obtain a sensitivity analysis that calculates the total process costs according to the two inputs of the tool: units per year and project lifetime. The range of variables, as seen above, goes from 1 to 900 units per year during 4 to 10 years. The range of the first input variable is limited at its maximum by the maximum production capacity by MJF - 899 sets per year, as seen above. Regarding the second input variable, since case study’s project lifetime is 7 years, it was made the analysis comprising the time span from 3 years less to 3 years more. The sensitivity analysis is complemented by a 'heat map' analysis, which uses a color scale from red to green, red being the least favorable values (in this case, the most expensive conditions according to the inputs) and green being the most favorable values (the less expensive conditions).

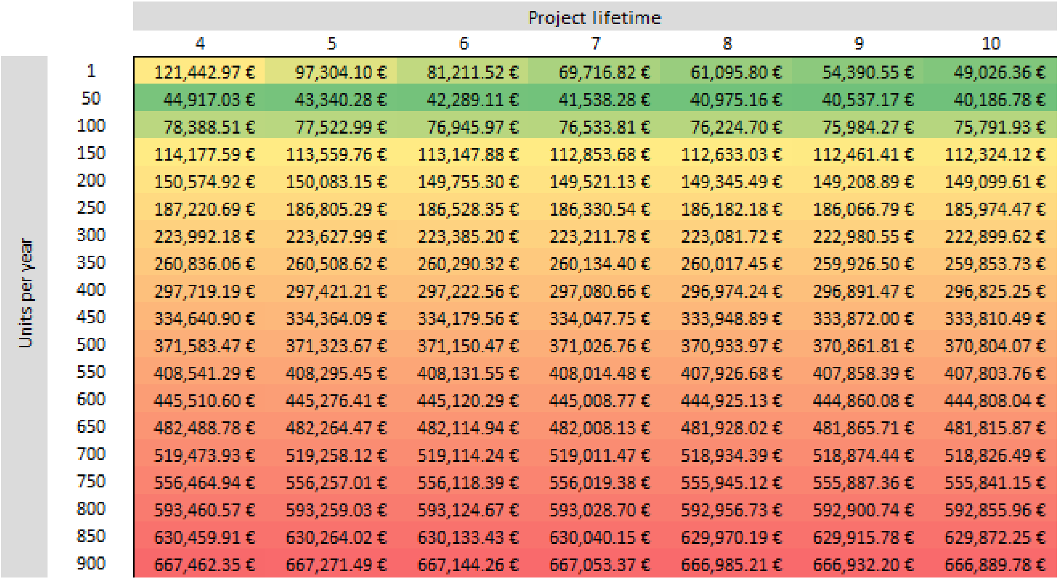
The analysis was done in order to study if there are conditions for which the investment in a Multi Jet Fusion printer is justifiable in comparison with the investment in an injection molding machine. One of the analyses made is for the total costs of producing the number of sets inputted – recalling that a set is a group of 1 Big Channel, 1 Medium Channel and 1 Small Clip. The results were the following:

Table 59 - Sensitive Analysis for set production by injection molding.



	Project lifetime						
Units per year	4	5	6	7	8	9	10
1	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
50	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
100	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
150	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
200	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
250	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
300	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
350	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
400	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
450	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
500	142,597.44 €	114,639.02 €	96,000.07 €	82,686.53 €	72,701.38 €	64,935.15 €	58,722.17 €
550	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
600	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
650	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
700	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
750	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
800	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
850	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €
900	75,506.71 €	61,527.49 €	52,208.02 €	45,551.25 €	40,558.68 €	36,675.56 €	33,569.07 €

Table 60 - Sensitive Analysis for set production by MJF.



	Project lifetime						
Units per year	4	5	6	7	8	9	10
1	121,442.97 €	97,304.10 €	81,211.52 €	69,716.82 €	61,095.80 €	54,390.55 €	49,026.36 €
50	44,917.03 €	43,340.28 €	42,289.11 €	41,538.28 €	40,975.16 €	40,537.17 €	40,186.78 €
100	78,388.51 €	77,522.99 €	76,945.97 €	76,533.81 €	76,224.70 €	75,984.27 €	75,791.93 €
150	114,177.59 €	113,559.76 €	113,147.88 €	112,853.68 €	112,633.03 €	112,461.41 €	112,324.12 €
200	150,574.92 €	150,083.15 €	149,755.30 €	149,521.13 €	149,345.49 €	149,208.89 €	149,099.61 €
250	187,220.69 €	186,805.29 €	186,528.35 €	186,330.54 €	186,182.18 €	186,066.79 €	185,974.47 €
300	223,992.18 €	223,627.99 €	223,385.20 €	223,211.78 €	223,081.72 €	222,980.55 €	222,899.62 €
350	260,836.06 €	260,508.62 €	260,290.32 €	260,134.40 €	260,017.45 €	259,926.50 €	259,853.73 €
400	297,719.19 €	297,421.21 €	297,222.56 €	297,080.66 €	296,974.24 €	296,891.47 €	296,825.25 €
450	334,640.90 €	334,364.09 €	334,179.56 €	334,047.75 €	333,948.89 €	333,872.00 €	333,810.49 €
500	371,583.47 €	371,323.67 €	371,150.47 €	371,026.76 €	370,933.97 €	370,861.81 €	370,804.07 €
550	408,541.29 €	408,295.45 €	408,131.55 €	408,014.48 €	407,926.68 €	407,858.39 €	407,803.76 €
600	445,510.60 €	445,276.41 €	445,120.29 €	445,008.77 €	444,925.13 €	444,860.08 €	444,808.04 €
650	482,488.78 €	482,264.47 €	482,114.94 €	482,008.13 €	481,928.02 €	481,865.71 €	481,815.87 €
700	519,473.93 €	519,258.12 €	519,114.24 €	519,011.47 €	518,934.39 €	518,874.44 €	518,826.49 €
750	556,464.94 €	556,257.01 €	556,118.39 €	556,019.38 €	555,945.12 €	555,887.36 €	555,841.15 €
800	593,460.57 €	593,259.03 €	593,124.67 €	593,028.70 €	592,956.73 €	592,900.74 €	592,855.96 €
850	630,459.91 €	630,264.02 €	630,133.43 €	630,040.15 €	629,970.19 €	629,915.78 €	629,872.25 €
900	667,462.35 €	667,271.49 €	667,144.26 €	667,053.37 €	666,985.21 €	666,932.20 €	666,889.78 €

5.5.2 Sensitivity Analysis Conclusions & Opportunities

By analysis the results from the Table 59 and Table 60, it is possible to take some conclusions:

- Given the very high cost of raw material in MJF, the option is restricted to a reduced number of units per year and a reduced number of years of project. As stated before, this technology is still recent and in development phase, and so the materials are still more expensive. In case of a drop in MJF's raw materials cost in the future, these conclusions would change completely.
- The great advantage of AM would be the flexibility of producing any type of needed parts without resorting to inflexible molds each time a new design is pretended. But, once again, raw material costs on MJF exceeds the investment savings in the case of large annual quantities throughout the project.
- MJF only compensates for productions below 100 sets per year for any number of project years. The quantities are so small, that even with the very expensive raw material cost, MJF pays off.
- From 100 pieces, MJF continues to be the best choice for projects up to 7 years and 100 sets, and up to 5 years and 150 sets. From 200 sets on, injection molding is the most suitable process in any number of years of project.
- The sensitivity analysis is, in short, very conditioned, on the one hand by the costs of the IM's machine and molds, but on the other hand by the cost of the raw materials for MJF. The evolution of the cost of both, can quickly change the conclusions presented.

Even if for the majority of the scenarios injection molding is the most cost-effective solution, some additional qualitative conclusions may be taken:

- The injection machine is able to work with several molds and therefore, can produce several different parts per year, and the longer the duration of the project, the better. In this project, despite the IM being better in most cases, the machine's capacity is far from being used at full and therefore, economies of scale are far from its potential. If the company considers expanding to different kind of parts in the future, and making better use of capacity, it will make more sense to consider AM as an option, for which it is necessary to develop a new study.
- In case the company is a startup and is only linked to this specific project, but can have the perspective of expanding its production to several different small quantity parts, and therefore values flexibility more because it will not require larger batches, then it is worth to consider to adopt AM, even with higher costs coming from the raw materials. It is to be expected that, with the growth and development of the technology, the cost of raw materials will go down, or progressively replaced by equally efficient but cheaper powder solutions.
- Applying this project to existing companies that already have injection equipment where these new molds could be used, means that AM is not an option, because the investment in the 3 molds are, under the case study conditions, cheaper than the MJF printer.

In such case, a third way, that combines both technologies, could be interesting to study and may have economic added value for the company, as long as the investment cost in AM is less than the total cost of acquiring the 3 molds. The idea that results from the analysis of the case IM vs AM is using MJF or even a more economical AM technology to print the molds themselves instead of the parts. However, the printer would need to be compatible with special raw materials of high temperature resistance and high dimensional stability.

In any project where injection machines already exist, printing the molds inhouse instead of buying them at more expensive prices, high delivery times and reduced flexibility for design changes that are often necessary, would bring enormous advantages:

- A mold could be printed in-house in less time than the lead time of waiting for the mold ordered.
- A printed mold could cost less than an ordered mold, saving the supplier profit margins.
- In case of any mold change, size adjustment or evolution that the client needs during the project, a new mold can always be redesigned and printed as demanded, instead of asking for changes to existing molds which would be expensive and not always possible.
- At the end of each project, the printed molds can be discarded or recycled without the need for storage at warehouses. If in the future, the same molds would be needed, for another project or for small quantities in the same project, one could simply print it again. Keeping parts or molds in stock for years, for 'just in case scenarios' is anti-economical.

In summary, this third way, which combines the need for large injection productions with the savings in printed molds, could be a way to enormously reduce investment costs, save time in delivery times and have the flexibility of being able to print molds in-house at very economical prices, whenever and wherever necessary. However, being AM still at development stages, there are currently still a lot of limitations in terms of mechanical and strength properties that make this solution possibly suitable for very particular cases. Such analysis is not part of this thesis and would require other types and deeper investigations, but it is certainly worth mentioning the highly disruptive possibility for molding industry of a solution that complements both processes.

5.6 Limitations

The development and design of the cost model was done as close to reality as possible. However, there are some limitations and conditions that conditioned the results and had an impact on the conclusions obtained. Here are some:

- For lack of real, concrete numbers that could be used, estimates and assumptions were made throughout the work;
- Due to lack of resources, no auxiliary design software were used. For example, the use of CAD software to redesign the parts for printing would have allowed to remove weight and raw material from the parts, decreasing the printing cost. Similarly, CAM software would allow an optimized distribution of the parts on the printing platform and obtain real printing data such as production time per batch;
- In the cost analysis some costs were not considered, for example post-processing costs in the AM or the costs of wasted raw materials or defective finished parts. Depreciation of assets (injection molding machine, mold, printer, building, etc.) and amortization of the investment in the MJF printer over time were not considered either.

References

1. Dumitrescu, G. C., & Nase, I. A. T. Ă. (2016). 3D Printing – A New Industrial Revolution. *Knowledge Horizons. Economics*, *8*(1), 32–39.
2. Trommnau, J., Kühnle, J., Siegert, J., Inderka, R., & Bauernhansl, T. (2019). Overview of the state of the art in the production process of automotive wire harnesses, current research and future trends. *Procedia CIRP*, *81*, 387–392. https://doi.org/10.1016/j.procir.2019.03.067
3. Nguyen, H. G., Kuhn, M., & Franke, J. (2020). Manufacturing automation for automotive wiring harnesses. *Procedia CIRP*, *97*, 379–384. https://doi.org/10.1016/j.procir.2020.05.254
4. Rex Plastics. (2013). *How much do plastic injection molds cost?* https://rexplastics.com/plastic-injection-molds/how-much-do-plastic-injection-molds-cost
5. Anonymous. (n.d.). *Injection Molding in Small Series*. Retrieved June 1, 2021, from http://www.injectionmoldschina.com/injection-molding-for-small-series/
6. Losek, J. (2021). *The Cost of Injection Molding*. https://icomold.com/much-injection-molding-cost/
7. Anonymous. (2019). *The Cost of 3D Printing vs Injection Molding*. https://www.slant3d.com/slant3d-blog/the-cost-of-3d-printing-vs-injection-molding
8. Cotteleer, M. (2014). *3D opportunity: Additive manufacturing paths to performance, innovation, and growth*. https://www2.deloitte.com/us/en/insights/deloitte-review/issue-14/dr14-3d-opportunity.html
9. Sirova, E., & Rodrigues, M. (2019). Spare Parts Management in the Context of Industry 4.0. *Poprad Economic and Management Forum 2019*, *February*, 141–150.
10. Kress, C. (2015). *Rapid Maufacturing vs Injection Molding*. *May 2015*.
11. Berman, B. (2012). 3-D printing: The new industrial revolution. *Business Horizons*, *55*(2), 155–162. https://doi.org/10.1016/j.bushor.2011.11.003
12. Anonymous. (n.d.). *Payback period definition*. Retrieved June 2, 2021, from https://debitoor.com/dictionary/payback-period
13. Anonymous. (n.d.). *Payback method*. Retrieved June 4, 2021, from https://www.praxisframework.org/en/library/payback-method
14. Yazaki. (2020). *Yazaki group*. www.yazaki-group.com
15. Yazaki. (2019). *Yazaki - Key Facts*. https://www.yazaki-europe.com/about-us/key-facts
16. Rogers, T. (2015). *Everything You Need To Know About Injection Molding*. https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-injection-molding
17. Khosravani, M. R., & Nasiri, S. (2020). Injection molding manufacturing process: review of case-

based reasoning applications. *Journal of Intelligent Manufacturing*, *31*(4), 847–864. https://doi.org/10.1007/s10845-019-01481-0

18. Hyatt, J. S., & Hyatt, J. W. (1872). *Improvement in Process and Apparatus for Manufacturing Pyroxyline*. *133*, 1–7. https://patents.google.com/patent/US133229A/en
19. Anonymous. (2018). *A Brief History of Plastic Injection Molding*. https://nbplastics.com/blog/brief-history-plastic-injection-molding/
20. Anonymous. (n.d.). *The Outline of Injection Molding*. Retrieved June 6, 2021, from https://www.polyplastics.com/en/support/mold/outline/index.html#inj3
21. Panda, B., Tan, M. J., Gibson, I., & Chua, C. K. (2016). The disruptive evolution of 3D printing. *Proceedings of the International Conference on Progress in Additive Manufacturing*, *Part F1290*(May 2021), 152–157.
22. Tofail, S. A. M., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., & Charitidis, C. (2018). Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Materials Today*, *21*(1), 22–37. https://doi.org/10.1016/j.mattod.2017.07.001
23. Anonymous. (2017). *The History of 3D Printing: 3D Printing Technologies from the 80's to today*. https://www.sculpteo.com/en/3d-learning-hub/basics-of-3d-printing/the-history-of-3d-printing/
24. Sculpteo. (n.d.). *The History of 3D Printing: 3D Printing Technologies from the 80s to Today*. Retrieved May 15, 2021, from https://www.sculpteo.com/en/3d-learning-hub/basics-of-3d-printing/the-history-of-3d-printing/
25. Anonymous. (2021). *S. Scott Crump Net Worth*. https://pt.wallmine.com/nasdaq/ssys/officer/2064639/s-scott-crump
26. Anonymous. (2016). *The Official History of the RepRap Project*. https://all3dp.com/history-of-the-reprap-project/
27. Anonymous. (2018). *History of 3D Printing: It's Older Than You Are (That Is, If You're Under 30)*. https://redshift.autodesk.com/history-of-3d-printing/
28. Anonymous. (2016). *A Revolution for Medical 3D Printing: Pr. Kelly tells us about 3D Printing Bone*. https://www.sculpteo.com/blog/2016/11/30/medical-3d-printing-pr-daniel-kelly-tells-us-about-3d-printing-bone/
29. ASTM. (2015). *Standard Terminology for Additive Manufacturing Technologies*. https://www.astm.org/Standards/F2792.htm
30. Shahrubudin, N., Lee, T. C., & Ramlan, R. (2019). An overview on 3D printing technology: Technological, materials, and applications. *Procedia Manufacturing*, *35*, 1286–1296. https://doi.org/10.1016/j.promfg.2019.06.089
31. ExOne. (n.d.). *What is Binder Jetting?* Retrieved May 25, 2021, from https://www.exone.com/en-

US/case-studies/what-is-binder-jetting

32. All3DP. (2020). *The Types of 3D Printing Technology*. https://all3dp.com/1/types-of-3d-printers-3d-printing-technology/
33. Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., Nandwana, P., & Chmielus, M. (2021). Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, *119*(May 2020), 100707. https://doi.org/10.1016/j.pmatsci.2020.100707
34. Loughborough University. (n.d.). *About Additive Manufacturing - Binder Jetting*. Retrieved May 26, 2021, from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/
35. Loughborough University. (n.d.). *About Additive Manufacturing - Directed Energy Deposition*. Retrieved May 26, 2021, from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/
36. Masood, S. H. (2014). Advances in Additive Manufacturing and Tooling. *Comprehensive Materials Processing*.
37. Loughborough University. (n.d.). *About Additive Manufacturing - Material Extrusion*. Retrieved May 26, 2021, from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/
38. Kothari, A. (n.d.). *What Are the Different Types of 3D Printing?1. Kothari, A. (n.d.). What Are the Different Types of 3D Printing? Retrieved May 25, 2021, from https://www.futurelearn.com/info/courses/getting-started-with-digital-manufacturing/0/steps/184102*. Retrieved May 25, 2021, from https://www.futurelearn.com/info/courses/getting-started-with-digital-manufacturing/0/steps/184102
39. Loughborough University. (n.d.). *About Additive Manufacturing - Material Jetting*. Retrieved May 26, 2021, from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/
40. All3DP. (n.d.). *What Is Material Jetting? – 3D Printing Simply Explained*. Retrieved May 27, 2021, from https://all3dp.com/2/what-is-material-jetting-3d-printing-simply-explained/
41. Loughborough University. (n.d.). *About Additive Manufacturing - Powder Bed Fusion*. Retrieved May 27, 2021, from

https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/

42. Chueh, Y. H., Zhang, X., Ke, J. C. R., Li, Q., Wei, C., & Li, L. (2020). Additive manufacturing of hybrid metal/polymer objects via multiple-material laser powder bed fusion. *Additive Manufacturing*, *36*(July), 101465. https://doi.org/10.1016/j.addma.2020.101465
43. Anonymous. (n.d.). *Powder Bed Fusion*. Retrieved May 27, 2021, from https://engineeringproductdesign.com/knowledge-base/powder-bed-fusion/
44. 3DPrintUK. (n.d.). *When to choose SLS or MJF?* https://www.3dprint-uk.co.uk/sls-vs-mjf-3d-printing-technology/
45. Protolabs. (2021). *Multi Jet Fusion (MJF)*. https://www.protolabs.com/services/3d-printing/multi-jet-fusion/
46. Materialise. (n.d.). *Multi Jet Fusion*. https://www.materialise.com/en/manufacturing/3d-printing-technology/multi-jet-fusion
47. Jasveer, S., & Jianbin, X. (2018). Comparison of Different Types of 3D Printing Technologies. *International Journal of Scientific and Research Publications (IJSRP)*, *8*(4), 1–9. https://doi.org/10.29322/ijsrp.8.4.2018.p7602
48. Loughborough University. (n.d.). *About Additive Manufacturing - Sheet Lamination*. Retrieved May 27, 2021, from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/
49. Anonymous. (n.d.). *Sheet Lamination*. Retrieved May 27, 2021, from https://engineeringproductdesign.com/knowledge-base/sheet-lamination/
50. Loughborough University. (n.d.). *About Additive Manufacturing - Vat Photopolymerisation*. Retrieved May 28, 2021, from https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation/
51. Mesago. (2018). *Formnext AM Field Guide*.
52. Markets & Markets. (2017). *Aerospace 3D Printing Market - Global Forecast to 2022*. https://www.marketsandmarkets.com/Market-Reports/aerospace-3d-printing-market-7890041.html
53. Han, P. (2017). Additive Design and Manufacturing of Jet Engine Parts. *Engineering*, *3*(5), 648–652. https://doi.org/10.1016/J.ENG.2017.05.017
54. Anonymous. (2021). *Industrial Applications of 3D Printing: The Ultimate Guide*. https://amfg.ai/industrial-applications-of-3d-printing-the-ultimate-guide/
55. Anonymous. (2019). *SmarTech Analysis Issues New Report on Automotive Additive Manufacturing*

Market. https://www.globenewswire.com/news-release/2019/08/01/1895642/0/en/SmarTech-Analysis-Issues-New-Report-on-Automotive-Additive-Manufacturing-Market-Sees-a-9-Billion-USD-Opportunity-on-the-Horizon.html

56. de Vries, C. (2017). Volkswagen Autoeuropa: Maximizing Production Efficiency with 3D Printed Tools and Fixtures. *Ultimaker B.V.*
57. Nichols, M. R. (2019). How does the automotive industry benefit from 3D metal printing? *Metal Powder Report*, *74*(5), 257–258. https://doi.org/10.1016/j.mprp.2019.07.002
58. Kholgh Eshkalak, S., Rezvani Ghomi, E., Dai, Y., Choudhury, D., & Ramakrishna, S. (2020). The role of three-dimensional printing in healthcare and medicine. *Materials and Design*, *194*, 108940. https://doi.org/10.1016/j.matdes.2020.108940
59. Anonymous. (2020). *3D Printing in the Medical Industry*. https://www.rapidmade.com/3d-printing-in-the-medical-industry
60. Vasamsetty, P., Pss, T., Kukkala, D., Singamshetty, M., & Gajula, S. (2019). 3D printing in dentistry - Exploring the new horizons. *Materials Today: Proceedings*, *26*, 838–841. https://doi.org/10.1016/j.matpr.2020.01.049
61. MarketWatch. (n.d.). *3D Printing Medical Implants Market Size, Detail Analysis for Business Development, Top Companies 2027*. Retrieved May 18, 2021, from https://www.marketwatch.com/press-release/3d-printed-orthopedic-implants-market-future-growth-outlook-2021-with-top-countries-data-industry-analysis-by-size-share-revenue-key-players-current-trends-development-strategy-business-prospect-and-forecast-to-20
62. Anonymous. (2018). *Wire Harness Overview*. http://www.teskablo.com/haber/583/advantages-of-Wire-harnesses--cable-assemblies.html
63. Rambo, S. (2019). *Shedding Pounds In Automotive Electronics*. https://semiengineering.com/shedding-pounds-in-automotive-electronics/
64. Anonymous. (2018). *The Wire Harness Manufacturing Process: Step by Step*. https://blog.jemelectronics.com/wire-harness-manufacturing-process
65. Anonymous. (2020). *The Wire Harness Manufacturing Process*. https://precmfgco.com/blog/wire-harness-manufacturing-process/
66. Anonymous. (n.d.). *A Comprehensive Guide for Wiring Diagram*. Retrieved May 20, 2021, from https://www.edrawmax.com/wiring-diagram/
67. Anonymous. (2012). *Wire Harness Software*. https://www.ien.eu/article/wire-harness-software/
68. Anonymous. (2020). *What To Know About Electronic Cable & Harness Assembly*. https://blog.matric.com/what-to-know-about-electronic-cable-harness-assembly
69. Anonymous. (2019). *A Comprehensive Guide for Wiring Diagram*. https://www.edrawmax.com/wiring-diagram/

70. Anonymous. (n.d.). *Manufacture More Time*. Retrieved May 24, 2021, from https://www.panduit.com/en/landing-pages/harness-board-system-and-fixture.html
71. Sanz, I. (2020). *Shift 3D Webinar | 3D Printing Wire Harness Assembly and Testing Parts*. https://www.youtube.com/watch?v=DdY4YAaisT0
72. Anonymous. (n.d.). *Wire Harness and Cable Assembly*. Retrieved May 24, 2021, from https://www.lacroproducts.com/custom-cable-services/
73. Anonymous. (2021). *Wire harness test equipment*. https://www.fpc.cz/wire-harness-testing
74. Anonymous. (n.d.). *Mectronik wire harness*. Retrieved May 25, 2021, from https://www.tenkateracingproducts.com/mectronik-wire-harness-kit-yzf-r6-17-008-h2590-10.html
75. Anonymous. (n.d.). *An Approach to Case Analysis*. Retrieved June 9, 2021, from https://plato.acadiau.ca/courses/Busi/IntroBus/CASEMETHOD.html
76. Perry Cain. (2020). *Supports in 3D Printing: A technology overview*. https://www.hubs.com/knowledge-base/supports-3d-printing-technology-overview/#introduction
77. Dibya Chakravorty. (2021). *3D Printing Supports – The Ultimate Guide*. https://all3dp.com/1/3d-printing-support-structures/
78. KARLO DELOS REYES. (2021). *The Link Between 3D Printing, Surface Finish and Mold Tools*. https://www.additivemanufacturing.media/articles/the-link-between-3d-printing-surface-finish-and-mold-tools
79. Beamler. (2019). *Post-processing in 3D printing*. https://www.beamler.com/post-processing-3d-printing/
80. Varotsis, A. B. (n.d.). *What is SLS 3D printing?*
81. Alkaios Bournias Varotsis. (2020). *HP MJF vs. SLS: A 3D printing technology comparison*. https://www.hubs.com/knowledge-base/hp-mjf-vs-sls-3d-printing-technology-comparison/#appearance
82. Xometry Europe. (2020). *MJF vs SLS: 3D Printing Technologies Compared*. https://xometry.eu/en/mjf-vs-sls-3d-printing-technologies-compared/
83. Holtz, T. (2017). *MJF vs. SLS: A Comparison of Polyamide 3D Printing Technologies*. https://www.protolabs.com/resources/blog/comparing-multi-jet-fusion-to-selective-laser-sintering/
84. Sculpteo. (n.d.). *The history of 3d printer: from rapid prototyping to additive fabrication*. Retrieved July 15, 2021, from https://www.sculpteo.com/blog/2017/03/01/whos-behind-the-three-main-3d-printing-technologies/
85. Gokuldoss, P. K., Kolla, S., & Eckert, J. (2017). Additive manufacturing processes: Selective laser

melting, electron beam melting and binder jetting-selection guidelines. *Materials*, *10*(6). https://doi.org/10.3390/ma10060672

86. ICAO. (2020). *The World of Air Transport in 2019*. https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019.aspx
87. Anonymous. (2021). *Dutch couple become Europe's first inhabitants of a 3D-printed house*. https://www.theguardian.com/technology/2021/apr/30/dutch-couple-move-into-europe-first-fully-3d-printed-house-eindhoven

Appendix A

Detailed History & Evolution of AM

1. The 1980's

The 1980s were taken the first steps in research and development in 3D Printing field, in which the first patents were also formalized. The first approach to 3D printing was granted by Japanese Doctor Hideo Kodama. This Professor from Nagoya Municipal Industrial Research Institute developed a system in which a vat of photopolymer material was exposed to a UV light that solidified the part and built up the model in layers, which at the time it was called Rapid Prototyping (RP) technologies. Dr. Kodama applied for a patent for his revolutionary system in Japan in May 1980 and the results as journal papers were published in April and November in 1981. Although it did not have the desired success at the time, since the full patent specification was not filled within the one-year deadline after application, this was the first attempt to describe a layered manufacturing technique.[24]

In 1984, a French team composed by Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography (SLA) process, after the three men started working together to build 3D printer based on the fact that when two lasers cross each other, a liquid (monomer) can become a solid (polymer). However, the application of the French inventors was abandoned by their companies at the time: French National Center for Scientific Research (CNRS), French General Electric Company and CILAS, claiming as main reasons the "lack of business perspective and sectoral applications".[84]

At the same time, the American Charles “Chuck” Hull also filed his own patent for the stereolithography process. He described the process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed", allowing engineers to create prototypes of their designs in a more time effective manner or designers to create 3D models using digital data, which can then be used to create tangible objects. This kind of printing starts with a vat of liquid resin and uses a UV laser to harden the liquid one layer at a time. As each layer finishes, a platform in the vat lowers just enough so that the laser can create the next layer of hardened plastic.[27] On March 11th 1986, Hull’s patent was granted, making this engineer the father of 3D printing. After that moment, he co-founded the world's first 3D printing company, 3D Systems Corporation, to develop his rapid prototyping system. Two years later, the brand released the first commercial 3D printer, the SLA-1.

In that same year of 1988, Carl Robert Deckard, teacher at the University of Texas, brought a patent for the Selective Laser Sintering (SLS) technology, another 3D printing technique in which powder grains are fused together locally by a laser.[23]

Meanwhile, the also American Steven Scott Crump developed and patented the Fused Deposition Modelling (FDM) technology, a special application of plastic extrusion. In 1989, he co-founded Stratasys, selling, some years later, the first FDM machine of the market.[25]

2. The 1990’s

During the 1990s most 3D printing technologies emerged and the first CAD tools were developed. In these years, the evolution of additive manufacturing was fast, since the basics were already stablished. At that time, all the metalworking to transform a mass of raw material into a desired shape was associated with metal removal processes, by using tools or heads moving through a block of material, nowadays called non-additive processes. Nonetheless, new automated techniques for material deposition were being developed, which started to challenge the traditional concept of production. Sacrificial and support materials had also become more common, enabling new object geometries.

In 1995, Selective Laser Melting (SLM), another printing technology, was being developed at the Fraunhofer Institute ILT in Aachen, Germany. This is a specific 3D printing technique, which utilizes high power-density laser to fully melt and fuse metallic powders to produce near net-shape parts with near full density.[85]

Several experiments and tests were carried out in order to expand AM to new areas. One of the most relevant case studies at the time was carried out in 1999 by Scientists at Wake Forest Institute for Regenerative Medicine when the first 3D-printed organ was implanted in humans. These experts printed synthetic scaffolds of a human bladder and then coated them with the cells of human patients. The newly generated tissue was then implanted into the patients, with little to no chance that their immune systems would reject them, as they were made of their own cells.[23]

3. The 2000’s

Leveraged on the studies carried out in the previous decade, the 2000’s were a period of great innovations in medicine field, where AM also started to get some relevant media visibility.

After the beginning of the millennium, scientists 3D printed the first kidney, although the first transplant into a patient was just made after 13 years.

A relevant milestone was also the initiation of the RepRap Project in the University of Bath, England, in 2004 by Adrian Bowyer. It consisted on the development of a low-cost self-replicating rapid prototype, a 3D printer that could print most of its own components. By being open-sourced, this project led not only to the spreading of the FDM desktop 3D printers, but also to the increasing of the popularity of the technology in the makers’ community.[26]

In 2006, the first SLS machine became commercially viable, which opened the door to on-demand manufacturing of industrial parts, which started to trigger in consumers the concept of mass customization, which served as the motto for the following years.[27]

4. The 2010’s

Over the past years since 2010, additive manufacturing has penetrated into various industrial fields. At the same time, there has been an increase in accessibility of this technology to all people. The first years of the decade had become the years of 3D printing, mainly due to the FDM patent expiration. This factor opened new possibilities and, with it, AM was becoming a real and affordable prototyping and production technique for businesses. More and more small and big companies were taking advantage of the low prototyping price that 3D printing offers, and started to fully integrate it in their innovation and production processes.[23]

One place where additive manufacturing is making a significant inroad is in the aerospace industry. With a marked growth in the last few years in number of passengers carried on scheduled services - almost 4.5 billion in 2019, according to International Civil Aviation Organization (2020)[86] -, it is crucial for air companies to search for fuel efficient and easily produced jet engines. To satisfy these needs in their customers, aircraft manufacturers have been looking towards AM as a way to reduce cost, reduce the number of nonconforming parts, reduce weight in the engines to increase fuel efficiency and find new, highly complex shapes that would not be feasible with the antiquated manufacturing methods.[30] Even still playing a small role in the total number of parts in the jet engine manufacturing process, the return on investment on AM can already be seen by the reduction in parts, the rapid production capabilities and the optimized design in terms of performance and cost.[30]

Apart from that, new other discoveries and innovations have been made. In 2010, it was 3D printed the first car, which was called Urbee, using a very large 3D printer.[23]

In addition, Daniel Kelly’s lab has taken an important step in medical field, in 2016, after being able to 3D print the first human bone. For that, the scientists used a two-head commercial 3D bioprinter with two diferent materials: the environment material to provide mechanical support and the bio-ink. In the spaces between the filaments, they printed a bio-ink that contained stem cells. After it, the team made sure that the material degraded and progressively disappeared, while the tissue developed into bone.[28]

In 2018, 3D Printed concrete was being created, which made it possible for the first family to move into a fully printed house in 2021. The house was 1022 square feet and perfectly habitable, taking just two days to print.[87]

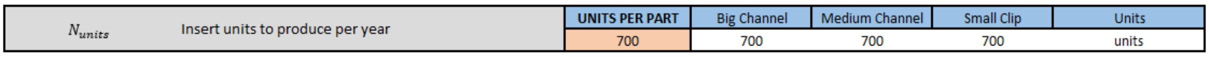
Appendix B

Costs Calculator

A calculation tool was developed in order to obtain the manufacturing costs for both processes - plastic injection molding and additive manufacturing - for each of the three parts based on 2 inputs: units to be produced per year for each of the three parts (Big Channel, Medium Channel, Small Channel) and the project lifetime in years. If one or both variables change, all costs are recalculated accordingly. The following is the explanation of the use of this "Cost Calculator" using as example of inputs 700 units per year during 8 years.

The only step customizable by the user is the first one - the entering of the input values – identifiable by the orange color.

Table 61 - Entering the input 1: number of units to produce per year.



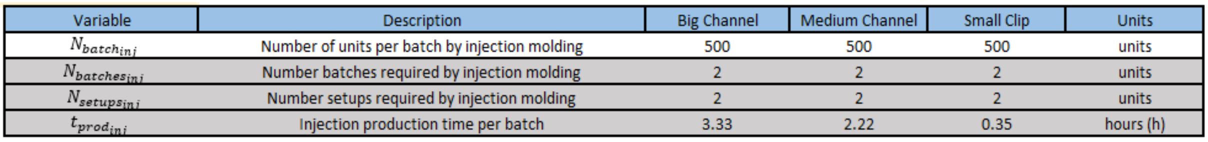
		UNITS PER PART	Big Channel	Medium Channel	Small Clip	Units
N_{units}	Insert units to produce per year	700	700	700	700	units

Table 62 - Entering the input 1: project lifetime.

		LIFETIME
$t_{lifetime}$	Insert project lifetime	8

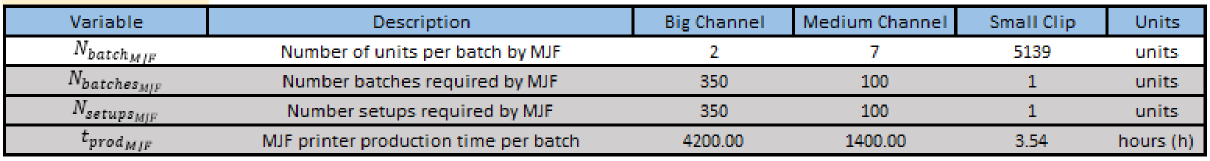
After receiving the inputs, the Cost Calculator indicates the number of batches required to produce the requested number of parts. This step is crucial, because, as highlighted before, units per batch by plastic injection are different from units per batch by additive manufacturing. In addition to the number of batches, the number of setups is also indicated. These two values may vary slightly, because while the batches may not be complete in Additive Manufacturing (and therefore assume decimal values), the number of setups must always be unitary - a batch may be produced at 50% of capacity but the setup process must be done at 100% to allow the production:

Table 63 - Number of batches and setups required by injection molding.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$N_{batch_{inj}}$	Number of units per batch by injection molding	500	500	500	units
$N_{batches_{inj}}$	Number batches required by injection molding	2	2	2	units
$N_{setups_{inj}}$	Number setups required by injection molding	2	2	2	units
$t_{prod_{inj}}$	Injection production time per batch	3.33	2.22	0.35	hours (h)

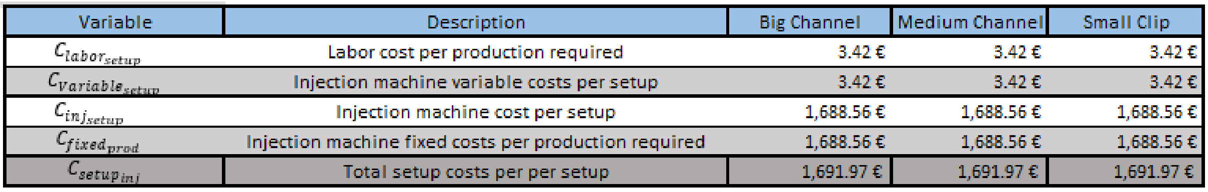
Table 64 - Number of batches and setups required by Multi Jet Fusion.



Variable	Description	Big Channel	Medium Channel	Small Clip	Units
$N_{batch_{MJF}}$	Number of units per batch by MJF	2	7	5139	units
$N_{batches_{MJF}}$	Number batches required by MJF	350	100	1	units
$N_{setups_{MJF}}$	Number setups required by MJF	350	100	1	units
$t_{prod_{MJF}}$	MJF printer production time per batch	4200.00	1400.00	3.54	hours (h)

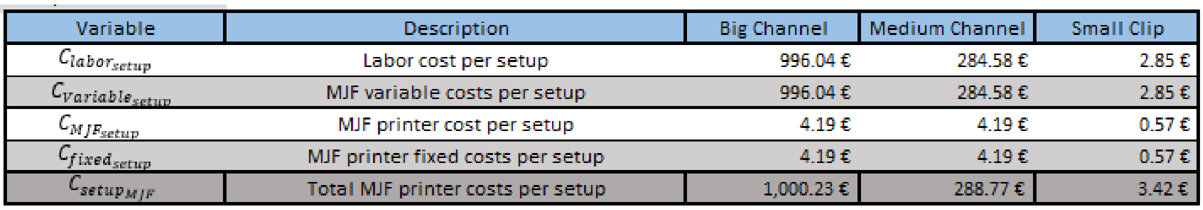
Having the number of setups required, it is then possible to obtain the setup costs relative to the number of units to be produced, subdivided into variable costs (labor costs) and fixed costs (injection machine costs or printer costs):

Table 65 - Setup costs by injection molding.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{labor_{setup}}$	Labor cost per production required	3.42 €	3.42 €	3.42 €
$C_{variable_{setup}}$	Injection machine variable costs per setup	3.42 €	3.42 €	3.42 €
$C_{inj_{setup}}$	Injection machine cost per setup	1,688.56 €	1,688.56 €	1,688.56 €
$C_{fixed_{prod}}$	Injection machine fixed costs per production required	1,688.56 €	1,688.56 €	1,688.56 €
$C_{setup_{inj}}$	Total setup costs per per setup	1,691.97 €	1,691.97 €	1,691.97 €

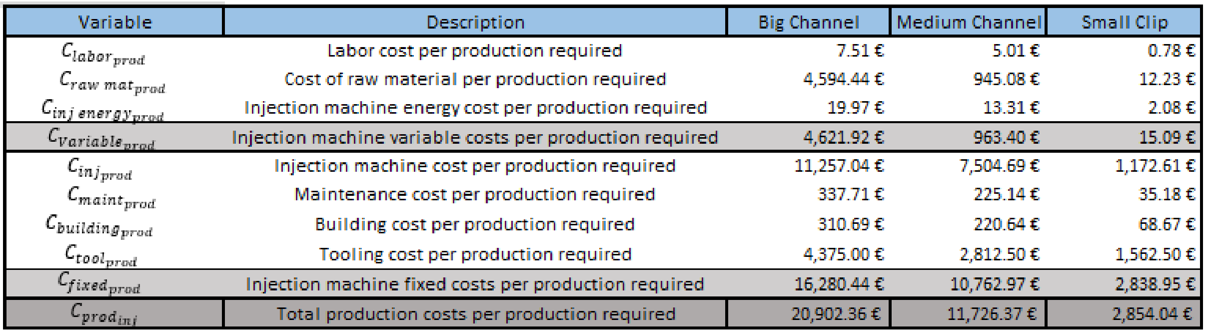
Table 66 - Setup costs by Multi Jet Fusion.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{labor_{setup}}$	Labor cost per setup	996.04 €	284.58 €	2.85 €
$C_{variable_{setup}}$	MJF variable costs per setup	996.04 €	284.58 €	2.85 €
$C_{MJF_{setup}}$	MJF printer cost per setup	4.19 €	4.19 €	0.57 €
$C_{fixed_{setup}}$	MJF printer fixed costs per setup	4.19 €	4.19 €	0.57 €
$C_{setup_{MJF}}$	Total MJF printer costs per setup	1,000.23 €	288.77 €	3.42 €

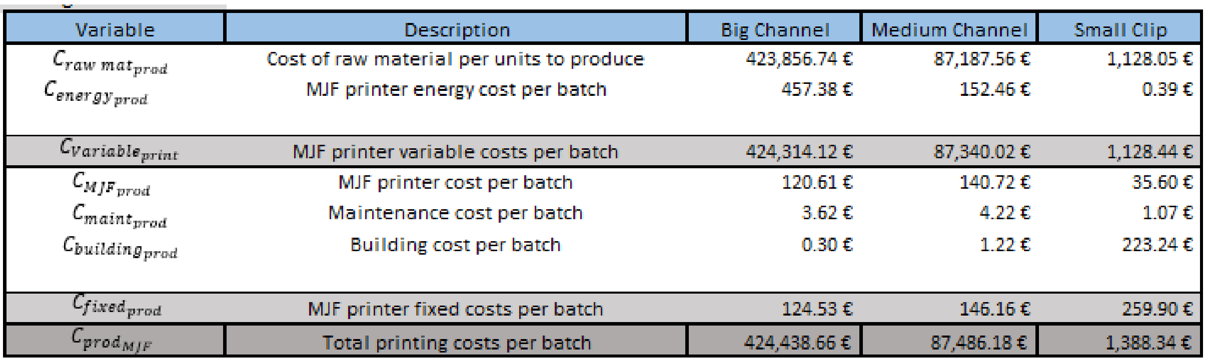
In the same way, it is possible to visualize both the production costs per part in the case of plastic injection molding, and the printing and after printing costs in the case of additive manufacturing by MJF. It is important to highlight that both the injection machine and the printer, for comparison purposes, are considered fully dedicated machines, which means that 100% of the machine costs of the respective processes must be allocated to the amount of the units produced during the predefined time period.

Table 67 - Production costs by injection molding.



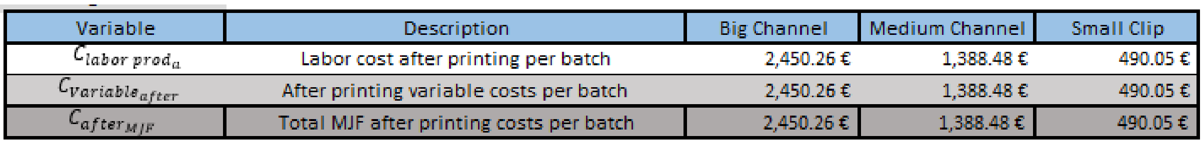
Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{labor_{prod}}$	Labor cost per production required	7.51 €	5.01 €	0.78 €
$C_{raw\ mat_{prod}}$	Cost of raw material per production required	4,594.44 €	945.08 €	12.23 €
$C_{inj\ energy_{prod}}$	Injection machine energy cost per production required	19.97 €	13.31 €	2.08 €
$C_{variable_{prod}}$	Injection machine variable costs per production required	4,621.92 €	963.40 €	15.09 €
$C_{inj_{prod}}$	Injection machine cost per production required	11,257.04 €	7,504.69 €	1,172.61 €
$C_{maint_{prod}}$	Maintenance cost per production required	337.71 €	225.14 €	35.18 €
$C_{building_{prod}}$	Building cost per production required	310.69 €	220.64 €	68.67 €
$C_{tool_{prod}}$	Tooling cost per production required	4,375.00 €	2,812.50 €	1,562.50 €
$C_{fixed_{prod}}$	Injection machine fixed costs per production required	16,280.44 €	10,762.97 €	2,838.95 €
$C_{prod_{inj}}$	Total production costs per production required	20,902.36 €	11,726.37 €	2,854.04 €

Table 68 - Printing costs by Multi Jet Fusion.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{raw\ mat_{prod}}$	Cost of raw material per units to produce	423,856.74 €	87,187.56 €	1,128.05 €
$C_{energy_{prod}}$	MJF printer energy cost per batch	457.38 €	152.46 €	0.39 €
$C_{variable_{print}}$	MJF printer variable costs per batch	424,314.12 €	87,340.02 €	1,128.44 €
$C_{MJF_{prod}}$	MJF printer cost per batch	120.61 €	140.72 €	35.60 €
$C_{maint_{prod}}$	Maintenance cost per batch	3.62 €	4.22 €	1.07 €
$C_{building_{prod}}$	Building cost per batch	0.30 €	1.22 €	223.24 €
$C_{fixed_{prod}}$	MJF printer fixed costs per batch	124.53 €	146.16 €	259.90 €
$C_{prod_{MJF}}$	Total printing costs per batch	424,438.66 €	87,486.18 €	1,388.34 €

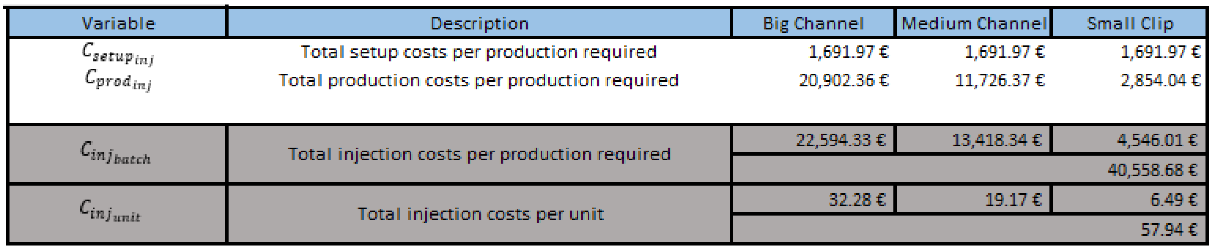
Table 69 - After-printing costs by Multi Jet Fusion.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{labor\ prod_a}$	Labor cost after printing per batch	2,450.26 €	1,388.48 €	490.05 €
$C_{variable_{after}}$	After printing variable costs per batch	2,450.26 €	1,388.48 €	490.05 €
$C_{after_{MJF}}$	Total MJF after printing costs per batch	2,450.26 €	1,388.48 €	490.05 €

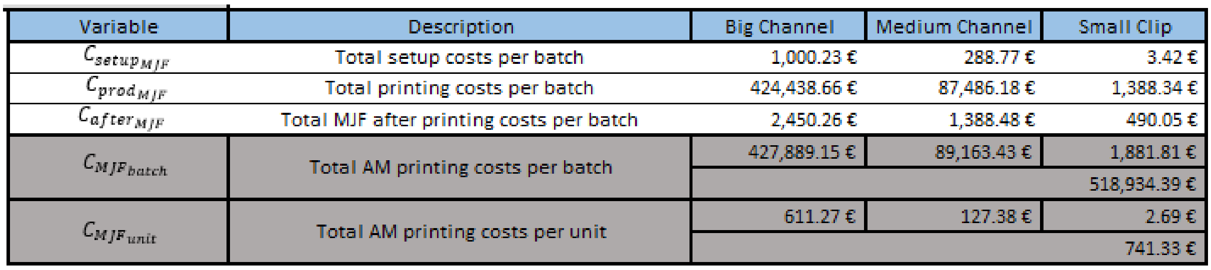
Finally, it is possible to compare the total costs between the two processes for the predefined inputs. These costs are givens for the entire production (per part e per set) and per unit (per part e per set):

Table 70 - Total costs by injection molding.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{setup_{inj}}$	Total setup costs per production required	1,691.97 €	1,691.97 €	1,691.97 €
$C_{prod_{inj}}$	Total production costs per production required	20,902.36 €	11,726.37 €	2,854.04 €
$C_{inj_{batch}}$	Total injection costs per production required	22,594.33 €	13,418.34 €	4,546.01 €
		40,558.68 €		
$C_{inj_{unit}}$	Total injection costs per unit	32.28 €	19.17 €	6.49 €
		57.94 €		

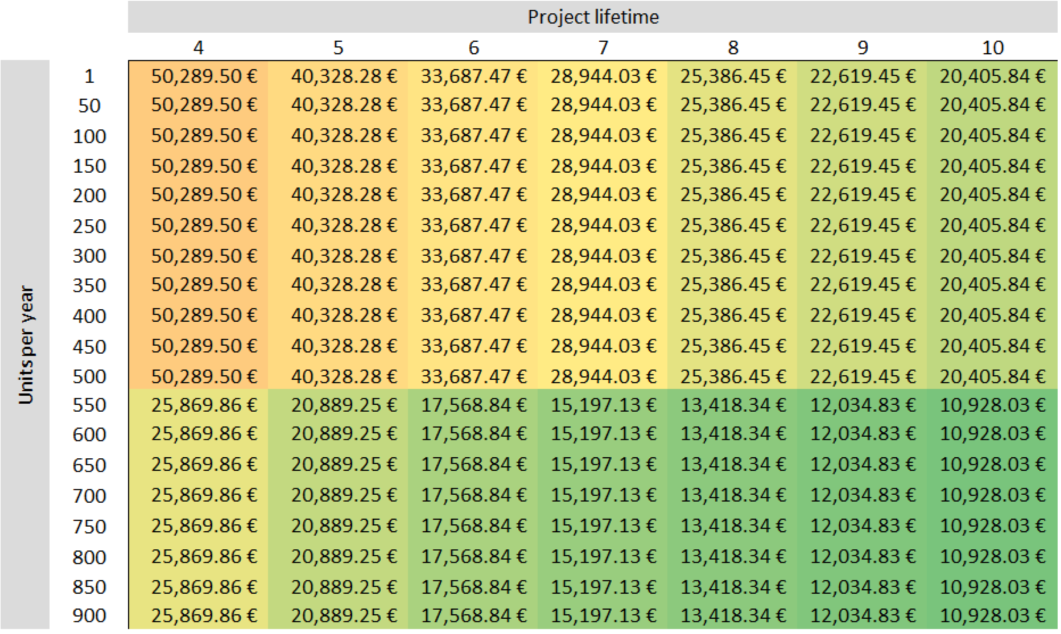
Table 71 - Total costs by Multi Jet Fusion.



Variable	Description	Big Channel	Medium Channel	Small Clip
$C_{setup_{MJF}}$	Total setup costs per batch	1,000.23 €	288.77 €	3.42 €
$C_{prod_{MJF}}$	Total printing costs per batch	424,438.66 €	87,486.18 €	1,388.34 €
$C_{after_{MJF}}$	Total MJF after printing costs per batch	2,450.26 €	1,388.48 €	490.05 €
$C_{MJF_{batch}}$	Total AM printing costs per batch	427,889.15 €	89,163.43 €	1,881.81 €
		518,934.39 €		
$C_{MJF_{unit}}$	Total AM printing costs per unit	611.27 €	127.38 €	2.69 €
		741.33 €		

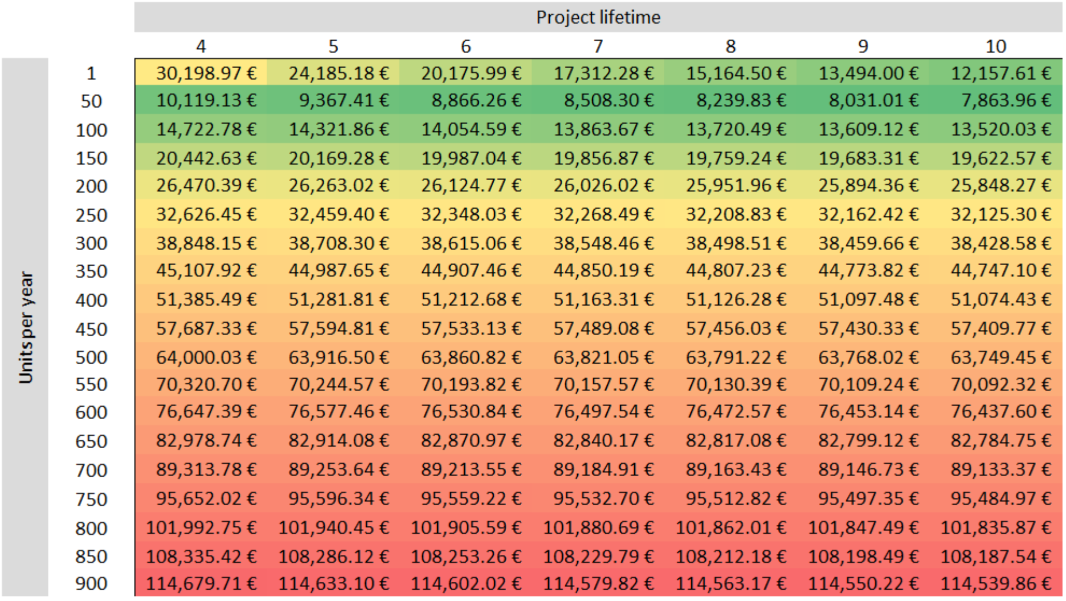
In addition to cost breakdown, the Cost Calculator also presents a sensitivity analysis of the total costs according to the variation of the two input variables: units to be produced per year and the project lifetime from a range of 1 to 900 units per year and 4 to 10 years lifetime. This analysis is made for each one of the three parts produced by each process plus an analysis for the totals of producing the sets inputted by IM or by MJF, which gives a total of 8 analysis. The final costs for all the above options are supported by a heat map for more direct interpretation of the results. This analysis is compared between the costs of the individual parts and the total costs. Below is an example for the Medium Channel:

Table 72 - Sensitive Analysis for Medium Channel by injection molding.



		Project lifetime						
		4	5	6	7	8	9	10
Units per year	1	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	50	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	100	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	150	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	200	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	250	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	300	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	350	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	400	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	450	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	500	50,289.50 €	40,328.28 €	33,687.47 €	28,944.03 €	25,386.45 €	22,619.45 €	20,405.84 €
	550	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	600	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	650	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	700	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	750	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	800	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	850	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €
	900	25,869.86 €	20,889.25 €	17,568.84 €	15,197.13 €	13,418.34 €	12,034.83 €	10,928.03 €

Table 73 - Sensitive Analysis for Medium Channel by MJF.



		Project lifetime						
		4	5	6	7	8	9	10
Units per year	1	30,198.97 €	24,185.18 €	20,175.99 €	17,312.28 €	15,164.50 €	13,494.00 €	12,157.61 €
	50	10,119.13 €	9,367.41 €	8,866.26 €	8,508.30 €	8,239.83 €	8,031.01 €	7,863.96 €
	100	14,722.78 €	14,321.86 €	14,054.59 €	13,863.67 €	13,720.49 €	13,609.12 €	13,520.03 €
	150	20,442.63 €	20,169.28 €	19,987.04 €	19,856.87 €	19,759.24 €	19,683.31 €	19,622.57 €
	200	26,470.39 €	26,263.02 €	26,124.77 €	26,026.02 €	25,951.96 €	25,894.36 €	25,848.27 €
	250	32,626.45 €	32,459.40 €	32,348.03 €	32,268.49 €	32,208.83 €	32,162.42 €	32,125.30 €
	300	38,848.15 €	38,708.30 €	38,615.06 €	38,548.46 €	38,498.51 €	38,459.66 €	38,428.58 €
	350	45,107.92 €	44,987.65 €	44,907.46 €	44,850.19 €	44,807.23 €	44,773.82 €	44,747.10 €
	400	51,385.49 €	51,281.81 €	51,212.68 €	51,163.31 €	51,126.28 €	51,097.48 €	51,074.43 €
	450	57,687.33 €	57,594.81 €	57,533.13 €	57,489.08 €	57,456.03 €	57,430.33 €	57,409.77 €
	500	64,000.03 €	63,916.50 €	63,860.82 €	63,821.05 €	63,791.22 €	63,768.02 €	63,749.45 €
	550	70,320.70 €	70,244.57 €	70,193.82 €	70,157.57 €	70,130.39 €	70,109.24 €	70,092.32 €
	600	76,647.39 €	76,577.46 €	76,530.84 €	76,497.54 €	76,472.57 €	76,453.14 €	76,437.60 €
	650	82,978.74 €	82,914.08 €	82,870.97 €	82,840.17 €	82,817.08 €	82,799.12 €	82,784.75 €
	700	89,313.78 €	89,253.64 €	89,213.55 €	89,184.91 €	89,163.43 €	89,146.73 €	89,133.37 €
	750	95,652.02 €	95,596.34 €	95,559.22 €	95,532.70 €	95,512.82 €	95,497.35 €	95,484.97 €
	800	101,992.75 €	101,940.45 €	101,905.59 €	101,880.69 €	101,862.01 €	101,847.49 €	101,835.87 €
	850	108,335.42 €	108,286.12 €	108,253.26 €	108,229.79 €	108,212.18 €	108,198.49 €	108,187.54 €
	900	114,679.71 €	114,633.10 €	114,602.02 €	114,579.82 €	114,563.17 €	114,550.22 €	114,539.86 €

Finally, the Cost Calculator shows the distribution of costs for both processes taking into account the inputs - in this case for 700 units per year over 8 years.

Table 74 - Costs Distribution by injection molding.

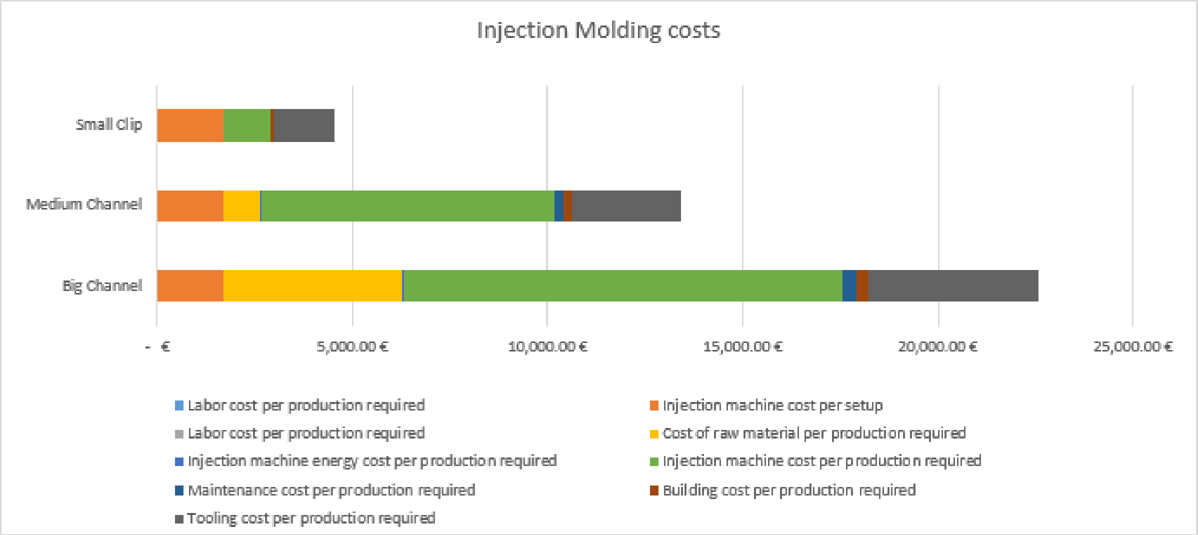


Table 75 - Costs Distribution by MJF.