An Economical Comparison between Additive Manufacturing and Subtractive Manufacturing

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Abstract

Additive manufacturing (AM) is a rising technology in the aerospace sector due to its weight saving and free geometry design capabilities. Its recent introduction to new materials, namely metals, is pushing the technology further and establishing it as a direct competitor with conventional production methods based on subtractive manufacturing (SM). In order to evaluate the introduction of this new technology as part of the production line, there is a need to understand the overall economical aspect and its main cost drivers, of both metal additive manufacturing (MAM), and the current technology, subtractive manufacturing. In this thesis, two cost models were created to better understand and evaluate the economical differences between AM and SM. Furthermore, a database of 3000 sample was generated in order to evaluate a high production volume case for both manufacturing scenarios. The results of this research show that AM cannot be considered economically advantageous relatively to SM. From the three main direct cost drivers, Material, Energy, and Labor, only the last presents a lower cost for AM. The high material costs for the same metal in powder form (compared to its solid form for SM), and the high energy expenditure an AM machine demands to operate, can raise the total cost to as much as three times the cost of SM production. Nonetheless, AM proved to be the most economical option for parts with a complex geometry, overcoming the high material and energy costs.
Keywords: additive, subtractive, high volume production, metal, cost model

1. Introduction

Additive Manufacturing (AM) is introducing new materials and new processes that are radically changing the geometric possibilities encountered in the manufacturing sector [7]. This uprising process, also called 3D Printing, consists in manufacturing a 3D part layer-by-layer, that is, building 2D sheets of material, one at a time. The material comes in a powder form that is then sintered or comes already molten and is deliberately deposited to form a new layer [4]. Together with the help of support structures, AM provides geometric liberty that is not usually found in Subtractive Manufacturing (SM) [3].

Subtractive Manufacturing, also referred to as CNC (Computer Numerical Control) machining, starts with a solid block of material, contrary to AM. The process consists of removing material from the starting block, which can be done manually or with a CNC machine [8]. The last one is controlled by a programmed software that dictates the cutting tool movement.

One of the advantages of SM is its high accuracy and repeatability, being one of the most used manufacturing processes when facing precision dimensional requirements [11]. This is one of the main reasons why additive manufacturing still cannot fully replace this conventional method. The high geometric complexity of AM comes with low tolerance compared with the high precision that SM presents.

The existent research doesn't compare the benefits between additive and subtractive manufacturing. For doing so, it is important to understand the existent cost models for each manufacturing process and its main cost drivers [6] and this way evaluate the most economical option. There is also a lack of research for high production volume of different pieces using additive manufacturing. The existing research focuses only on the production of a single part. This thesis aims at completing the existing research with a high geometric diversity of parts which will allow for a more detailed economic review.

2. Background

To evaluate the economics that support each technology, one has first to understand the theory behind Additive and Subtractive Manufacturing.

Starting with the current use of technology, it analyses the advantages and limitations of both processes. After defining the main variables and specifications that can affect the processes, the last section discusses the main cost models that will serve as a base to the cost model presented in this thesis.

2.1. Additive Manufacturing

The aerospace sector represents a big part of the successful applications of AM. With an aim for innovation, the sector started to identify possible points where AM could have a major impact. The manufacturing process capabilities like weight reduction and endless geometries were the most important decision points for the adoption of this new technology. Nevertheless, its benefits in maintenance, repair, and overhaul (MRO) [5] are of equal importance.

2.1.1 Aerospace Sector

The now-famous fuel nozzle manufactured by GE Aviation was a major case of success that validated the value added by Additive Manufacturing. Before being produced as a single piece using 3D Printing, the nozzle consisted of 20 individual components. The final product presents hidden channels and cavities that made it impossible to be machined as a single part. GE decided to invest 50M to renovate the Auburn, AL plant and install 10 AM machines. This machine capacity allows for 1000 nozzles to be produced by year, with an estimation of reaching 40000 parts/year [7].

Despite all the success, the adoption rate of AM is still slow. This is mainly due to a lack of certifications that is very difficult to obtain mainly because of the repeatability and stability factors of AM processes. Nonetheless, there are some standards in circulation, e.g., a standard for components made with a TiAlV alloy using Powder Bed Fusion [1]. The responsible organizations are the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA).

2.1.2 Processes

One of the most used processes in the aerospace sector is Powder Bed Fusion (PBF). Although it is not the most economical option, PBF meets the strict requirements that are common in this sector.

Powder Bed Fusion is characterized by a powder bed of material distributed homogeneously to form a thin layer. A controlled laser beam scans the powder bed and fuses the material together into a solid. After the layer is completed, the powder bed is lowered. This height distance corresponds to the layer thickness, which is of extreme importance to the quality of the final piece [4].

Aside from the powder bed, there is usually a reservoir which provides fresh material supply and from where a new layer of powder is added to the powder bed. This is done using a roller or blade which is often vibrated to encourage a more even distribution of powder [4]. After the new layer is fused with the already built object part, the platform lowers the model accordingly, and the process continues layer by layer.

There are five main techniques based on this process: Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM), Selective Heat Melting (SHM), and Selective Laser Sintering (SLS).

2.2. Subtractive Manufacturing

Subtractive manufacturing, as the name self-explains, starts from a bulk piece and continually removes material through processes like drilling, milling, turning until reaching the desired shape. Contrary to manually controlled systems through levers or handwheels, the subtractive machine, also known as CNC (Computer Numerical Control) machine, is an automated machine that follows a program of instructions, known as the G-code [11].

The CNC machine is capable of executing different processes to shape an object, though each process requires a different set of tooling. The main processes used to manufacture tooling is milling [9].

The main advantage of Subtractive Manufacturing that is still an issue for Additive Manufacturing it is its repeatability. The CNC machine is capable of producing the same piece over and over again without flaws [11]. By starting with the same bulk piece of material and feeding the same program to the machine, one can expect the same quality.

2.2.1 Milling Process

The milling process is used for removing layers of material from the bulk piece. This is done with the milling cutter which is a rotating cutting tool with sharp teeth that cut away material from the main piece in the form of small chips. Besides removing complete layers from the surface, the milling cutter is also used to machine slots and pockets.

The CNC processes are controlled by parameters that need to be carefully selected as they will define the finish quality. The main parameters that influence the manufacturing process are: cutting speed (rpm), feed rate (mm/min), depth of cut (mm), and material removal rate (mm^3/min).

2.3. Cost Model Review

Additive Manufacturing has come a long way from Rapid Prototyping to now being considered as a Rapid Manufacturing option. In order to

substitute traditional methods, it also has to show economic value besides its technical and low lead time value [13]. There are several studies with the aim of creating a highly detailed and suitable cost model that will help assess the manufacturing process' economic validity.
Hopkins and Dickens, 2003 [6] divided the costs into three parts: machine costs, labor costs, and material costs. They assumed that the machine produces only one type of piece at a time with maximum capacity and that the machine is working 90% up-time during the time interval of one year. Comparing with injection molding, the break-even point was at around 5500 built pieces.
Ruffo et al., 2006 [14] created a cost model comprised of two main parts: direct and indirect costs. The activities included are Material,Software ,Hardware ,Capital equipment depreciation, Labour, Maintenance, Production overhead, and Administration overhead, and are all accounted into indirect costs with the exception of material. Ruffo et al., 2006 considered that the costs involved in labor and machine, among others, are not directly involved because they are annual payees.

Liu et al., 2013 [10] developed a feature-based method for estimating the time for NC machining. Since the time necessary for machining is dependent on different factors like machine characteristics, cutting speed, and cutting force, it is hard to develop an accurate model to account for all the factors. The authors developed a time estimation method based on geometry-process information.

3. Methodology

To help in the decision process of which method, Additive Manufacturing or Subtractive Manufacturing, is the most economical one, two cost models were developed to better understand the variables involved.
The main cost drivers analyzed are Manufacturing Auxiliary Costs, Material, Energy, and Labor, as stated by Hopkins and Dickens, 2003 [6]. For each cost model, besides the main cost drivers explanation, there is extra atention dedicated to processing time and energy expenditure, as these represent more complex parameters to estimate.
The last part is the methodology used to generate the N samples that will serve as a case study for a high volume production scenario.

3.1. AM Cost Model

When producing a piece, there are direct and indirect costs involved, as stated by Ruffo and Hague, 2006 [14]. The direct costs are mainly related with material cost, energy cost and labor cost. The indirect costs are related with the machine cost and auxiliary costs (software, consumables, maintenance and building area), as stated by Ruffo et al., [13]. The cost model described in this section is based in the work of Ruffo and Hague, 2006 [14] and Ruffo et al., [13].

Table 1: AM: Indirect Costs

Variable	Name	Unit
	AM Machine	
-	Machine	-
M_C	Machine Purchase Cost	\$
M_L	Machine Lifespan	year
	Man. Auxiliary Costs	
-	Software	-
S_L	Software Lifespan	year
Aux_c	Consumables	\$/year
Aux_m	Maintenance Cost	\$/year
Aux_{rent}	Yearly Rent Rate	\$/m^2
Aux_{ba}	Building Area	m^2
$Total_{Ind}$	Total indirect cost	\$/hr

The indirect costs presented in Table 1 are summed and divided by the hours of production per year. This way the value $Total_{Ind}$ can be easily applied to each produced part depending on its manufacturing time.
The direct costs are presented in Table 2, namely Material, Energy, and Labor. The building chamber dimensions indicates the maximum part size. The layer thickness will dictate the total number of layers that will be used as one of the inputs for the time estimation described in the next sub-section.
The Specific Energy Consumption is retrieved from the work of Yoon et al., 2014 [15] and has a value of 50 kWh/kg for FDM and 24.2 kWh/kg for DMLS.

Table 2: AM: Machine, material, energy, and labor specifications

Variable	Name	Unit
	AM Machine	
-	Machine	-
BC_x	Building chamber X	mm
BC_y	Building chamber Y	mm
BC_z	Building chamber Z	mm
BC_V	Building chamber Vol.	mm^3
L_t	Layer Thickness	mm
	Material	
-	Raw material	-
M_{dens}	Density of material	kg/mm^3
M_c	Cost per kg	\$/kg
	Energy	
SEC_{AM}	Specific Energy Consmp.	MJ/kg
E_R	Energy Rate	\$/MJ
	Labor	
L_r	Labor Cost Rate	\$/hr

3.1.1 Time estimation

Ruffo and Hague, 2006 divided the building time variable T_{build} in three variables presented in equation 1.

$$T_{build} = t_{xy} + t_z + t_{HC} \tag{1}$$

where t_{xy} is the time it takes to scan the section and its border, t_z is the time it takes to add the new layers of powder, also known as the recoating time, and t_{HC} accounts both for the time to preheat the powder bed or to cool down after scanning.

In order to calculate the variable t_z, Ruffo and Hague, 2006 [14] determined equation 2 from empirical data:

$$t_z = (180 - 120 * Pr_{ext}) * z + 400 \tag{2}$$

Pr_{ext} is actually the inverse of the value P_{max}:

$$Pr_{ext} = \frac{BB_V}{BC_V} = \frac{1}{P_{max}} \tag{3}$$

,where BB_V is the part bounding box volume P_{max} is the maximum number of parts per build.

To determine the scanning time t_{xy}, Ruffo and Hague, 2006 [14] also used an empirical method. They define that the scanning time is a fraction υ of the total time it requires to scan the entire bounding box volume, t_{xy_box}:

$$t_{xy} = \upsilon * t_{xy\_box} \tag{4}$$

In order to obtain the scaling factor υ, a new variable is defined. $Compact\ ratio$, C_r, is the ratio between the $Total\ Volume$ and $Bounding\ Box\ Volume$:

$$C_r = \frac{P_v}{BB_V} \tag{5}$$

After a series of experimental tests, the authors concluded two different equations depending on the value of C_r. The reason to differentiate the equation was that neither was a good fit for every case. With the equations 14, the maximum error observed was of 12%.

$$\upsilon = \begin{cases} 0.3422 * {C_r}^2 + 0.2468 * C_r + 0.45, & C_r < 0.4 \\ 0.417 * e^{0.9283 * C_r}, & C_r > 0.4 \end{cases} \tag{6}$$

To calculate the variable t_{xy_box}, the authors used twenty tests in order to calculate the equation 7 with an estimation error lower than 10%.

$$t_{xy\_box} = 0.042 * {BB_x}^{-0.1809} * BB_V \tag{7}$$

The only unknown variable from equation 1 is T_{HC}. This value cannot be correctly estimated as it depends on a number of values such as external temperature and how fast the user is on cleaning and setting up the machine. For this reason, the author decided to keep this variable at a constant value of 60 min. When compared with empirical data, this value presented a maximum error of 13%. Finally, the building time variable can be estimated from the equation 1.

3.2. SM Cost Model

The indirect costs for SM are presented in Table 3 and are based in the work of Liu et al.,2013 [10] and Chang et al., 2013 [2]. The direct costs considered are the same as for AM, Material, Energy, and Labor, although different equations are used to calculate its values.

Table 3: SM: Indirect Costs

Variable	Name	Unit
	AM Machine	
-	Machine	-
M_C	Machine Purchase Cost	$
M_L	Machine Lifespan	year
	Man. Auxiliary Costs	
Aux_{cost}	Auxiliary Cost	$/year
Aux_{rent}	Yearly Rent Rate	$/m^2
Aux_{ba}	Building Area	m^2
$Total_{Ind}$	Total indirect cost	$/hr

3.2.1 Time Estimation

Following the work of Chang, 2013 [2], the time it takes to produce a unit follows the equation 8.

$$T_{SM} = T_{set} + T_{proc} + T_{idle} \tag{8}$$

The first element from equation 8 is the Setup time, T_{set} and it is the sum of the machine setup time, T_{mach} and tool Change time, T_{tool} as described by equation 9.

$$T_{set} = \sum_i T_{mach_i} + \sum_i \sum_j T_{tool_{ij}} \tag{9}$$

where i is the index for the ith machine and j is the index for the jth tool.

The second element from equation 8 is T_{proc} that is the active time and consists rough cutting time, T_r, finish cutting time, T_f and approaching time T_a.

$$T_{proc} = T_r + T_f + T_a \tag{10}$$

The time necessary for rough machining is proportional to the volume of material removed so it can be estimated from :

$$T_r = \frac{BB_V - P_V}{MRR} \tag{11}$$

The MRR variable depends on a number of different factors like main piece material, cutting tool material, operation, and geometry.

The time for the finish cutting, t_f and the approaching time account for only 3% of the processing time so in order to simplify the estimation process they will not be accounted for.

The idle time T_{idle} is the last element from equation 8. It accounts for the time it takes for reloading the part, T_{relo} and for the time necessary for engaging and disengaging the tool and for speed and feed adjustment, T_e.

The reloading time that accounts for the part handling and clamping and unclamping can be calculated from equation 12. Also, the T_e variable refers to a specific machine toold and an be obtained from the work of Ostwald, 1991 [12].

$$T_{relo} = NrSurf * (38 + 1.1 * W) \quad (12)$$

where W is the part weight in lb.

3.3. Generating N different pieces

While the cost model created can be used for predicting the building cost of one piece, the main purpose of the final part of this thesis is trying to understand which method between Additive Manufacturing and Subtractive Manufacturing is the most economical option in the long run. The cost models cited in the Cost Model Review section, when estimating the production cost for a higher volume, only use a single part and simulate if that part was to be produced in bulk mode [14, 13, 6]. The technology of additive manufacturing is used for rapid prototyping or rapid manufacturing [4], so high volume production it is not the main functionality. For this reason, this thesis tries to increase the variability of the produced parts and generate N different samples.

The first step is to analyze real parts and the behavior between selected variables in order for the N final samples to behave the same way. The variables analyzed are $Surface\ Area$, $Volume$, BB_V, and $CompactRatio$.
The source for gathering the different parts is the website *grabcad.com* which is a database of CAD files. There is obviously necessary to adopt a selection process to guarantee that the chosen parts can be both manufactured by additive and subtractive processes.
The features that were analyzed to guarantee that the parts were machinable with CNC are minimum wall thickness, minimum hole diameter, internal edges, low access features, and threads. The values were retrieved from 3D Hubs and are presented in Table 4.

Table 4: CNC Design Guidelines

Feature	**Recommended size**
Minimum feature size	D 2.5 mm
Internal edges	R 8 mm
Minimum wall thickness	0.8 mm (metals) 1.5 mm (plastics)
Holes	D: drill bit sizes Depth: 4x D
Threads	Size: M6+ Length: 3x D

The values retrieved for each selected part are $Surface\ Area$, $Volume$, BB_x, BB_y, BB_z, and BB_V. The C_r value is then calculated from Equation 5.
The results were conclusive and show a good correlation between the variables that were analyzed. Further work will be conducted to improve the correlation.
The first analysis was conducted regarding the variables $Volume$ and $Bounding\ Box\ Volume$.
The best regression to fit the data is a polynomial regression of second order. The coefficient of determination, R^2, obtained is 0.7719 and the regression is defined by equation 13.

$$P_V = 7 * 10^{-9} C_r^2 + 0.1695 C_r \quad (13)$$

In order to improve the regression, the data is grouped. The condition adopted is the same used by Ruffo, 2006 [13] where the authors presented two regressions for parts with a compact ratio, Cr, higher or lower than 0.4.

The results now show a fitted regression which is concluded from a higher R^2. The two regressions for $Cr < 0.4$ and $Cr > 0.4$ are both polynomial regressions of second order with an R^2 of 0.8656 and 0.9976, respectively:

$$\mathrm{P}_V = \begin{cases} 8 * 10^{-9} BB_V^2 + 0.1217 BB_V, & C_r < 0.4 \\ 2 * 10^{-9} BB_V^2 + 0.4582 BB_V, & C_r > 0.4 \end{cases} \quad (14)$$

As the regression for the data with $Cr < 0.4$ still presents an R^2 of 0.8656, there is still room for improvement. A correlation analysis regarding only the data with $Cr < 0.4$ was conducted in order to find if grouping this data and this way fitting the data with two regression curves was a better option. The results turned out positive.
The data can be grouped for $Cr < 0.1$ where the R^2 is 0.9832 and $0.1 < Cr < 0.4$ with R^2 of 0.9405.

The three final equations that will be used to represent the data are:

$$\mathrm{P}_V = \begin{cases} 3 * 10^{-9} BB_V^2 + 0.0662 BB_V, & C_r < 0.1 \\ 6 * 10^{-9} BB_V^2 + 0.17262 BB_V, & 0.1 < C_r < 0.4 \\ 2 * 10^{-9} BB_V^2 + 0.4582 BB_V, & C_r > 0.4 \end{cases} \quad (15)$$

With the system of equations defined, the next step is to generate N number of samples to be used as data for the high volume production case. The method used for generating N samples of data that follow the original data is through the trendlines described in the system 15, at which will be added noise to create an error. As there are different types of noise, there is the need to analyze the error from the original data in order to replicate it. The error is simply obtained by subtracting the $Part\ Volume$ values to regression equations from system 15.

The results were obtained with the software $EasyFit$ from *http://mathwave.com/*. The errors were inserted to the $EasyFit$ software that automatically calculates the parameters for the density functions. As examples, some of the density functions analyzed are Cauchy, Normal, Laplace, Beta, Gamma, Logistic, Log-Logistic, Johnson SU, Pert, Power Function, Uniform, Weibull. The software also calculates the Anderson-Darling statistic that measures how well the data follows the distribution function. The density function chosen to represent the error distribution is the one that presents the lower Anderson-Darling statistic.

For $C_r < 0.1$, the error follows a Log-Logistic probability density function, PDF, with parameters: $\alpha = 7.6171$ (scale), $\beta = 215750$ (shape) and $\lambda = -22573$ (location). For $0.1 < C_r < 0.4$, the error follows a Cauchy PDF with parameters $\sigma = 79680$ (scale) and $\mu = -39407$ (location). For $C_r > 0.4$, the error also follows a Cauchy PDF with parameters $\sigma = 29087$ (scale) and $\mu = 7598.6$ (location).

Another important aspect for replicating the original data is to analyze to variable $Bounding\ Box\ Volume$ distribution. It is not correct to assume that it will have a Uniform distribution. The BB_V varies between 0 and 250x250x325 mm3 (maximum building chamber dimensions), so it is less likely that a piece will completely fill the volume.
The software $EasyFit$ is used again to identify the best fitting PDF which for this case is the Log-logistic PDF with parameters $\alpha = 1.0942$, $\beta = 1599800$ and $\lambda = -213.1$.

The errors were generated in python with the package *scipy* and the command $scipy.stats.fisk.rvs(\beta, \lambda, \alpha)$ and $scipy.stats.cauchy.rvs(\mu, \sigma)$ for the Log-logistic (also known as Fisk distribution) and Cauchy PDF respectively. After generating the errors, the values are multiplied by the noise magnitude which is the standard deviation of the original data error. There was also the need to clean the data in order to respect the building chamber and for $P_V < BB_V$.

4. Results and Discussion

In the first subsection, *Case Study*, the cost model described in the *Methodology* chapter will be applied to a selected case study with the aim to estimate the Additive Manufacturing and Subtractive Manufacturing total costs and its main cost drivers. In the subsection, *High Volume Production*, the data generated in the *Methodology* section will be analyzed by both cost models in order to understand the best option between AM and SM for high volume production.

4.1. Case Study

For the case study, the piece selected is an APU (auxiliary power unit) air inlet mold. Currently, the piece weighs approximately 80 kg and is made of stainless steel. Its high weight requires lifting equipment to move the mold between stations which adds to the overall production time. In order to improve its ergonomy and reduce lead time, the mold was produced by additive manufacturing.

For the additive printing, the mold was separated into 7 individual pieces: the base, 5 pieces that compose the neck, and the top. The components were printed in FDM, in a Fortus 900 mc (which has the largest build size of any FDM printing system).

For this project, the chosen material is ULTEM 1010. The material properties assure structural stability of the piece when faced with high pressure and temperature, which is the state for this case study since the place is cured in the autoclave. ULTEM 1010 also presents low porosity so it doesn't compromise the final piece and the mold itself. The printing project required a volume 5145 cm^3 of material for the main parts and an extra of 944 cm^3 for the support structure. The total printing time was 136 h.

4.1.1 Cost model application

Starting with additive manufacturing, the indirect costs are described first. Being this the study of a single part, and considering that the indirect costs are distributed over the total production volume, the same needs to be simulated. The average working hour considered is of 30 hr per week, 50 weeks per year. This way, the total indirect costs can be described in $\$/hr$ and added to the total production cost for each individual piece, depending on its processing time.

Table 5: AM: Indirect Costs

Variable	Value	Unit
	AM Machine	
Machine	Fortus 900 mc	-
M_C	400 000	$
M_L	8	year
	Man. Aux Costs	
-	2 139	-
S_L	8	year
Aux_c	1 426	$/year
Aux_m	28 223	$/year
Aux_{rent}	139	$/m^2
Aux_{ba}	100	m^2
$Total_{Ind}$	62,36	$/hr

The direct costs are presented in Table 6. The values were obtained from the CODI company that produced the mold. As specified at the beginning of the chapter, the machine used is a Fortus 900 mc from Stratasys and the material Ultem 1010, a new material that offers a high tensile strength an weight reduction when compared with commonly used metal alloys.

Table 6: AM: Machine, material, energy, and labor specifications

Variable	Value	Unit
	AM Machine	
Machine	Fortus 900 mc	-
BC_x	914.4	mm
BC_y	609.6	mm
BC_z	914.4	mm
BC_V	506 249 976	mm^3
L_t	0.254	mm
	Material	
Material	Ultem 1010	-
M_{dens}	1.28E-6	kg/mm^3
M_c	140	$/kg
	Energy	
SEC_{AM}	86.6	MJ/kg
E_R	0.0225	$/MJ
	Labor	
L_r	15	$/hr

The total mold volume is 9 983 340 mm^3. The lattice structure used to reduce weight and save on material cost allow for a volume reduction of 51%. The total volume used in the cost model is then 4 891 836 mm^3.
There is an alteration that needs to be made to the cost model regarding the building time estimation for this case study, as this part was produced using the process Fused Deposition Modeling. The equation used is

$$T_{build} = 0.005390527 + 0.064608959 * Surf_{area} + 0.102169623 * P_V - 0.011981463 * XY - 0.001236407 * BB_z * Surf_{area} \quad (16)$$

,where XY is the projected area of the part to the working plane (Amini, 2014).
Using this equation, the estimated time is 132.47h which has a 3% error from the real building time of 136h.

For subtractive manufacturing, there was no information about the machine. After some research in CNC selling websites, it is concluded that an average CNC milling machine costs around $250 000 and that the Consumables (tools) and Maintenance Cost accounts for 30% of the machine value [11].

Table 7: SM: Indirect Costs

Variable	Value	Unit
	AM Machine	
Machine	CNC milling	-
M_C	250 000	$
M_L	8	year
	Man. Aux Costs	
Aux_{cost}	75 000	$/year
Aux_{rent}	139	$/m^2
Aux_{ba}	100	m^2
$Total_{Ind}$	80,1	$/hr

The mold was machined in two separate parts: the bottom part and the top part. The bottom part has a volume of 6 870 450 mm^3 and, considering its dimension, can be manufactured from a 500x400x300mm block of material. The top part has a volume of 3 112 890 mm^3 and can be manufactured from a 300*200*60mm block of material.

Table 8: SM: Machine, material, energy, and labor specifications

Variable	Value	Unit
	Material	
Material	Stainless Steel	-
M_{dens}	8E-6	kg/mm^3
M_c	2.5	$/kg
	Energy	
SEC_{SM}	50	J/mm^3
E_{sb}	kWh	
E_R	0.0225	$/MJ
	Labor	
L_r	15	$/hr

4.2. Cost Model Results

The results obtained after applying the cost model were clear and conclusive and are presented in Figure 1 and 2 for subtractive and additive manufacturing.

Subtractive					
Total Cost					
		per piece		per year	percent
Main Machine Cost	$	156,25	$	31 250,00	11%
Auxiliary Cost	$	223,54	$	44 708,00	16%
Material Cost	$	960,00	$	192 000,00	68%
Energy Cost	$	42,87	$	8 573,19	3%
Labor Cost	$	36,00	$	7 200,00	3%
Total Cost	$	1 418,66	$	283 731,19	100%
Direct Cost					
Material Cost	$	960,00	$	192 000,00	92%
Energy Cost	$	42,87	$	8 573,19	4%
Labor Cost	$	36,00	$	7 200,00	3%
Total Cost	$	1 038,87	$	207 773,19	100%

Figure 1: SM Cost model result.

Additive					
Total Cost					
		per piece		per year	percent
Main Machine Cost	$	250,00	$	50 000,00	15%
Auxiliary Cost	$	322,05	$	64 409,80	19%
Material Cost	$	1 087,94	$	217 588,22	65%
Energy Cost	$	15,14	$	3 028,36	1%
Labor Cost	$	9,00	$	1 800,00	1%
Total Cost	$	1 684,13	$	336 826,39	100%
Direct Cost					
Material Cost	$	1 087,94	$	217 588,22	98%
Energy Cost	$	15,14	$	3 028,36	1%
Labor Cost	$	9,00	$	1 800,00	1%
Total Cost	$	1 112,08	$	222 416,59	100%

Figure 2: AM Cost model result.

For a better distribution of the indirect costs, namely Main Machine Cost and Auxiliary Cost, it is considered the production of 200 parts over the interval of one year.

From a first observation, the cost for producing the mold with subtractive manufacturing is 16% lower than producing with additive manufacturing. The total cost is divided into five main sections: Main Machine Cost, Auxiliary, Energy, Material, and Labor. As can be seen in the last column of Figure 1 and 2, for Subtractive Manufacturing and for Additive Manufacturing, the cost distribution is similar for both cases. For both SM and AM, the main costs resides in the Material purchase and Auxiliary costs. Although the percentage of the total cost is the same, there is a higher cost for AM. The reason is the high machine cost and Maintenance cost needed to operate the AM machine. For this case, the SM machine cost value used is $250 000 while for AM is $440 000, which shows in the final results.

There is an obvious difference in the amount of material needed. This goes in line with the functioning method for SM that starts from a bulk piece and successively removes material until reaching the desired final geometry. This can lead to material waste of more than 80% [4]. When talking about AM, the process is the opposite. It starts from nothing and continually builds material layer by layer. In the end, the only wasted material is the material needed for the support that can be reduced with the right building positioning. Although the high difference in the amount of material, this does not reflect the total material cost. Because there is an opposite difference in the material price, the total material price for AM and SM are similar.

Another value worth referring is the Labor Cost. For the case of Subtractive Manufacturing, the piece needs to constantly be re-positioned and the tools changed. This requires a person to accompany the whole process. For the case of Additive Manufacturing, once the machine starts printing, it does not require any modification, so the Labor Cost during printing is zero.

When considering only the Direct Costs involved, the price of a single piece produced using AM is $1 112, while the price when using SM is $1 038.

4.3. High Volume Production

The first analysis is a cost trend plot with all the N samples produced with the three subsets regarding C_r.

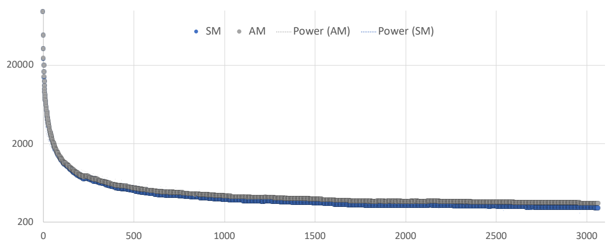

Figure 3: Cost trend.

By analyzing the trend lines, since they are both power functions and the exponent determines the rate of decay, one can conclude that the cost for SM decreases 21% faster than AM. For the N pieces production, SM has a lower average cost of $95 compared with AM of $210.

The indirect cost is a fixed cost that accounts for the machine purchase, so it will only raise the cost but not affect its behavior for the N pieces produced. For this reason, the rest of the study will analyze the direct costs for a better understanding of the costs drivers. The direct cost for AM is $720 996 and for SM $289 289.

An important study to be conducted is the total cost regarding C_r which is represented in Figure 4. A lower C_r implies that for the same Bounding Box Volume, the Part Volume will be lower when compared with a higher C_r piece. And the Part Volume is directly proportional with the piece weight where the ratio is the material density.

Since the AM build is a layer by layer process that starts with no initial amount of material and continuously builds until reaching the desired proportions, it is expected the amount of material needed to be proportional with C_r. Since the Material Cost is one of the main cost drivers, it is also expected for the Total Cost to be proportional with C_r, and this can be in fact evidenced by Figure 4.

For SM, the same behavior cannot be expected. The amount of material needed it is not proportional to the Part Volume but to the Bounding Box Volume. Since it is a subtractive process, it starts with a bulk piece and continuously removes material. In this case, it is the amount of material removed, and thus the energy and labor needed to remove this material, that will be proportional with C_r.

For this case though, the SM cost is almost identical for each C_r group. There is extra weight that comes with a higher C_r and so a higher material cost. For the case of SM, the higher material cost is compensated by a lower energy need as there is less material to remove. For AM the same cannot be stated as the price of material is extremely high, precisely ten times higher than SM.

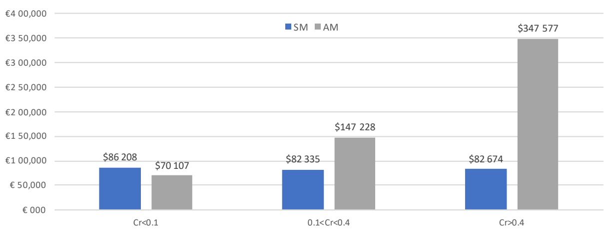

Figure 4: Total cost regarding C_r.

Direct costs, Material, Energy, and Labor, will be individually analyzed in the next subsections.

4.3.1 Material

For both cases, the great percentage is attributed to the material cost. For the parts produced with subtractive manufacturing there is a high buy-to-fly ratio. The price of material considered, \$2.5 for solid form and \$25 for powder form of stainless steel, adds to the total cost of additive a bigger expense than the extra weight needed for subtractive. Three different cases were analyzed to better understand the material direct cost: parts with same volume, same material price, and a 57% reduction in volume for additive manufacturing. For the first case, AM is the best option for a compact ratio lower than 0.1, but it surpasses the cost of SM for the rest two groups by two and five times respectively. When considering the same material price, AM is the best option for parts with a compact ratio lower than 0.4. As for the last case, when considering the use of lattice structure that allows for a 57% volume reduction, AM is the best option for parts with the lower compact ratio and is only 6% higher than SM for parts with a compact ratio between 0.1 and 0.4.

4.3.2 Energy

The energy values present a big discrepancy, being the total energy cost for AM (\$50 138) more than five times higher than the for SM (\$8 968). For AM, there is more energy needed for a higher C_r as that implies a higher volume and thereafter a higher mass. For SM, a higher C_r implies less material to remove and so it is expected the energy to decrease as the C_r value increases. The discrepancy between the AM and SM values is explained next.

The Specific Energy Values used for SM and AM were retrieved from Yoon et al.,2014 [15]. For SM, the value used is 50 J/mm^3 (Table 5, Milling, Steel, in [15]) and for AM the value is 24.2 kWh/kg (Table 7, Other processes, DMLS, in [15]). The material used in this study, 316L stainless steel, has a density of 8E-6 kg/mm^3. For this material, the SEC for SM is equivalent to 1.73 kWh/kg, which is almost fourteen times lower than AM SEC.

4.3.3 Labor

The labor accounts for 4% and 21% of the total cost for AM and SM respectively. It is the only direct cost where SM is more expensive than AM.

The reason is that for AM the only labor needed is for setting the machine and post-processing. Once the machine starts building, there is no human assistance needed and the building process runs continuously.

For SM, there is labor involved throughout the process. Starting with setting the machine and the post-processing, there is also the need for human assistance during the process. This involves reloading the piece for the machine to process a different side or changing the tool. The total labor cost for AM is \$27 567 and for SM \$60 417.

5. Conclusions

Relatively to the mold case study, the results were conclusive, there is an obvious choice which is subtractive manufacturing. From an ergonomic point of view, its light weight made the mold unstable while applying the carbon-fiber layers. It was necessary to fixate the mold to the working table which in turn added an extra step to the overall production. Most importantly, this was a special case as the mold has to be able to support high pressures and temperatures during the autoclave curing process. The mold did not pass the test as the final produced part did not meet the dimensional specifications.

From an economical point of view, the additive process turned out to be more expensive. The main cost driver for both manufacturing processes was the material cost. In the case of SM, the main material cost influencer is the amount of material used. The mold presents a buy-to-fly ratio of 4.81 which leads not only to a high initial material weight compared with the final product, but also to high amounts of energy. The total cost for additive manufacturing is $1 684 and for subtractive manufacturing $1 418.

Relatively to the high volume production case where the N generated samples are analyzed, there are several conclusions to be noted. Because additive manufacturing is recognized for its free geometry complexity, the economical cost analysis takes into account the compact ratio of the parts which is directly related to its complexity.

First, considering the total direct and indirect costs involved, the total cost for additive manufacturing for producing the N samples is twice as much as the cost for subtractive manufacturing. While analyzing the total cost regarding the compact ratio, the cost trend is not the same among the the three groups analyzed. For the higher compact ratios, additive manufacturing is the most expensive option but that is not the case when the compact ratio is lower than 0.1. This goes in line with the existent research, concluding that additive manufacturing is in fact the best option for parts with high complexity.

When considering only the direct costs involved, Material, Energy and Labor, AM presents a higher cost for all with the exception of Labor. The constant need to have a worker to reload the part and change the tooling for subtractive manufacturing increases the cost. For Material and Energy, although AM presents a higher cost, when analyzing the values regarding the Compact Ratio variable, AM is actually the best option for parts with a low compact ratio.

The results agree with the current literature and conclude that additive manufacturing is the best option for parts with high geometric complexity when compared with subtractive manufacturing.

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