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COMPARATIVE COSTS OF ADDITIVE MANUFACTURING VS. MACHINING: THE CASE STUDY OF THE PRODUCTION OF FORMING DIES FOR TUBE BENDING

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Abstract

Additive manufacturing processes for metallic components become economically viable when they substitute conventional processes that make use of moulds and dies to produce casting or semi-finished parts with high added value. Common examples are: i) components in aerospace or energy sectors obtained by investment casting in high-temperature alloys; ii) personalized prostheses and implants in biocompatible metals in the biomedical sector. In both cases, the annual batch size is low and often limited to a single or few pieces. However, for many other sectors decision making for process substitution from conventional to AM processes requires a correct economic analysis. The cost of AM processes depends also on the use of technological advantages. The paper explores the economic feasibility of selective laser melting (SLM) process when producing tube-forming tools. The analysed industrial case addresses the whole annual production of bending tools, traditionally made by milling from a solid block. The aim of this work is to identify the levers of the process that make additive production advantageous, even in more traditional sectors like tooling when different tool materials are used (namely a tool steel and a bronze alloy) and when hybrid manufacturing (subtractive plus additive) is carried out.

1 Introduction

Metal additive manufacturing technologies provide several advantages in terms of shape and details obtainable on the single product. This enables highly customizable production and development of new products taking advantage of such geometrical flexibilities. Biomedical implants are an example to where highly customized production is relatively easy to justify in terms of cost. Weight reduction and in-process assembly of diverse components is another factor to the adoption of these techniques in the aerospace and aviation sectors. However, metal additive manufacturing processes in general, and selective laser melting (SLM) in particular, are highly costly production options compared to more conventional ones. The high capital cost of the machines and low productivity rates are the main reasons for the high production costs. Indeed, when metal additive manufacturing processes are required to be evaluated as substitutes to existing manufacturing routes composed of conventional processes, an economical evaluation is of vital importance. Tooling applications possess peculiarities, such as low number components produced with a large variety of shapes and sizes, that might suggest the substitution of the conventional process route with an additive manufacturing (AM) process chain. However, although the premises may appear highly suitable for AM, economic conditions may not necessarily be competitive to justify the substitution of conventional machining processes.

Several works have been reported in literature dealing with cost modelling of additive manufacturing (AM) processes [1]. Indeed, these models have been developed to confront AM technologies with conventional ones. Commonly, they conclude that small lot production of highly complex parts is more convenient with AM processes compared to casting or plastic deformation, which are post-processed to the final shape. The absence of dedicated tools and moulds within the AM process is a determining factor for reduced costs. On the other hand, such a comparison between the AM processes and machining for the production of small lot productions has not received the same amount of attention. Within a conventional production route, machining processes can give net-shape form to simple feedstocks such as bars, plates, and blocks by the use of standard tools. The production of tube bending tools is such a case whereby a small lot of highly variable shapes are produced by conventional machining processes.

Hopkinson and Dickens [2] proposed a cost model for AM processes considering three distinct technologies namely stereolithography, fused deposition modelling (FDM), and laser sintering (LS). The proposed model was simplified as it considered a limited number of input parameters. A main disadvantage is related to the fact that the model considered a single component throughout the whole production, leaving out a key advantage of the AM processes related to diversified production. In particular, the model did not consider the general costs, while it has been demonstrated that they tend to have a higher impact on the final cost as the level of production automation increases [3]. Despite considering a post-processing stage, the model did not include any preparatory phase, which might have a marked impact especially when customized products are concerned. The post-processing stage is considered only in terms of manual labour, whereas the use of finishing machinery is not considered.

Ruffo et al. [3] introduced a model for laser sintering, which can be easily adapted to SLM, due to the similarities between the two technologies. Also in this case, the model is rather simple to implement, yet lacks consideration regarding the post-processing stage, general costs and considered a single component throughout the production. Later on, Ruffo and Hague [4] introduced a modified model considering mixed production. More recently, Rickenbacher et al. [5] proposed a cost model specific to the SLM process. Differently, this model considered a decomposition of the process in different phases, considering the associated cost item. The model also considered the details regarding pre- and post-processing as well as consumables such as process gas and material change. General costs and considerations over mixed production are missing, leaving a margin for improvement for future models. Lindemann et al. [6] also proposed similar improvements. However, also in this case mixed production has been left out and the cost of a single component type has been analysed.

In this work, a new cost model specific for additive manufacturing by selective laser melting is proposed. The case study consisted of the production of customizable tube bending tools with high variability in shape and limited lot over the year. The novel aspects of this model are as follows:

- Cost model considering all the production phases (i.e. pre-, AM, post-production).
- The use of a real industrial case comparing the results to the existing conventional production performance.
- Comparison with a challenging conventional production case with machining, where dedicated tools are not required and small lots are considered.
- Model applied at build job level with mixed products.
- Considering part modifications such as hybrid production and weight reduction enabled by the SLM process.

Table 1 – Nomenclature, definition and units of the terms in the cost models

Symbol	Definition	Units
$C_{T,P}$	Total cost for a generic production process per year	€
C_1	Material cost	€
C_2	Tooling and consumables cost	€
C_3	Equipment cost	€
C_4	Overhead cost	€
$C_{T,Add}$	Total cost for the additive SLM production process per year	€
$C_{T,Pre}$	Total pre-processing cost	€
$C_{T,SLM}$	Total SLM production cost	€
$C_{T,Post}$	Total post-processing and finishing cost	€
$C_{b,Add}$	Total additive SLM production cost per build-job	€
$C_{b,Pre}$	Total pre-processing cost per build-job	€
$C_{b,SLM}$	Total SLM production cost per build-job	€
$C_{b,Post}$	Total post-processing and finishing cost per build-job	€
	SLM PRODUCTION COST	
$C_{b,SLM,1}$	Material cost in SLM process per build-job	€
$C_{b,SLM,2}$	Tooling cost in SLM process per build-job	€
$C_{b,SLM,3}$	Equipment cost in SLM process per build-job	€
$C_{b,SLM,4}$	Overhead cost in SLM process per build-job	€
C_m	Material cost	€/kg
C_{re}	Cost of the re-coater blade	€
C_{plate}	Cost of the substrate plate	€
$C_{gas\ cyl}$	Cost of the argon canister	€
C_{filter}	Cost of the filter cartridge	€
C_C	Capital cost of the SLM system	€
$\dot{C}_{oh}$	Overhead rate for the SLM operations	€/h
L_{re}	Re-coater blade life per build job	#
L_{plate}	Substrate plate life per build job	#
$L_{gas\ cyl}$	Argon canister life per build job	#
L_{filter}	Filter cartridge life per build job	#
V_p	Volume of the part in the build-job	mm^3
V_b	Volume of the build-job (print area x height of highest part)	mm^3
V_W	Volume of un-melted powder in the build-job	mm^3
f	Not-recycled powder fraction	%
ρ_{sol}	Solidified material density	$kg/\ mm^3$
ρ_{pow}	Powder material density	$kg/\ mm^3$
N	Number of parts produced per build-job	#
L	Load factor of SLM system	%
t_{wo}	Capital write-off time for SLM system	h
t_b	Building time per build-job	h
	PRE-PROCESSING PRODUCTION COST	
$C_{b,Pre,3}$	Equipment cost in the pre-processing per build-job	€
$C_{b,Pre,4}$	Overhead cost in the pre-processing per build-job	€
C_{comp}	Capital cost of the hardware and the software licences	€
t_{comp}	Computing time per build-job	h
$t_{wo,comp}$	Capital write-off time for hardware and software licences	h
L_{comp}	Load factor of the computing equipment	%
$\dot{C}_{oh,comp}$	Overhead rate for the computing operation	€
	POST-PROCESSING PRODUCTION COST	
$C_{b,Post,3}$	Equipment cost in the post-processing per build-job	€
$C_{b,Post,4}$	Overhead cost in the post-processing per build-job	€
C_{mill}	Cost of the 5-axis milling machine	€
C_{EDM}	Cost of the wire-EDM machine	€
C_{oven}	Cost of the induction heating furnace	€/kg
L_{mill}	Load factor of the 5-axis milling machine	%
L_{EDM}	Load factor of the wire-EDM machine	%
$\dot{C}_{oh,fin}$	Overhead rate for finishing operations	€/h
t_{mill}	Milling time per build-job	h
t_{EDM}	Wire-EDM time per build-job	h

2 Cost model

The cost model applied in this work is based on the classification of cost terms proposed by Ashby et al. [7], where the total cost per each phase of a generic production cycle $C_{T,P}$ is composed by four terms (as shown in Table 1):

$$C_{T,P} = C_1 + C_2 + C_3 + C_4 \qquad \text{Equation 1}$$

with C_1 material cost, C_2 tooling and die cost, C_3 equipment cost and C_4 overhead cost.

Usually, C_1 accounts for all the materials used and wasted in the process, C_2 accounts for all the tools and dies dedicated to the production of the entire batch, C_3 accounts for the non-dedicated equipment and machine cost and C_4 accounts for the overhead costs including direct costs (i.e. operator and energy), and indirect cost (i.e. administration, maintenance and safety).

In the additive manufacturing with the SLM process the total cost of a product is the result of three fundamental steps: pre-processing, selective laser melting and post-processing. Therefore, the total cost $C_{T,Add}$ is given by three contributions:

$$C_{T,Add} = C_{T,Pre} + C_{T,SLM} + C_{T,Post} \qquad \text{Equation 2}$$

where $C_{T,Pre}$, $C_{T,SLM}$ and $C_{T,Post}$ are pre-processing, SLM production and post-processing costs respectively.

Since the SLM process is usually employed for the production of parts with different geometries and shapes in few quantities within a single build-job, it is convenient to evaluate the costs considering the build-job consisting of different parts rather than a single part. Accordingly, the total costs per build-job $C_{b,Add}$ of all the parts that printed on the same platform is:

$$C_{b,Add} = C_{b,Pre} + C_{b,SLM} + C_{b,Post} \qquad \text{Equation 3}$$

where $C_{b,Pre}$, $C_{b,SLM}$ and $C_{b,Post}$ are pre-processing, SLM production and post-processing total costs per build-job respectively.

2.1 SLM production cost per build-job.

The SLM production cost per build-job $C_{b,SLM}$, which defines the cost contributions related to the AM production step can be formulated as:

$$C_{b,SLM} = C_{b,SLM,1} + C_{b,SLM,2} + C_{b,SLM,3} + C_{b,SLM,4} \qquad \text{Equation 4}$$

where the single terms are:

– Material cost per build-job $C_{b,SLM,1}$

In the SLM process, the material cost includes the powder used to selectively melt the volume of the printed N number of parts in the build job along with their supports and the un-melted powder (which is partially wasted and partially re-used). $C_{b,SLM,1}$ can be further defined as:

$$C_{b,SLM,1} = V_P \cdot \rho_{sol} \cdot C_m + f \cdot V_W \cdot \rho_{pow} \cdot C_m \qquad \text{Equation 5}$$

where V_P is the volume of all the parts and supports in the same build-job, ρ_{sol} and ρ_{pow} the density of solidified material and powder respectively, C_m the powder cost, V_W the volume of the un-melted powder, f the powder fraction which cannot be recycled. The volume of the un-melted powder V_W depends on the build-job volume V_b:

$$V_w = V_b - V_P \qquad \text{Equation 6}$$

where V_b is given by the overall print area multiplied by the height of the tallest part of the build-job.

– Tooling and consumables cost per build-job $C_{b,SLM,2}$

Usually Ashby's model includes in the category C_2 the cost for tooling and dies (which is affected by batch size and cost of tools/dies). However, in SLM production no moulds or dies are used while auxiliary tools and materials are consumed during each build-job, sometimes partially, sometimes totally. For every build job the substrate plate must be partially milled and the re-coater blade deteriorates. Moreover, per each job, a fixed quantity of inert gas (argon) is used and the filter cartridge is consumed. Therefore, $C_{b,SLM,2}$ is re-interpreted as the consumables cost per build-job:

$$C_{b,SLM,2} = \frac{C_{re}}{L_{re}} + \frac{C_{plate}}{L_{plate}} + \frac{C_{gas\ cyl}}{L_{gas\ cyl}} + \frac{C_{filter}}{L_{filter}} \quad \text{Equation 7}$$

where C_{re}, C_{plate}, $C_{gas\ cyl}$ and C_{filter} are the cost of the re-coater blade, plate, argon cylinder and filter cartridge while L_{re}, L_{plate}, $L_{gas\ cyl}$ and L_{filter} the respectively life expressed in numbers of build-jobs.

– Equipment cost per build-job $C_{b,SLM,3}$

The equipment cost per build-job $C_{b,SLM,3}$ can be estimated from the capital cost of the equipment C_C :

$$C_{b,SLM,3} = \frac{C_C}{L \cdot t_{wo}} \cdot t_b \quad \text{Equation 8}$$

once the building time per job t_b, the load factor L (that means the time the machine is operating) and the capital write off time t_{wo} are known.

– Overhead cost per build-job $C_{b,SLM,4}$

This includes the direct cost of the machine operator in addition to the indirect cost associated with floor space, energy and maintenance. In this model administrative costs (safety, administration, legal) are not considered. Hence, the overhead cost $C_{b,SLM,4}$ is estimated as:

$$C_{b,SLM,4} = \dot{C}_{oh} \cdot t_b \quad \text{Equation 9}$$

where $\dot{C}_{oh}$ is the overhead rate.

2.2 Pre-processing cost per build-job

The pre-processing phase is mainly constituted by operations at the computer for elaborating the 3D model, adding supports and applying design for additive rules along with post-processing of tool path and machine instructions. In the present model, the pre-processing cost $C_{b,Pre}$ accounts only for two main terms as:

$$C_{b,Pre} = C_{b,Pre,3} + C_{b,Pre,4} \quad \text{Equation 10}$$

The single terms can be further defined as follows.

– Equipment cost per build-job $C_{b,Pre,3}$

$C_{b,Pre,3}$ is equipment cost of computer and software licences for CAD and CAM processing:

$$C_{b,Pre,3} = \frac{C_{comp}}{L_{comp} \cdot t_{wo,comp}} \cdot t_{comp} \quad \text{Equation 11}$$

where C_{comp} is the hardware and software cost, L_{comp} and t_{comp} are respectively the load factor and time for computing the job file.

– Overhead cost per build-job $C_{b,Pre,4}$

The overhead costs per part is due to the operator cost, floor space, energy and maintenance cost and can be estimated as:

$$C_{b,Pre,4} = \dot{C}_{oh,com} \cdot t_{comp}$$

Equation 12

where $\dot{C}_{oh,comp}$ is the overhead rate.

2.3 Post-processing cost per build-job

The post-processing cost per build-job $C_{b,Post}$ mainly accounts for three operations: 1) part removal from the substrate plate by means of wire EDM (along with support removal); 2) finishing of functional features and surfaces by milling; 3) stress relief and heat treatments.

Cost of consumable material (lubricant and tool inserts mainly) could be neglected while no moulds and dies are used. Therefore, the tooling cost C_2 is neglected and the post-processing cost is reduced to:

$$C_{b,Post} = C_{b,Post,3} + C_{b,Post,4}$$

Equation 13

The single terms can be further defined as follows.

– Equipment cost per build job $C_{b,Post,3}$

$C_{b,Post,3}$ is the cost of the equipment used for the removal and finishing operations (i.e. wire EDM, milling and induction heating oven):

$$C_{b,Post,3} = \frac{C_{mill}}{L_{mill} \cdot t_{wo}} \cdot t_{mill} + \frac{C_{EDM}}{L_{EDM} \cdot t_{wo}} \cdot t_{EDM} + C_{oven} \cdot V_P \cdot \rho_{sol}$$

Equation 14

where C_{mill} and C_{EDM} are the cost of the wire EDM system and 5-axis milling center; with their respective load factors (L_{mill} and L_{EDM}) and operation time per build-job (t_{mill} and t_{EDM}). Furthermore, C_{oven} is the cost of the induction-heating oven per unit of mass treated.

– Overhead cost per build-job $C_{b,Post,4}$

The overhead cost $C_{b,Post,4}$ is linked to the operator , floor space and energy cost and is calculated as:

$$C_{b,Post,4} = \dot{C}_{oh,fin} \cdot (t_{mill} + t_{EDM})$$

Equation 15

where $\dot{C}_{oh,fin}$ is the overhead rate for finishing operation (assumed to be the same for the two finishing operations).

3 Case study: forming dies for tube bending

3.1 Classification of production class: high mix-low volume

The rotary draw bending process is performed on fully electric CNC machines. Figure 1 shows the main elements of a typical rotary tube bending machine.

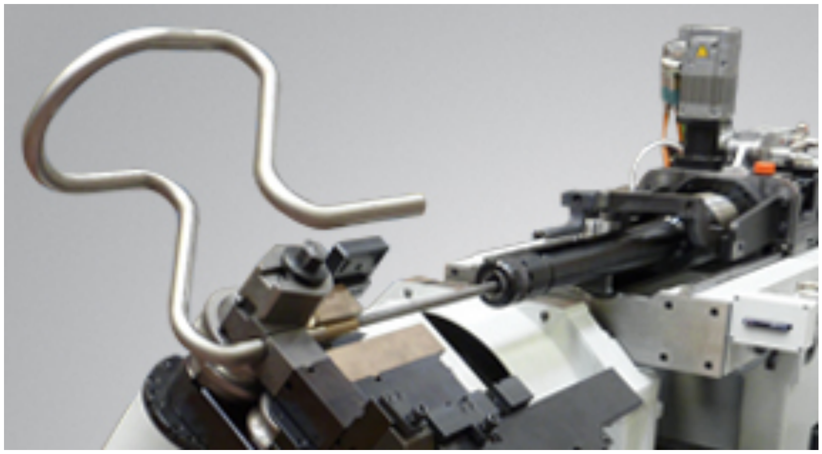


Figure 1: Typical rotary tube bending machine (courtesy BLM Group)

The straight tube is initially clamped by the bending die (Component 1 in Figure 2) and the clamping die (Component 2 in Figure 2), which draws the tube section according to a predefined radius by rotating. A wiper die (Component 4 in Figure 2) acts as a constrain for the straight part of the tube, allowing a controlled sliding of the tube during the drawing operation. The wiper die fills the gap between the tube and the bending die on the inner radius, to avoid the occurrence of wrinkles.

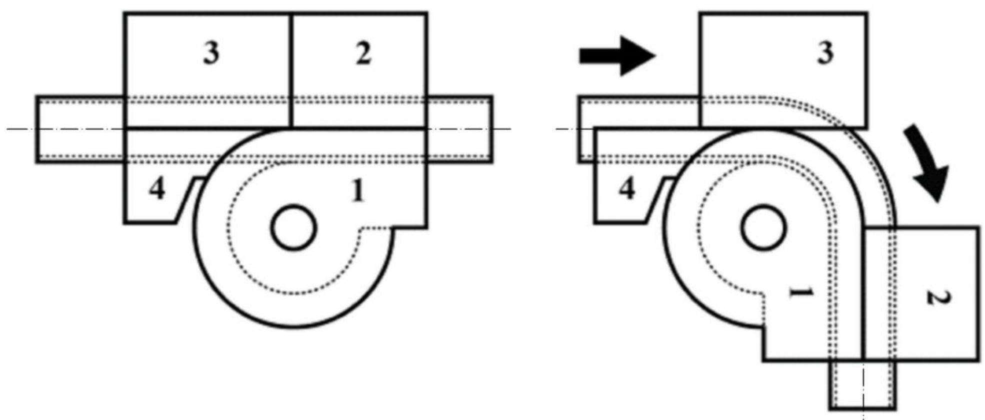
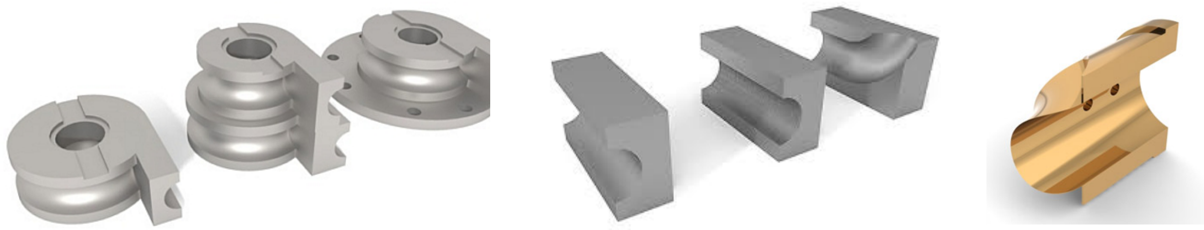


Figure 2:Steps and main components in the rotary tube bending process: 1) Bending die; 2) Clamping die; 3) Pressure die; 4) Wiper die

Clamping and bending dies are made of hardened tool steels. Often, the clamping surfaces are coated or case hardened to increase their wear resistance (see Figure 3a and Figure 3b). On the other hand, the wiper die is made of bronze alloys (see Figure 3c) or more deformable materials in order to avoid sticking and premature breaks. A starter kit of bending, clamping, and wiper dies is included in each bending machine being sold. Similar kits are provided by machine manufacturers as spare parts and consumables.



(a) *(b)* *(c)*

Figure 3: Examples of shapes and material for a) bending dies; b) clamping dies; c) wiper die.

Within this work, the entire production in 2015 of these first kits for machines capable to bend average size tubes was analysed. The dimensional range of the considered tubes was between 12.50 mm and 50 mm in diameter and between 15 mm and 250 mm bending radius. Table 2 summarizes the total die production in 2015 in these ranges.

Table 2: Total production of starter die kits in 2015 with corresponding number of variants and quantity for each die type.

Component	N of variants	Total quantity	Material
Bending dies	78	98	Tool steel - 40CrMnMo7
Clamping dies	130	157	Tool steel - 40CrMnMo7
Wiper dies	79	105	Bronze – Ampco 18
Total	**287**	**360**	

Figures in Table 2 puts in evidence that the production of the starter kits is characterised by a large number of variants (in terms of shape and geometry), which are produced in a small batch sizes (in terms of number of parts per year). Moreover, the bending and clamping dies are machined with a 5-axis CNC milling machine from round bars or prismatic blocks of 40CrMnMo7 cold work tool steel in pre-hardened conditions. After machining the clamping surfaces, these are ion nitrided and eventually mirror-like polished. On the other hand, the wiper dies are obtained through5-axis CNC milling machining of the commercial bronze alloy Ampco 18. Successively, the functional surfaces are mirror-like polished. Both nominal and chemical compositions of 40CrMnMo7 tool steel and Ampco 18 bronze are given in Table *3*.

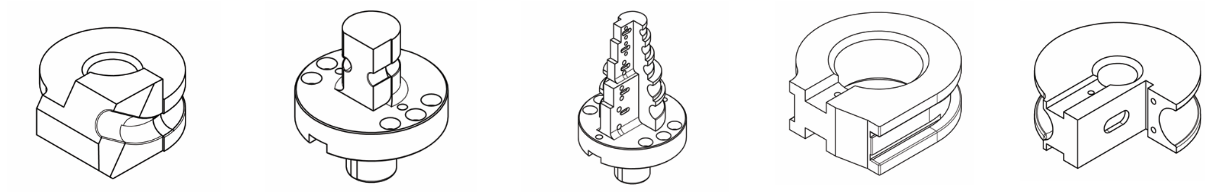
Table 3: Nominal chemical composition of the materials originally used (wt. %)

Material	C	Si	Mn	P (max	S (max	Cr	Mo	Al	Cu	Fe
40CrMnMo7	0.30-0.45	0.20-0.40	1.30-1.60	0.035	0.035	1.80-2.10	0.15-0.25			Bal.
Ampco18								10.5	Bal.	3.5

The analysed industrial case is representative of a high mix-low volume production. This explain why 5-axis CNC milling machining is the method actually employed to produce all the three classes of dies. Milling allows flexibility in terms of shapes and materials as well as a medium productivity without requiring expensive moulds and dies.

3.2 Families of bending, clamping and wiper dies

Given the large variability in shapes and material of the investigated components, the bending, clamping and wiper dies were grouped in families similar in geometry, material, manufacturing process and function. The bending dies were grouped into five families (as shown in Figure 4) whose batch size for the year 2015 is listed in Table 4 along with their weight and height (on the plate).



(1) (2) (3) (4) (5)

Figure 4 - Families of bending dies: 1) shaped; 2) single-block; 3) multi-block; 4) complete; 5) with inserted tooling

Figure 4 and Table 4 evidence similarities in the shape, weight and height for code 1, 2 and 5 while code 3 is significantly more complex in shape, heavier and taller. On the other hand, code 4 is the smallest, lightest and shortest.

Table 4 - Families of bending dies: yearly quantity, weight and maximum height (on the SLM platform)

Nomenclature	Code	Quantity	Weight [kg]	Height[mm]	Total weight [kg]
Shaped	1	3	4.125	124.7	12.38
Single-block	2	8	3.414	127.1	27.31
Multi-block	3	4	4.593	175.4	18.37
Complete	4	63	1.957	110.1	123.29
With insert	5	20	3.279	133.1	65.58
Total		**98**			**246.93**

The clamping dies are classified in two macro-groups: clamping dies to be fixed on the bending die (therefore without a base as support) and clamping dies with a prismatic base as a support. The clamping die to be fixed on the bending die in Figure 5 is a tool that is inserted on the correspondent bending die (see Figure 4e).

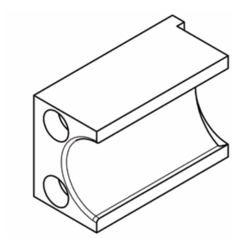
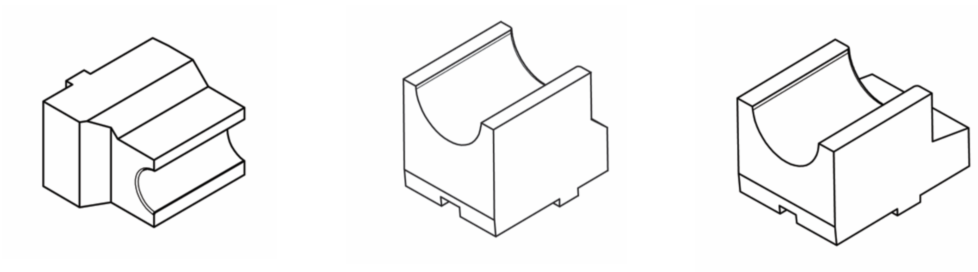


Figure 5 – Insert clamping dies for bending dies

Clamping dies with a prismatic base are characterised by a standard support with a prismatic shape and parametric dimensions, that can be grouped in three classes: small, medium and large (see Figure 6).



(a) *(b)* *(c)*

Figure 6 - Families of hybrid clamping dies: a) small; b) medium; c) large

Since the base of the clamping dies in Figure 6 has a prismatic and simple shape, the SLM processing allows for two alternative approaches: 1) fully additive through SLM; 2) hybrid (subtractive + additive) sequence in two steps (as shown in Figure 7): machining of the support (see Figure 7b) through conventional 5 axis CNC milling process and additive manufacturing of the personalized upper part through SLM process directly onto the support surface (as indicate Figure 7c). To this purpose, an *ad hoc* platform is required, which houses the machined supports and aligns the parts in the right position for the SLM process. A preliminary cost analysis, here not reported for the sake of briefness, shown the economic convenience in adopting this hybrid (*subtractive + additive*) solution with respect to the *full additive* alternative.

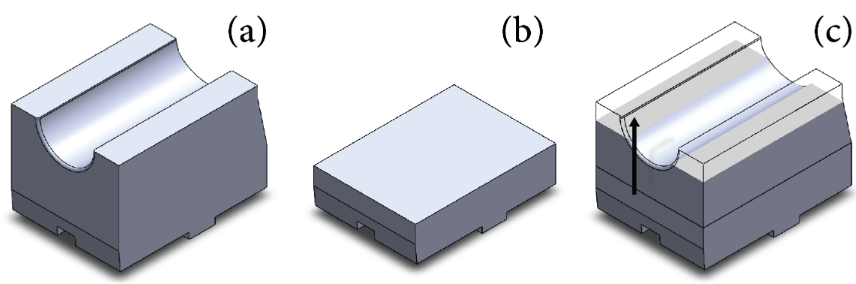


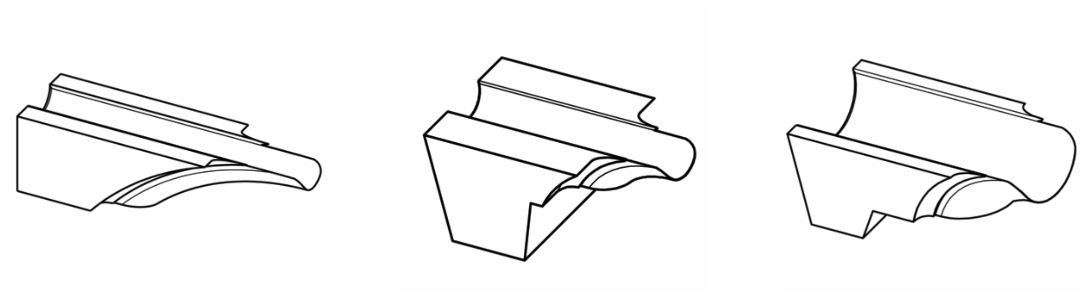
Figure 7 – Production method for hybrid clamping dies: a) hybrid clamping dies made up of a bottom support and a top personalized part; b) bottom support machined by CNC milling; c) top personalized part manufactured by SLM directly on top of the support

The clamping dies results in the four families whose batch size for the year 2015 year is listed in Table 5 together with their weight and height.

Table 5 - Families of clamping dies: yearly production and weight

Nomenclature	Code	Quantity	Weight [kg]	Height [mm]	Total weight [kg]
Insert	1	43	0.738	80	31.73
Hybrid-small	2	18	0.356	30	6.0
Hybrid-medium	3	58	0.534	30	30.96
Hybrid-large	4	38	0.782	30	29.72
Total		**157**			**98.82**

The wiper dies are grouped in three families (as shown in Figure 8) mostly based on the length of the wiper die surface.



(a) (b) (c)

Figure 8 - Families of wiper dies: a) small; b) medium; c) large

The batch size for each of the three families is similar whereas the long wiper die is significantly heavier and taller (as listed in Table 6).

Table 6 Families of wiper dies: yearly production and weight

Nomenclature	Code	Quantity	Weight [kg]	Height [kg]	Total weight [kg]
Long	1	30	1.162	160	34.8
Intermediate	2	36	0.738	98	26.5
Short	3	39	0.729	93	28.4
Total		**105**			**89.9**

3.3 Year and quarter batch size of the entire die production

In the year 2015, the production for tube bending dies was planned on a quarterly base. Therefore, every three months the batch size for the three types of dies was scheduled according to the quantities in Table 7.

Table 7 – Quarterly production lot for bending, clamping and wiper dies

Bending die code	Quantity	Clamping die code	Quantity	Wiper die code	Quantity
1	1	1	11	1	10
2	2	2	4	2	9
3	1	3	14	3	8
4	15	4	10		
5	5				
Quarter total	**24**		**39**		**27**
Year total	**96**		**156**		**108**

3.4 Number of build job and building time estimation

One of the inputs of the cost model is the building time for each build-job t_b. This term depends on the division of the yearly production (in this case in quarter lots) and on the available SLM systems. In this study, a Renishaw AM 250 system (Stone, UK) with a 200 W power modulated fiber laser was used. This system is equipped with an inert gas chamber mounting a 250x250 mm^2 platform.

Two commercial, gas atomized powder types were selected with properties similar to the original 40CrMnMo7 tool steel and Ampco18 bronze. The production of a new powder (in particular for the wiper dies in Ampco18) was not considered because of the high start-up cost of a new powder production. The original 40CrMnMo7 tool steel was substituted by gas atomized 18Ni300 maraging steel powder (Sandvik Osprey, Neath, UK). On the other hand, pure copper powder (LPW, Cheshire, UK) was investigated instead of Ampco18 bronze. Both powders had a particle size between 15 and 45 μm.

The chemical composition of both gas-atomised powders are listed in Table 8. Table 9 provides the standard process parameters indicated by the powder supplier in the case of 18Ni300 maraging steel [8]. On the other hand, only indicative process parameters for pure Cu were considered, due to a lack of process data with the given SLM system.

Table 8 – Nominal chemical composition of the powders employed in the study (wt. %)

Element	Ni	Co	Mo	Ti	Cr	Si	Mn	Al	Cu	O	P	Fe
18Ni300	17.6	9.6	5.3	0.7	0.49	0.1	0.1	0.09	0.05			bal.
Pure Cu									99.9	0.08	<0.15	

Table 9 – SLM process parameters suggested by the industrial practice in case of 18 Ni300 steel and pure copper.

Process parameters	18Ni300	Pure Cu
Laser maximum power (W)	200	200
Point distance (μm)	65	80
Hatch distance (μm)	80	90
Focal position (mm)	0	0
Thickness layer (μm)	40	25
Pulse width (μs)	80	140

The building time depends on the number of build-jobs and the volume of the components per job. In order to maximize the usage of the available build volume, two kinds of dies, bending and insert clamping dies were disposed on the same platform. An optimized mixing of these two categories was obtained by implementing the heuristic nesting of the build preparation software (Magics 20, Materialise, Leuven, Belgium). On the contrary, the hybrid clamping dies and wiper dies were manufactured on separate build-jobs since the first required tailored platforms while the second were built on a different metallic alloy. Therefore, three classes of build-jobs were prepared namely, mixed bending dies with insert, hybrid clamping dies and wiper dies. The final allocation resulted in the total number of build-jobs listed in Table 10. Total building time and productivity levels are also listed.

Table 10 Total number of build-jobs per bending dies with insert, hybrid clamping dies and wiper dies in a quarter.

Build-job class	**Number of build-jobs**	**Total volume (cm^3)**	**Total building-time (h)**	**Productivity (cm^3/h)**
Bending dies with insert	8	8976.6	1173.7	7.6
Hybrid clamping dies	4	2213.4	282.4	7.8
Wiper dies	2	3208.1	653.6	4.9
Total	**14**	**14398.1**	**2109.7**	

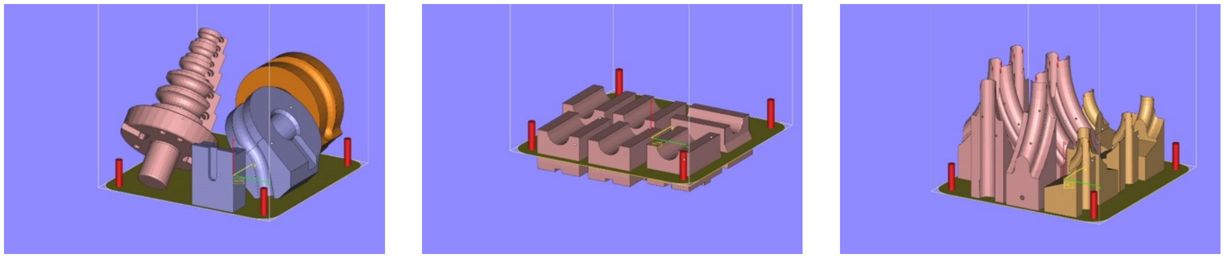
As expected, the SLM processing of maraging steel is more productive than the SLM processing of the copper alloy since the high reflectivity and high thermal diffusivity of copper require slower scanning speed and lower layer thickness.

Starting from the allocation of parts indicated in Table 10, the pre-processing, building and post-processing times per each component for the corresponding die families can be evaluated (as shown in Table 11).

Table 11: Processing time for the classes of bending, clamping and wiper dies detailing the production planning for a given quarter.

Build-job class	**Build-job**	**Volume** V_p **[mm^3]**	**Building time** t_b **[h]**	**Pre-process time** t_{comp} **[h]**	**Post-process** t_{EDM} **[h]**	**Time** t_{mill} **[h]**
Bending dies with insert	1	1,698,662	221.47	10.5	1.8	13.1
	2	1,272,369	165.70	9.7	1.6	7.9
	3	859,566	113.28	6.7	1.4	8.6
	4	859,566	113.28	6.7	1.4	8.6
	5	859,566	113.28	6.7	1.4	8.6
	6	859,566	113.28	6.7	1.4	8.6
	7	859,566	113.28	6.7	1.4	8.6
	8	1,707,732	220.12	10.5	1.4	16.0
Hybrid clamping dies	9	642,991	81.73	9.3	0.0	0.0
	10	703,941	89.34	10.2	0.0	0.0
	11	595,134	75.82	8.6	0.0	0.0
	12	271,360	35.49	3.9	0.0	0.0
Wiper dies	13	1,998,364	418.53	8.7	1.7	15.8
	14	1,209,722	235.05	7.3	1.3	6.7
TOTAL		14,398,105	2109.61	112.0	15.0	102.4

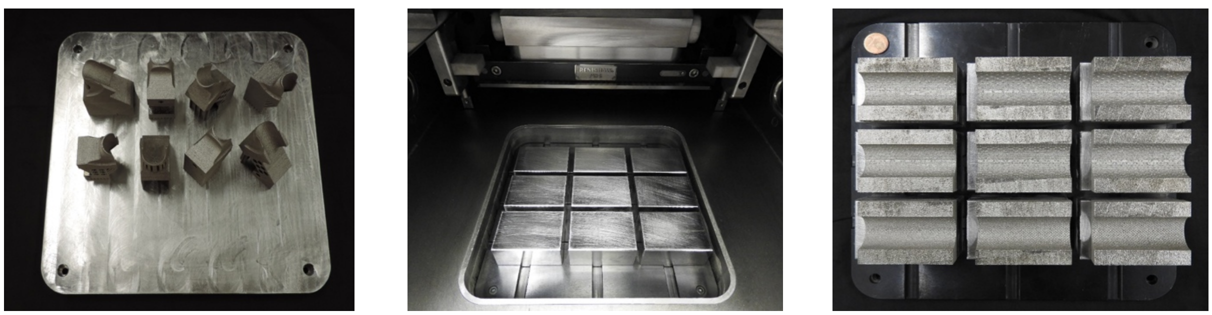
An example of the component layout on the substrate platforms is shown in Figure 9 for each of the three different classes of platforms.



(a) (b) (c)

Figure 9 – Allocation on the platform and nesting of the different families: a) mixed disposal for bending dies and insert clamping dies in maraging steel; b) platform with hybrid clamping dies in maraging steel; c) platform with wiper dies in pure copper.

Figure 10 shows representative moments of the SLM production: the wiper stand-alone platform, the hybrid plate with support bases ready for the SLM processing and the hybrid clamping dies realised.



(a) (b) (c)

Figure 10 – Representative moments of the tube bending die production in a mixed and hybrid configuration: a) wiper stand-alone platform, b) hybrid plate with support bases ready to be SLM printed, c) hybrid clamping dies at the end of the SLM process.

From the data collected by AddMe Lab, the laboratory for additive processes of the Mechanical Engineering department of the Politecnico di Milano with a Renishaw AM 250 machine indicates that a maximum load factor of 0.77 can be considered for the SLM process . Therefore, considering a maximum number of hours per year of 8438.4 and a maximum load factor of 0.77, the demand of build jobs in Table 11 is satisfiable by two Renishaw AM 250 systems. A single AM 250 machine with a load factor of 0.96 would be required, whereas with two AM250 the load factor is reduced to 0.48. Therefore, two SLM machines are considered in the present study although their production would be under-loaded.

5 Cost model analysis

Table 12 includes a detailed list of the main costs and load factors used in the model. The listed values are in line with literature and the data from the industrial partners of the AddMe Lab[9].

Table 12 – Main costs and load factors used in the model

Symbol	Cost	Symbol	Cost
C_m Cu	95 €/kg	C_{comp}	11,600 €
C_m 18Ni300	69 €/kg	L_{comp}	5.1 %
C_{re}	2.50 €	$t_{wo,comp}$	5 years
C_{plate}	241.50 €	$C_{oh,comp}$	20.98 €/h
$C_{gas\ cyl}$	60 €	C_{mill}	630,000 €
C_{filter}	27 €	C_{EDM}	175,000 €
C_C	500,000 €	C_{oven}	1.46 €/kg
C_{oh}	8.69 €/h	L_{mill}	20 %
L_{re}	3	L_{EDM}	10 %
L_{plate}	12	$C_{oh,fin}$	20 €
$L_{gas\ cyl}$	4		
L_{filter}	1		
f	5.4 %		
ρ_{sol} Cu	7450 kg/m^3		
ρ_{sol} 18Ni300	8100 kg/m^3		
ρ_{pow} Cu	3955 kg/m^3		
ρ_{pow} 18Ni300	4300 kg/m^3		
L	48 %		
t_{wo}	8 years		

The cost analysis applied to the overall annual production allows to conclude that the selective laser melting is more expensive than the conventional milling production process. In comparison, the SLM additive process results being 60% more costly, as shown in Figure 11.

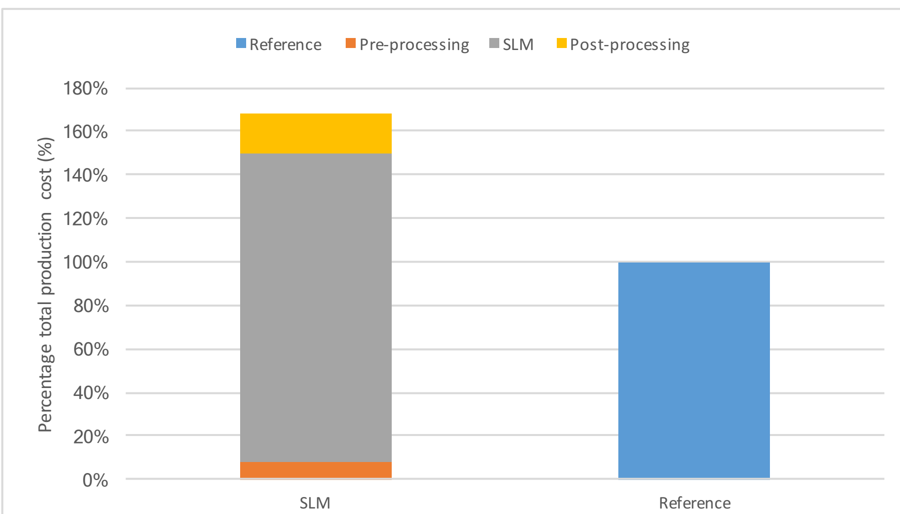


Figure 11 – Total cost of the SLM annual production in respect to the total cost for traditional production

Overall, considering the AM production chain, the cost relative to the SLM process resulted as the higher cost, whereas pre- and post-processing costs were responsible for only 13% of the production total cost ($C_{T,Add}$, as indicated Figure 12). The contribution given by the four terms to the SLM total cost ($C_{T,SLM}$) is presented in Figure 13. The major cost driver consists in the equipment cost (52% of the total SLM cost), while the overhead costs are the second term (30% of the total cost).

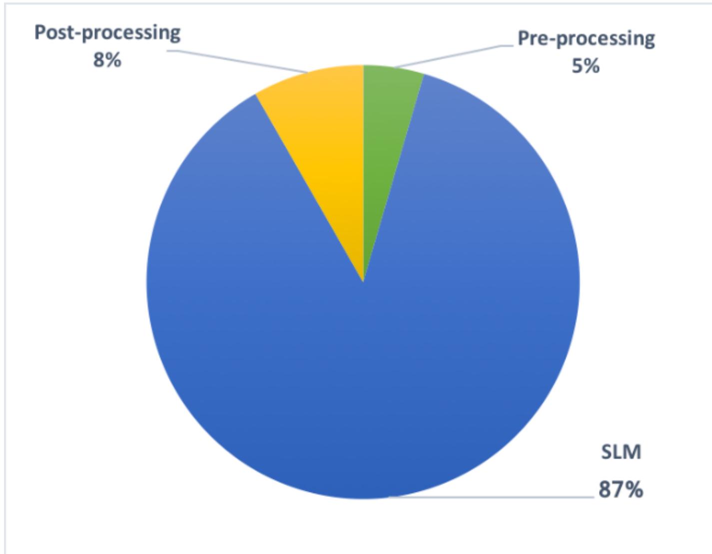


Figure 12 - Division of the production total cost ($C_{T,ADD}$) in the tree steps: pre-processing, SLM and post-processing

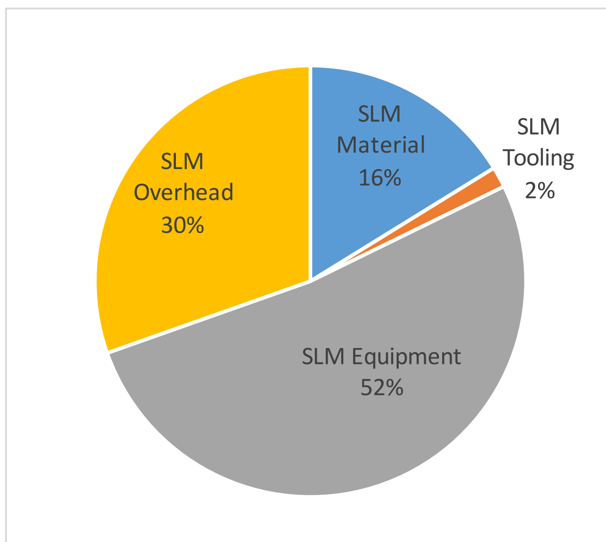


Figure 13 - Division of the total SLM production cost ($C_{T,SLM}$) for cost terms.

Contrarily to expectations, the material cost accounts for only 16% of total cost. This is due to the relatively low cost of maraging steel powder, since 77% of the build volume required it (whereas pure copper powder was limited to the remaining 23%). With reference to more demanding fields, such as aerospace and biomedical, where more costly powders are commonly used (such as titanium or nickel-based alloys) in the present study the cost of the powder was not a predominant lever. Finally, the lowest contribution to the total SLM production cost was related to the tooling cost since the cost of goods and materials consumption during build-jobs is almost negligible.

Figure 14 shows the cost analysis at build-job level. Orange bars are the reference total production cost in for the milling process. The differences are both related to the SLM productivity and the cost of the same component produced by the conventional method. Indeed, build no 1 and 8 are characterized by similar build times and volumes. Hence, the production costs through SLM are similar. However, the products obtained in build job 8 cost much less obtained conventionally, resulting in a much higher relative cost.

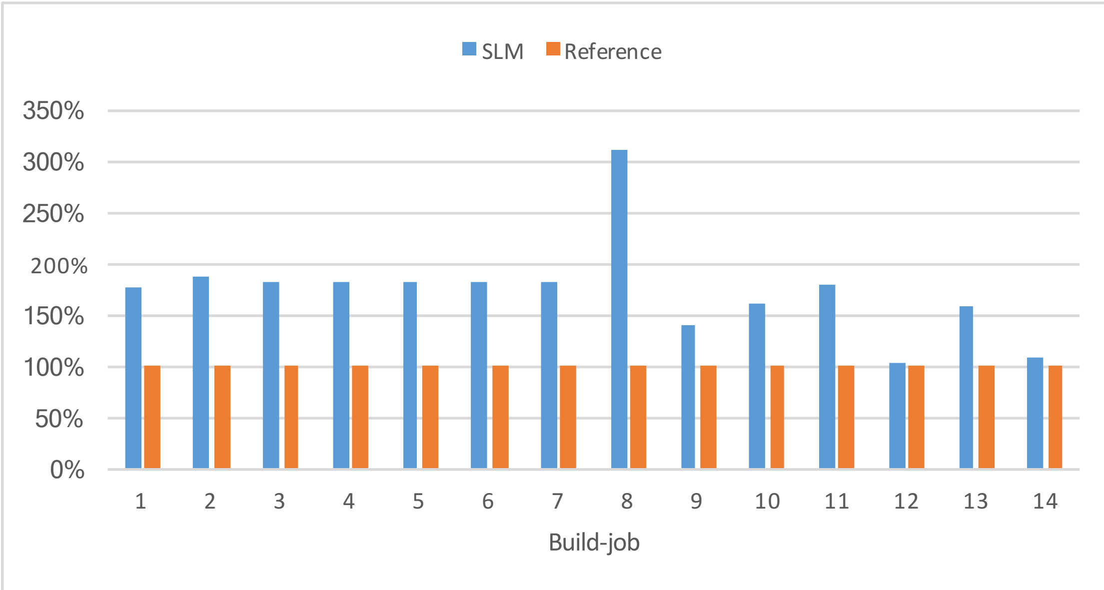


Figure 14 – Cost comparison per build-job

In order to assess the impact of the most significant inputs of the cost model on the total production cost, a sensitivity analysis was performed. One-factor-at-a-time approach was selected in this initial stage. From the previous analysis, the cost inputs worthy to be explored are the parameters which regulate the equipment $C_{b,SLM,3}$ and overhead $C_{b,SLM,4}$ costs respectively. Hence, the SLM capital cost C_C and the load factor L in Equation 8 were varied. The building time present in Equation 8 and Equation 9, was varied as well. t_b in fact, influences the process productivity once the build volume is assigned (see Table 10). A variation in the material cost was also investigated since two possible scenarios might occur. On one hand, the cost of the powder could increase because a new bronze alloy is developed; on the other hand, the cost of powder could decrease due to an increment in the producers of iron-based powder. Finally, the freedom in design allowed by SLM additive process was investigated through the removal of non-essential material and the use of lattice structures. A lattice structure can be applied to the overall volume of the dies. This results in a reduction in the weight of the components thus reducing material consumption whilst maintaining a high level of mechanical performance and surface finishing. This is particularly beneficial and results in considerably lower material costs and a significant reduction in building time. Table 13 presents the different sources of variability considered in the sensitivity analysis and respective levels.

Figure 15 shows the results of the sensitivity analysis. With respect to the baseline total cost of SLM production, the most effective input parameter is productivity. When productivity doubles, the cost of the SLM production cost comes closer to the reference cost (i.e. the actual milling process) but is still not economically viable. The second most influencing factor is the 30% mass reduction which causes a significant reduction on the SLM process cost. If we consider a best case variation of the different factors leading to the most favourable possible situation as underlined values in Table 13, the total production cost is reduced to 60% of the reference cost.

Table 13 – Different sources of uncertainty in the main inputs of the cost model. Underlined conditions depict the best case.

	SLM system cost	Load factor	Productivity	Material cost	Mass reduction
		0.80	200%		
Increment		0.65	150%	150%	
Baseline	500.000 €	0.48	100%	100%	0%
Decrement	400.000 €			50%	15%
	300.000 €				30%

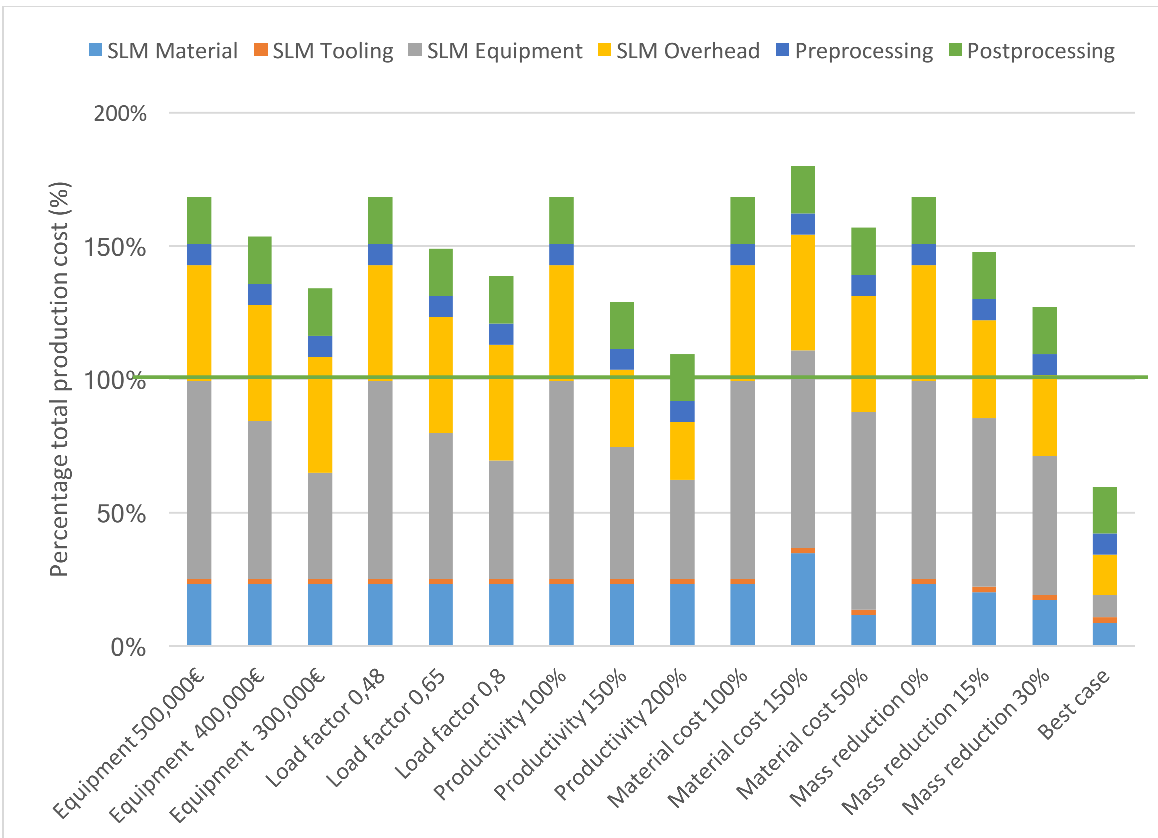


Figure 15 - Variation of different influence factors on the total production cost

6 Conclusions

In this work, a dedicated cost model for a production route consisting of pre-, SLM, and post-processing stages has been developed. The developed model was applied to a case study consisting in the production of tube bending tools with a large variation in type and small lot size. Different possibilities such as the production of the components without any geometrical modifications, use of hybrid production, and weight reduction were analysed. The main results can be summarised as follows.

- In the case of adopting the SLM process without any geometrical modifications to the parts, the AM process is not economically viable compared to the conventional route based on machining.
- The cost decomposition depicts that the SLM processing step is the most influencing factor, which increases the overall part cost.

- The AM process may become economically viable with the current component design. with an increase in the productivity of SLM systems (for example thought the use of multiple lasers) and reduced machine cost.
- The factor which is most difficult to assess is the added value to the produced parts and therefore stands out as the main challenge for the viability analysis. Reduction in mass and light-weight design are useful in terms of increased productivity (reduced build time due to reduced scanning path), in addition to an improved product performance. Such assessment therefore requires an analysis from the product life cycle point of view.

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