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

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.

2 THE 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. 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.

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.

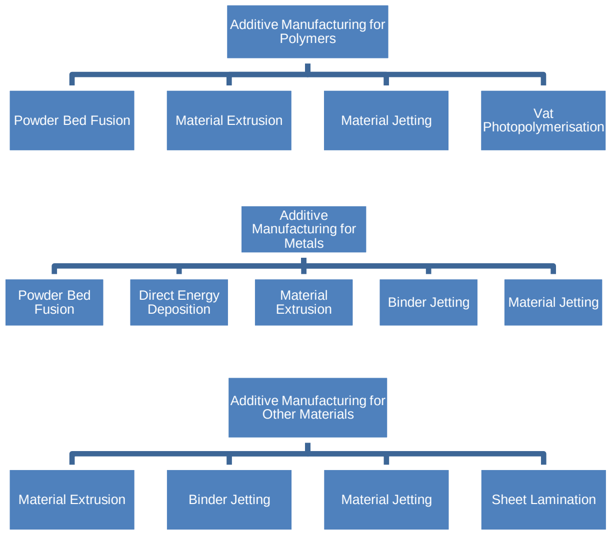
3 LITERATURE REVIEW

3.1 INJECTION MOLDING

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. Regarding the manufacturing itself, the process is cyclic and consists of plasticizing stage and injection stage.
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.
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.

3.2 ADDITIVE MANUFACTURING

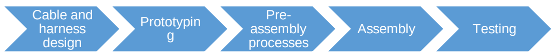
Additive Manufacturing (AM), also known as 3D Printing, is, according to Panda (2016), one of the most promising technologies that have connected digital and physical domains without the need of tooling and human intervention, being used in several areas. Its ability to turn digital models into physical 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. 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.
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) catalogued 3D Printing processes 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 some technologies and is best suited to a different type of material. The following diagram shows the separation of processes between polymers, metals and others:



3.3 WIRE HARNESS 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.
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 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.
Manufacturing the wire harness is a process that requires several steps that vary according to the final assembly implementation purpose and application. 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.



4. RESEARCH METHODOLOGY

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.
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 17: 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

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.
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 considered: suitability, mechanical properties, printable volume per batch, support structure, surface finish, post processing, technology cost.
Given the criteria defined above, the comparison between the five 3D printing technologies considered for this study is carried out. This comparison is made according to two types of evaluation:

- Qualitative evaluation - based on the information researched and the findings.
- 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.

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. However, the goal 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

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.

Now 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.

5. RESULTS DISCUSSION & CONCLUSIONS

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 below. From those values, it is possible to draw some conclusions.

Table 1 - 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 2 - 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.

- 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, especially in the Big and Medium Channel. 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.

- 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.
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.

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.
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

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, is 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.
By analysis the results, 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.

5.5 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.