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A New Mixed Production Cost Allocation Model for Additive Manufacturing (MiProCAMAM)

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ABSTRACT

Additive Manufacturing (AM) maturity allows diffusion of this technology in conventional production environments. In the decision to adopt a new technology, production costs are one of the most important factors to analyse, even if it is not developed enough yet. Several cost models for AM have been proposed, but each of them focuses on a specific aspect of the process, lacking the ability to consider the effective costs associated with AM, i.e. regarding AM as part of a more general production context. This study develops a cost model that evaluates process costs of AM for relevant technologies such as stereolithography, selective laser sintering and electron beam melting. The proposed cost model allows estimation of the total cost per part; it is worth noting that the parts produced have different sizes, quantities and complexity characteristics, but the objects are all fabricated in the same build job. Nevertheless, it is important to note that the proposed cost model not only considers the AM working costs but also the pre- and post-processing steps directly linked to the AM building phase. The integration of AM on the shop floor is witnessed by the introduction of an index such as the Overall Equipment Effectiveness (OEE) index, which allows this evaluation to be more connected to real production system issues. At the end of the paper, an experiment to compare the results of the proposed model with those of previous studies is reported.

Keywords: Additive Manufacturing, Additive manufacturing cost model

INTRODUCTION

Additive manufacturing is a layer-by-layer fabrication technology that allows the formation of solid objects typically by using a laser beam or an electron beam. The American Society for Testing and Materials (ASTM) defines AM as a collection of technologies able to ‘join materials to make objects from 3D model data, usually layer upon layer, as opposed to the subtractive manufacturing methodologies’ (ASTM, 2012). The idea to create solid objects layer by layer comes from Charles Hull who, in 1986, obtained a patent for production of 3D objects using stereo-lithography (Hull, 1986).

Prototyping was the first application of this new technology. Originally AM allowed only the production of polymeric, resin or wood objects. Mechanical performances, dimensional and surface accuracy were low in quality. For this reason, it was possible to use the technology only for functional tests, aesthetic effect verification, ergonomics, easy handling and workability. Due to AM, the prototyping work became Rapid Prototyping (RP), which aims to realize prototypes quickly using additive technologies. ‘Rapid’ is related to the possibility of realizing objects in a shorter time than traditional systems and a subsequent time to market reduction for the development of new products.

From the beginning of this technology, it is possible to individuate materials such as the polymeric ones, with which the comparison with traditional production methods was first studied. AM in the first years of the new century was compared with injection moulding (IM) of polymeric objects. Hopkinson and Dickens showed that, for some geometrical analysis, it is more economical to use layer manufacturing methods than traditional approaches for production (Hopkinson and Dickens, 2003).

Over time, the growth of AM mechanical performances (Brugo et al., 2016; Huynh et al., 2016; List et al., 2014; Ma et al., 2016; Ordás et al., 2015; Park et al., 2014; Shamsaei et al., 2015; Thompson et al., 2015; Wang et al., 2015, 2016; Witherell et al., 2016; Yang et al., 2015) and the possibility of using other materials like metals (Bartkowiak et al., 2011; Baufeld et al., 2010; Gu et al., 2012; Kruth et al., 1998; Mazumdar, 2001; Murr et al., 2010, 2012a, 2012b; Quan et al., 2016; Travitzky et al., 2014; Williams et al., 2011) moved the comparison to metal subtracting manufacturing technologies. Subtractive manufacturing (SM) includes various processes that allow the cutting of solid raw materials to obtain the desired final shape.

A paper by Lindemann et al., 2012 identified some of the advantages and disadvantages of AM. Some advantages of AM are as follows: more flexible development, freedom of design and construction, less assembly, no production tools necessary, less spare parts in stock, less complexity in business because of fewer parts to manage, less time to market for products and faster deployment of changes. Some of the disadvantages are as follows: machine and material costs are high, the quality of parts is in need of improvement, rework is often necessary (support structures) and build time depends on the height of the part in the building chamber. Related to the advantages and disadvantages, it is important to understand that AM technologies have a deep impact on production systems. Production costs, lead time, energy consumption, production scheduling and production mixing are some of the most important aspects by AM.

Diffusion of AM requires a clear understanding of its economic aspects; further, this work aims to focus on those aspects by exploring the most relevant cost models defined on the argument and the building of a new cost model that is able to exploit the strengths of existing cost models, while avoiding their weaknesses or attempting to convert them into opportunities.

LITERATURE REVIEW

Several cost models have been proposed in the past. In this section, we analyse the main existing cost models in order to give an overview of the approaches used by each author, while trying to understand the present limits on this issue.

Hopkinson and Dickens, 2003 (HD) carried out an analysis of the rapid tooling (RT) and rapid manufacturing (RM) costs. The authors developed a technology that allows for the realization of finished products on a large scale. Hopkinson and Dickens reported a cost analysis that compares the traditional manufacturing method of injection moulding with layer manufacturing processes (stereolithography, fused deposition modelling and laser sintering) in terms of the unit cost for parts made in various quantities. The results showed that, for some geometries, up to relatively high production volumes (in an order of a thousand pieces), it is more advantageous to use the layer manufacturing methods. The costs of the parts were broken down into machine costs, labour costs and material costs. Energy was neglected for its low impact on costs.

$$\begin{aligned} Total\ cost\ per\ part \\ &= Machine\ cost\ per\ part \\ &+ Labour\ cost\ per\ part \\ &+ Material\ cost\ per\ part \end{aligned} \tag{1}$$

The proposed model provides a first approximation of the production costs. The work was realized when the technology had not matured; different aspects of Hopkinson and Dickens' research were further developed by other researchers.

The hypothesis of a large-scale production shifts the focus away from prototyping to manufacturing usage of additive technologies. The roughness of the economic model is probably due to the incomplete understanding of technology potential and its low performances.

Later, Ruffo et al. (Ruffo et al., 2006a) analysed the production costs of the same object (lever) used by HD and obtained by laser sintering. Their cost model offers a breakdown of the cost structure in various activities (activity based costing). This approach comprises a definition of the involved activities, calculation of the costs of each activity and summing of each cost. Activity costs are then split into direct and indirect costs. Material is grouped as a direct cost. Labour, machine, production overhead and administration overhead are indirectly allocated. The total cost of a single build is the sum of direct and indirect costs. The direct costs depend on the amount of material used and indirect costs depend on the duration of the process:

$$\begin{aligned} Cost\ of\ a\ build &= Direct\ costs \\ &+ Indirect\ costs \end{aligned} \tag{2}$$

Build time estimation is performed using an empirical estimation algorithm for the SLS process (Ruffo et al., 2006b). This approach is correct only in the case of production of several copies of the same geometry.

In their subsequent work, Ruffo et al. defined a new approach to calculate the cost per part in the case of mixed production of different parts in the same build chamber (Ruffo and Hague, 2007). They proposed three ways to calculate the unit cost of the parts: the first based on the parts volume, the second based on the cost of building a single part and the third based on the cost of a part built in high-volume production. These approaches allow for the allocation of the building costs of each of the different parts in the same build job.

Ruffo and Hague used a single allocation criterion to split build costs between each part; we think it is more accurate to use different allocation criteria to allocate costs of each productive step for each part. Rickenbacher et al. will use this approach in their cost model.

Baumers et al. (Baumers, 2012; Baumers et al.), (Baumers et al., 2012) were the first to examine the economic and energetic aspects and also the time necessary to realize the AM construction. The highlights of his work are enumerated below:

- Activity-based cost estimator of the type devised by Ruffo et al., 2006a;
- Energy costs grouped as direct;
- Estimate of total build time;
- Accurate analysis of energy consumption.

According to Baumers, indirect costs of AM and the presence of a fixed element of time consumption (for each layer and for each build) make the analysis of the build's unused capacity problem very important. HD assumes that there is no excess of capacity because the chamber of the machine is always full of objects. Ruffo et al. also based their model on the assumption that any excess capacity remains unused. Another important observation of Baumers et al. is that break-even cost models may not be able to capture the capabilities of geometrically less restrictive manufacturing processes to create a complex product. Furthermore, AM faces the disadvantage of not being able to offer the scale economies available to conventional manufacturing systems. Baumers et al. employed an activity-based cost estimator of the type devised by Ruffo et al. The cost estimate for the build is constructed by combining data on the total indirect and direct costs incurred. Unlike Ruffo et al., energy cost is grouped as a direct cost. The total cost for each build can be expressed as follows:

$$\begin{aligned} C_{build} = & \left(\dot{C}_{Indirect} \times T_{Build}\right) \\ & + \left(w \times P_{Raw\ material}\right) \\ & + \left(E_{Build} \times P_{Energy}\right) \end{aligned} \tag{3}$$

where

$\dot{C}_{Indirect}$: Indirect machine cost per hour [£/h];
T_{Build}: Total build time [h];
w: Total weight of the part in the build (including support structure) [kg];
$P_{Raw\ material}$: Price per kg of raw material [£/kg];
E_{Build}: Total energy consumption per build [MJ];
P_{Energy}: Mean price of electricity [£/MJ].

The time and energy estimator, and the grouping of energy in direct costs, make the cost model more accurate than previous ones. Baumers et al., however, do not consider other activities that are indirectly connected to the phase of building but are still relevant from the economic point of view (post-processing and material removal).

The estimate of the building time is obtained by combining fixed time consumption per build (warm-up and cool-down), layer dependent time consumption (time necessary to add powder) and laser deposition time for the sintering of the powder:

$$\begin{aligned} T_{Build} = & T_{Job} + \left(T_{Layer} \times n\right) \\ & + \sum_{z=1}^{z} \sum_{y=1}^{y} \sum_{x=1}^{x} T_{Vovel\ xyx} \end{aligned} \tag{4}$$

where

T_{Job}: Fixed time consumption per build [h/build];
n: Number of layers [-];
T_{Layer}: Fixed time consumption per layer [h/layer];
$T_{Voxel\ xyz}$: Time needed to process each voxel [h/voxel];

In the analysis of energy consumption, Baumers et al. divided the total energy between consumption for each job, single layer energy consumption, geometry dependent energy consumption and a constant base line level of energy consumption throughout the build:

$$\begin{aligned} E_{Build} = & E_{Job} + \left(\dot{E}_{Time} \times T_{Build}\right) \\ & + \left(E_{Layer} \times l\right) \\ & + \sum_{z=1}^{z} \sum_{y=1}^{y} \sum_{x=1}^{x} E_{Vovel\ xyx} \end{aligned} \tag{5}$$

where

E_{Job}: Fixed energy consumption per build [MJ/build];
$\dot{E}_{Time}$: Fixed energy consumption rate [MJ/h];
E_{Layer}: Fixed energy consumption per layer [MJ/layer];
l: Number of layer [-];
$E_{Voxel\ xyz}$: Energy required to process each voxel [MJ/voxel];

Lindemann et al. (Lindemann et al., 2012) investigated and modelled with Event-driven Process Chains all of the relevant cost processes of the AM production process. As a calculation method, they adopted a 'Time Driven Activity-based Costing' approach according to the duration of the activities. Lindemann et al. defined four main process phases as follows:

- Building job preparation;
- Building job production;
- Sample parts and support manual removal;
- Post processing to enhance material properties.

Lindemann et al. identified some things lacking in previous cost models and included the post-processing activity in their costing model, for example, quality control, surface treatment and support removal. The idea of considering the cost of the post processing helps to better understand the economic aspects related to the AM technology.

Rickenbacher et al., 2013 asserted that AM processes are interesting candidates for the replacement of conventional production processes like cutting or casting. The integration of AM processes into a production environment requires a cost-model that allows for the estimation of the real costs of a single part, although it might be produced in the same build job together with other parts of different geometries. The highlights of the proposed cost model are listed below:

- Cost calculation of a single part in a build also in case of a contemporary production of different parts.
- Analysis of the steps involved in the process.
- Cost model including all pre- and post- processing steps.
- Algorithm to calculate the time fraction for each part in the build job.
- Build time estimator derived by a linear regression on 24 different build jobs.

Rickenbaker et al.'s cost model is based on the generic cost model by Alexander et al. (Alexander et al., 1998). The cost of the single part (P_i) is obtained by summing the costs of the seven process steps which as defined below:

$$\begin{aligned} C_{tot}(P_i) = C_{Prep}(P_i) &+ C_{Buildjob}(P_i) \\ &+ C_{Setup}(P_i) + C_{Build}(P_i) \\ &+ C_{Removal}(P_i) \\ &+ C_{Substrate}(P_i) + C_{Postp}(P_i) \end{aligned} \tag{6}$$

where

$C_{tot}(P_i)$: Total manufacturing costs [€].
P_i: Part with i^{th} geometry [-].
$C_{Prep}(P_i)$: Cost for preparing geometry data (orientation and support structures) [€].
$C_{Buildjob}(P_i)$: Cost for build job assembly [€].
$C_{Setup}(P_i)$: Machine set up costs [€].
$C_{Build}(P_i)$: Cost for building up the part [€].
$C_{Removal}(P_i)$: Cost for removing the part from the SLM machine [€].
$C_{Substrate}(P_i)$: Cost to separate parts from substrate plate [€].
$C_{Postp}(P_i)$: Cost for post-processing [€].

Rickenbacher et al. developed an algorithm to calculate the time fraction for each part in the build job, although various heights are involved. In the *Coating time allocation* section, we will use this approach to allocate coating time for each part in the build job.

To estimate build time, Rickenbacher et al. use a linear regression model derived from 24 different build jobs. Our observations on their work are listed below:

- Even if the cost model includes a detailed analysis of the pre- and post-processing related to the AM process, a possible material removal step has not been included.
- Simple and effective algorithm to allocate the time fraction of the total build time to each part is realized.
- Energy consumption and its costs are not taken into account. Because of its impact on costs, this item is not negligible in metal AM processes. For this reason, we disagree with this approach.
- The authors do not explain which cost items are included in the machine's cost per hour. Because of the big impact of the cost item we think it is correct to clarify this aspect.
- The authors predict the building time through a formula of estimation that is calculated with parameters that are very different among themselves. Moreover, in the equation used for the total build time, the calculation does not take into account explicit possible warm-up and cool-down times. These elements could have a big impact on time consumption, for this reason, we think that it is correct to analyse them.

Even if we have doubts on the quality of the time estimator, the deep analysis of pre- and post-processing and the algorithm defined to calculate the time fraction for each part in the build job are important tools for AM technology, and it represents a good step forward in the effectiveness of cost estimation.

The model by Schröder et al. (2015) is the last model to be analysed. To develop their business model, Schröder et al. (2015) use an activity based cost. The relevant activities are defined using interviews submitted to a group of experts (small and medium companies having experience on AM technologies) and researchers on AM. The following seven main process steps were identified:

- Design & planning;
- Material processing;
- Machine preparation;
- Manufacturing;
- Post-processing;
- Administration and sales;
- Quality.

Schröder et al. increased the number of relevant activities included in the cost model. Design and planning have never been included in each of the cost models that have been analysed. AM, in fact, compared with subtractive technologies, requires extra design phases. AM is able to realize complex geometries that are not achievable using a material removal technique, in this case, costs of redesign have to be considered.

The relevant activities included in the cost model, not directly related to the building phase, give an overview on additive processes. We are unsure of the definition of administrations and sales activities. The cost model for AM should include only industrial costs. Administrative and sales costs should be included with all other overhead costs because they do not depend on the adopted technology.

Regardless of the technology in question (DMLS, EBM, LS, SLA and FDM), we can identify similar process phases that allow for the definition of a single cost model that is valid for each of them. Labour, machine, material, power source, warm-up time, build rate and energy consumption are the main activities involved in having an impact on finished product costs. Over time, every author adds something to the previous cost model, increasing its accuracy. Scarce understanding of the technology led older models to not effectively consider all the involved variables (energy consumption and labour). Nowadays, we have more accurate business models.

It is important to make some considerations about energy consumption. HD assumed energy consumption costs to be negligible for its low effect on total cost. This is due to the fact that the additive processes were only suitable to realize polycarbonate and polypropylene objects. Subsequently, energy costs were inserted between overhead costs (Ruffo et al., 2006a). Because of the higher energy consumption necessary to realize metallic objects, it was essential to take into account this cost item: Baumers, 2012 analysed the theme and inserted energy between direct costs.

Older cost models do not consider any post processing steps (Baumers, 2012; Hopkinson and Dickens, 2003; Ruffo et al., 2006a). However, Rickenbacher et al., 2013; Lindemann et al., 2012; Schröder et al., 2015 considered post-processing activities like surface treatments and quality controls. In some cases, AM can be a substitute of SM, whereas in other cases, after the building process using AM, some mechanical characteristics of the parts need to be enhanced (i.e. surface finish and tolerances) (Atzeni and Salmi, 2012). Existing cost models consider the activities directly connected to the building process of AM; however, due to the fact that AM allows the production of end use products, it is important to analyse all the activities involved in the cost model for the calculation of the full cost of a finished part like, for example, redesign costs (Atzeni et al., 2010; Hague et al., 2003) and material removal costs (Manogharan et al., 2016). For this reason, we consider it appropriate to define a production model that includes the post-processing cost of AM (Campbell et al., 2012; Manogharan et al., 2015).

Among all the cost models analysed, only Ruffo and Hague, 2007 and Rickenbacher et al., 2013 analysed the production cost in the case of production of a different geometry in the same build job. Contemporary production of different parts is one of the most important strengths of AM and, for this reason, we think that a cost model should be suitable for this production mode.

All the observations on the existing cost models, and the synthesis of their strengths and weaknesses, can lay the foundations to define and build a new cost model that will help solve the open issues analysed here.

COST ANALYSIS MODEL INTRODUCTION

The AM process includes several activities characterized by different cost items, and for this reason, our model calculates the unit cost per part, including support structures, by summing costs of each process step.

In this section, we introduce MiProCAMAM (Mixed Production Cost Allocation Model for Additive Manufacturing). Before analysing MiProCAMAM, we list its highlights as follows:

- The structure and the coating time allocation algorithm of the type proposed by Rickenbacher et al. (Rickenbacher et al., 2013) is re-used, even if changed in several parts.
- Possibility to calculate unit cost in case of production of different geometry in the same build job.
- The build time estimator of the type devised by Baumers et al. (Baumers et al., 2012) is the starting point for our work.
- Models including pre- and post-processes activities like geometry preparation, build job assembly, machine setup, parts and substrate plate removal are considered.
- Post-processing activities such as thermal and surface treatments, material removal and quality control are considered but neglected in the cost calculation. A single mathematical formulation for all possible post processing could not be exhaustive and out of the scope of the present paper, which aims to analyse cost of production of a part manufactured with the AM.
- The operator hourly cost is based on different skills required for each step.
- Computation of the effect of material change and additional work of using an inert gas during the building step (Rickenbacher et al., 2013) are included in the general calculation.
- Introduction of a waste factor for powder, to consider the possibility of re-using a part of the powder, used in the production.
- Time consumption estimator is modified by the Overall Equipment Effectiveness (OEE), to let the estimator better assess the effective production rate.

We identify, for a generic AM process, 5 process steps:

- Preparation;
- Build job;
- Setup;
- Building;
- Removal.

Afterwards, we will analyse each of them and define their unit cost per part with *i*th geometry.

MiProCAMAM allows for the calculation of the unit cost of different geometries (G_i), with their quantity (N_i), in the same build job.

MODEL FORMULATION

Let us introduce the new model presented here. In **Error! Reference source not found.**, the MiProCAMAM method structure is shown: *Process & geometries information* are the input information; *Build time* *estimator* and *Cost calculator* sections are the computational part of the model and *Process times and performances* and *Production cost* are the output of the model. Afterwards, we show the mathematical formulation of the computational parts and structure of the *Cost calculation tool* developed.

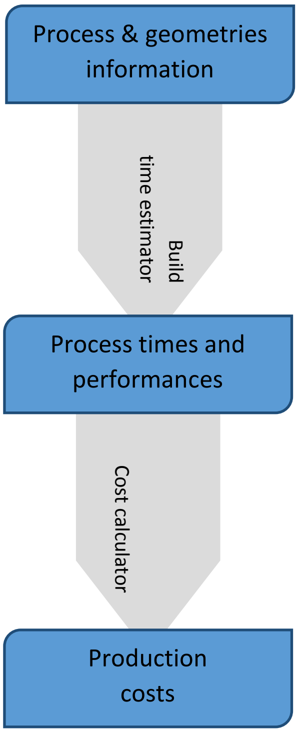


Figure 1: MiProCAMAM structure

Before describing the approach used to calculate the production cost, it is worth making some considerations about the building time. We have to specify that this study's aim is not to define a build time estimator for AM technologies, but to create a valid tool for the production cost estimator. A build time estimator is presently included in many of the AM machines or software solutions, respectively (Rickenbacher et al., 2013); moreover, several authors proposed methods to approximate the building time (Byun and Lee *, 2005; Pham and Wang, 2000; Ruffo et al., 2006b). For this reason, in our cost model an existing approach of other authors who focused their attention on the building time calculation theme will be used.

Total build time

Because different cost items are involved in each AM production phase, it is necessary to define the duration of each of them to correctly allocate costs on each part of the build job. The total build time is obtained by summing the four time consumption phases:

- Warm up;
- Scanning;
- Coating;
- Cool down.

$$T_{build}(G_i) = \big(W.up(G_i) + Scanning(G_i) + Coating(G_i) + C.down(G_i)\big) * \frac{1}{OEE} \qquad (7)$$

where

T_{build}:	Total building time [h].
G_i:	ith geometry [-].
$W.up$:	Warm up time [h].
$Scanning$:	Scanning time [h].
$Coating$:	Coating time [h].
$C.down$:	Cool down time [h].
OEE:	Overall equipment effectiveness [%].

Warm up, cool down and coating phases are fixed time consumption steps for each build job: coating time depends on the number of layers involved, and warm up and cool down depend on machine settings. The only active phase during the building is the scanning one. In this phase, the machine adds material to each object slice.

All time consumption phases are adapted by considering the OEE index. Older cost models and build time estimators only considered the uptime of the machine, neglecting, for example, performance and quality losses. Nakajima and Bodek, 1988 defined six big losses that can have a negative impact on a manufacturing process:

- *Planned Downtime* and *Breakdowns* that impact the Availability of the system;
- *Minor Stops* and *Speed Loss* that impact system Performances;
- Production *Rejects* and *Rejects on Start-up* that impact quality of the products.

These disturbances can be chronic or sporadic according to their frequency of occurrence (Patrik Jonsson and Magnus Lesshammar, 1999). Similar to all manufacturing systems or sub-systems, AM is also affected by losses and disturbances, although two of the six losses defined for generic manufacturing systems do not impact AM: speed loss and rejects on start up.

In a conventional manufacturing system, speed losses depend on the theoretical cycle time and actual cycle time. AM processes, instead, are not affected by these kinds of losses because the cycle time is always the theoretical one set before beginning the work (i.e. warm-up time, coating time and scan speed).

Also rejects on start-up do not affect AM. Additive processes, in fact, have no transitory phases in which production quality is lower. Like conventional manufacturing systems, AM is also affected by losses like: planned downtime, breakdowns, minor stops and production rejects.

Even if we assume an impact of OEE on the AM process, this paper does not aim to develop a specific mathematical formulation of the OEE calculation.

Generic formulation to adapt ideal time consumption by considering OEE impact is as provided below:

$$T_{real} = \frac{T_{theoretical}}{OEE} \tag{8}$$

Previous formulation is valid also for Setup step (T_{setup}), Build job assembly step ($T_{buildjob}$) and Removal step ($T_{removal}$).

This cost model provides an analytical computation for Setup time and its cost. For this reason, in OEE computation, we have to neglect the effect that impacts Planned Downtime.

Warm-up time

Warm-up time is the fixed time consumption for each build that is necessary to warm-up the chamber of the machine and generate correct atmospheric conditions before starting the building step. Allocation criterion of warm-up time is the volume of the part:

$$W.up(G_i) = W.up.build * \frac{V(G_i)}{\sum_i V(G_i) * N_i} \tag{9}$$

where

$W.up$:	Warm-up time [h].
$W.up.build$:	Build warm-up time [h].
G_i:	*i*th geometry [-].
V:	Volume of the geometry [cm^3]
N_i:	Quantity of part with *i*th geometry [-]

Scanning time

Scanning time is the time spent to aggregate the powder following the coating phase of each layer. To define the length of this time we use a parameter (a) that represents the average time to scan a unit area. This parameter, dependent on many machine parameters (such as beam diameter, hatch and laser speed), is obtained from a least squares regression of the time consumption data recorded during the deposition of each layer, using the area scanned per layer as the independent variable (Baumers et al., 2013). Although regression is an approximation of recorded data, we decided to use Baumers et al. approach for its effectiveness.

Scanning time also depends on the number of layers to realise and the average cross section of the part. The number of layers is obtained by dividing the height of the part and layer thickness. In this model, we assume that layer thickness is fixed. The average cross section is obtained by dividing part volume and its height. The calculation mode of scanning times makes no necessary allocation for criteria at this time for a single part.

$$Scanning(G_i) = \frac{N_L(G_i) * Av.cs(G_i) * a}{3600} \tag{10}$$

where

$Scanning$:	Scanning time [h].
G_i:	*i*th geometry [-].
N_L:	Number of layers [-].
$Av.cs$:	Average cross section [mm^2].
a:	Time to scanning unit area [s/mm^2].

$$N_L(G_i) = \frac{h(G_i)}{lt} \tag{11}$$

and

$$Av.cs(G_i) = \frac{V(G_i)}{h(G_i)} * 1000 \tag{12}$$

where

N_L:	Number of layers [-].
G_i:	*i*th geometry [-].
h:	Height of the geometry [mm].
lt:	Layer thickness [mm].
$Av.cs$:	Average cross section [mm^2].
V:	Volume of the geometry [cm^3].

Coating time

For the definition of $Coating(G_i)$ see *Coating time allocation* section.

Cool down time

Cool down time is the fixed time consumption for each build necessary to cool down objects and the machine chamber before the removal step. The duration of this phase directly impacts the mechanical characteristics of the objects realized. The allocation criterion of the cool down time is the volume of the part. Its formulation is the same as defined for 'Warm-up time'.

Coating time algorithm

Coating time is the time spent to add powder on each layer of the build job, and it has to be allocated according to the height of each part. If all parts in the build job have the same height, allocation would be easily realise: it would be correct to allocate the time consumption equally on each part. In the case of building parts with different heights, the best solution it is to use the following algorithm developed by Rickenbacher et al. (Rickenbacher et al., 2013):

1. Ordering of the parts by increasing height.
2. Calculation of the time fraction resulting from the amount of layers up to the smallest part height and dividing it equally among all parts. Another approach would be to divide it in proportion to the corresponding cross-section. This would require a layer-wise analysis of each part resulting in a more complex algorithm inappropriate for industrial use. Therefore, the first approach was chosen.
3. Choosing the next taller part.

4. Calculation of the time for the remaining part of the element that has to be printed, after the smallest one.
5. Division of the calculated time equally on all parts with a part height equal to or greater than the actual part's height.
6. Repetition of steps 3–5 until all the parts are processed.

Coating time allocation

In their paper, Rickenbacher et al., 2013 defined the algorithm to calculate the time fraction for each part without writing its mathematical formulation. This section aims to define it.

First, we have to define $Coating.build$ that is the total coating time of the build that depends on the following aspects:

- Maximum height of the parts in the build;
- Layer thickness:
- Coating time for each layer.

As for the scanning time calculation, we decided to use Baumers et al., 2013 approach to define the coating time for each layer (b).

Subsequently, we have to define the $Coating.ratio_k$, that is, the time fraction of the total coating time for allocation to each class of the different heights of parts in the chamber. Example in **Error! Reference source not found.** shows three classes of height ($k = 3$).

Finally, we are able to define $Coating(G_i)$, that is, the coating time, for each geometry, obtained by summing all the classes of different heights, the ratio between $Coating.ratio_k$ and the number of parts, for each geometry, present in the *k-class*.

$$Coating.build = \frac{h.max}{lt} * \frac{b}{3600} \tag{13}$$

$$Coating.ratio_k = Coating.build * \frac{h_k - h_{k-1}}{h_{max}} \tag{14}$$

$$Coating(G_i) = \sum_{1}^{n.class} \frac{Coating.ratio_k}{n.inv_k} \tag{15}$$

where

$Coating.build$:	Build coating time [h].
$h.max$:	Maximum height among all the geometries in the build [mm].
b:	Coating time for each layer [s].
lt:	Layer thickness [mm].
$Coating.ratio_k$:	Time fraction of coating ratio for each class of different height [h].
k:	Class of different heights of the geometries in the build [-].
h_k:	Height of each geometry sorted in ascending order [mm].
$Coating(G_i)$:	Coating time for each geometry [h].
$n.class$:	Number of different heights (classes) of the geometries [-].
$n.inv_k$:	Number of parts, for each geometry, present in the *k*-class [-].

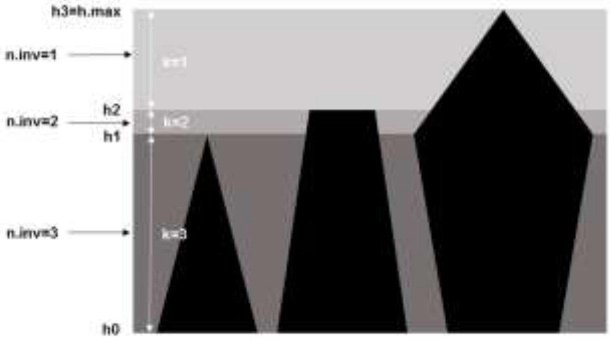


Figure 2: Simultaneous build-up of multiple parts with different heights (adapted by Rickenbacher)

Completion time

One of the innovative characteristics of this work is the definition of the completion time for each geometry. In this section we define it as the sum of the following aspects:

- Build job assembly time necessary to arrange all parts into a build job;
- Setup time;
- Total build time obtained by summing Warm-up, Scanning, Coating and Cool-down times;
- Removal Time necessary to remove objects and substrate plate from the machine chamber.

Substrate plate and support structures removal are typical AM steps to realize once the building phase is completed. In some cases, it could be necessary to realize further post processing work, such as thermal treatments or material removal. Rickenbacher et al. (Rickenbacher et al., 2013) included these phases in their cost model using a generic and non-exhaustive formulation of time and costs involved, grouping in a single cost item of all possible post-processing steps. We think, because of the heterogeneity of the post processing steps and the machines involved in these steps, it is correct to neglect these phases in the cost model and allocate their costs subsequently. This work's objective, in fact, is to calculate the times and production costs of AM, that is, a single production process phase to achieve a finished product.

In the formulation defined, completion time is rounded up to include a superior integer:

$$C(G_i) = \left\lceil \left(T_{buildjob} + T_{setup} + T_{removal} + \sum_i T_{build}(G_i) \right) * \frac{1}{N_{ws} * H_{ws}} \right\rceil \tag{16}$$

where

C: Completion time [days].
G_i: *i*th geometry [-].
T_{setup}: Time required for machine setup [h].
$T_{buildjob}$ Time required for build job assembly [h].
T_{build}: Total building time [h].
$T_{removal}$: Time required for removing parts from the machine chamber [h].
OEE: Overall equipment effectiveness [%].
j: *j*th post-processing working.
N_{ws}: Number of work shifts per day [-/day].
H_{ws}: Number of hours for each work shifts [h].

COST CALCULATOR

Total manufacturing cost

Total manufacturing cost, for each geometry, is obtained by summing the cost of each step:

$$C_{tot}(G_i) = C_{prep}(G_i) + C_{buildjob}(G_i) + C_{setup}(G_i) + C_{build}(G_i) + C_{removal}(G_i) \tag{17}$$

where

C_{tot}: Total manufacturing cost of each part with *i*th geometry [€/part].
G_i: *i*th geometry [-].
C_{prep}: Cost for preparing geometry data (orientation, support structures, etc.) [€/part].
$C_{buildjob}$: Cost for build job assembly [€/part].
C_{setup}: Machine setup costs [€/part].
C_{build}: Cost for building up a part with *i*th geometry [€/part].
$C_{removal}$: Cost for removing the part with *i*th geometry from the machine chamber [€/part].

Cost for preparing geometry data

The preparing geometry data step includes orientation and support structure generation for each geometry. Its total cost is allocated by dividing the total preparation cost of each geometry and its related quantity:

$$C_{prep}(G_i) = \left(C_{op.pre} + C_{PC}\right) * \frac{T_{prep}(G_i)}{N_i} \tag{18}$$

where

C_{prep}: Cost for preparing geometry data (orientation, support structures, etc.) [€/part].
G_i: *i*th geometry [-].
$C_{op.pre}$: Pre-processing operator’s hourly rate [€/h].
C_{PC}: Hourly rate of the workstation including costs of required software and tools [€/h].
T_{prep}: Time required for preparing CAD data [h].
N_i; Quantity of the part with *i*th geometry [-]

Cost for building job assembly

In the build job assembly, the step operator arranges all the parts into one build job. Rickenbacher et al. allocated this cost equally between all parts; we think it is more accurate to use the parts volume like the allocation criteria:

$$C_{buildjob}(G_i) = T_{buildjob} * (C_{op.pre} + C_{PC}) * \frac{V(G_i)}{\sum_i V(G_i) * N_i} \tag{19}$$

where

$C_{buildjob}$: Cost for build job assembly [€/part].
G_i: *i*th geometry [-].
$T_{buildjob}$: Time required for build job assembly [h].
$C_{op.pre}$: Pre-processing operator’s hourly rate [€/h].
C_{PC}: Hourly rate of the workstation including costs of required software and tools [€/h].
V: Volume of the geometry [cm^3].
N_i: Quantity of part with *i*th geometry [-].

Machine setup costs

This step includes the data import and machine setup phases. During this time, the machine cannot be used, and for this reason, we included its hourly cost. Also in this case we used the parts volume like the allocation criteria:

$$C_{setup}(G_i) = \left(C_{op.mach} + C_{mach}\right) * \left(T_{setup} + (F_{mat.ch} * T_{mat.ch})\right) * F_{inertgas} * \frac{V(G_i)}{\sum_i V(G_i) * N_i} \tag{20}$$

where

C_{setup}: Machine setup costs [€/part].
G_i: *i*th geometry [-].
$C_{op.mach}$: Machine operator’s hourly rate [€/h].
C_{mach}: Machine cost per hour [€/h].
T_{setup}: Time required for machine setup [h].
$F_{mat.ch}$: Factor to model the frequency of material changes [-].
$T_{mat.ch}$: Time required to change material [h].
$F_{inertgas}$: Factor to model extra effort required for handling in protective gas environment [-].
V: Volume of the geometry [cm^3].
N_i: Quantity of part with *i*th geometry [-]

Previous formulations also include a factor to consider the effort of extra work in the case of using protective gas ($F_{inertgas}$). Its value can either be 1 or 0. The factor to consider the additional time needed to change material ($F_{mat.ch}$) can either be 1 or 0, if there is a material change or not, respectively, to assign its cost directly to the build job. Furthermore, if the costs have to be divided on more build jobs, a fraction can be used in the formulation. For example, we can set it on 0.1 if we change the material every 10 build jobs. Previous factors are, typically, production losses included in OEE formulation. In this cost model we decided to provide an explicit formulation in order to give more accuracy of their impact on production timing. Clearly, to avoid overestimates, their effect is not included in OEE computation because they are included in the cost model.

Machine cost per hour is obtained by dividing the machine purchase cost by the machine depreciation period and its uptime per year:

$$C_{machine} = \frac{Machine\ cost}{h * upt} \tag{21}$$

where

$C_{machine}$:	Machine cost per hour [€/h].
$Machine\ cost$:	Machine purchase cost [€].
h:	Machine depreciation period [years].
upt:	Machine uptime [hours/year].

Cost for building up a part

The building step is the active phase of production. In this step, the machine concurrently builds all of the parts in the chamber. Cost items involved are:

- Machine;
- Energy;
- Material;
- Gas.

Building cost formulation also includes a waste factor for powder.

$$C_{build}(G_i) = T_{build}(G_i) * \left(C_{mach} + C_{inertgas} * Gas_{cons} + C_{energy} * P_{cons} * K_u\right) + M(G_i) * (C_{material} * W_f) \tag{22}$$

where

C_{build}:	Cost for building up a part with *i*th geometry [€/part].
G_i:	*i*th geometry [-].
T_{build}:	Total building time [h].
C_{mach}:	Machine cost per hour [€/h].
$C_{inertgas}$:	Cost of inert gas [€/m^3].
Gas_{cons}:	Average gas consumption [m^3/h].
C_{energy}:	Mean energy cost [€/kWh].
P_{cons}:	Power consumption [kW].
K_u:	Utilization factor [-].
M:	Mass of the geometry [kg].
$C_{material}$:	Material costs [€/kg].
W_f:	Waste factor for powder [-].

Cost for removing a part from the machine

After finishing the building job it is necessary to remove the objects and the substrate plate from the machine chamber. Also in this case we included a factor to model the extra time effort for handling in a protective gas environment. The allocation criteria of this cost is based on parts volume:

$$C_{removal}(G_i) = T_{removal} * \left(C_{op.mach} + C_{mach}\right) * \frac{V(G_i)}{\sum_i V(G_i) * N_i} * F_{inertgas} \tag{23}$$

where

$C_{removal}$:	Cost for removing the part with *i*th geometry from the machine chamber [€/part].
G_i:	*i*th geometry [-].
$T_{removal}$:	Time required for removing parts from the machine chamber [h].
$C_{op.mach}$:	Machine operator’s hourly rate [€/h].
C_{mach}:	Machine cost per hour [€/h].
V:	Volume of the geometry [cm^3].
N_i:	Quantity of part with *i*th geometry [-]
$F_{inertgas}$:	Factor to model extra effort required for handling in protective gas environment [-].

COST CALCULATION TOOL

MiProCAMAM has been developed in a mixed Excel®-Matlab® environment. In the Excel® part of the model we set all input information regard machine, material, objects geometries, labour costs etc. The Matlab® scripts, that represent the calculation and output area of the model, are composed by four sections (see Figure 3):

1. *Data import* to import all process information from Excel® sheets in the Matlab® Workspace.
2. *Build time estimator*;
3. *Cost calculator*;
4. *Build report.*

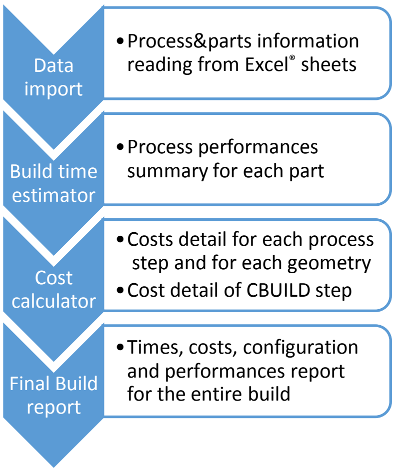


Figure 3: Tool structure

Build time estimator and Cost calculator scripts also show four performance indexes of the process. Their simple formulations, joined with their strengths, make them very useful to measure AM processes.

Build rate
Build rate is the ratio between the Build volume and the Total build time. It measures the volume deposed in a unit time:

$$Build\ rate = \frac{Build\ vol.}{Total\ build\ time} \qquad (24)$$

Capacity utilization
Capacity utilization is the ratio between the volume of the entire build and the chamber volume:

$$Capacity\ util. = \frac{Build\ vol.}{Chamber\ vol.} * 100 \qquad (25)$$

Capacity utilization adapted
Capacity utilization adapted has the same structure of Capacity utilization previously defined but, the denominator is multiplied for the ratio $h_{build}/h_{chamber}$. This formulation, proposed by Baumers et al., 2011, is useful to consider the effect of the height occupied in the chamber of the machine:

$$Capacity.util.adapted = \frac{Build\ vol.}{Chamber\ vol. * \frac{h_{build}}{h_{chamber}}} * 100 \qquad (26)$$

Specific build cost
It is the ratio between the Total build cost and the Build volume. It measures the cost of a unit of volume:

$$Specific\ build\ cost = \frac{Total\ build\ cost}{Build\ vol.} \qquad (27)$$

Specific build cost is one of the most important outputs of this cost model because it allows us to analyse cost performance of the entire build.

RESULTS

In order to validate MiProCAMAM in a mixed production case, we will use information provided by Baumers in his doctoral thesis (Baumers, 2012). In the B01 experiment (Figure 4), he built, contemporary, 85 stainless steel objects using an Eos Eosint M270 machine:

- Venturi pipe (69 parts);
- End cap (1 part);
- Belt link (8 parts);
- Turbine wheel (5 parts);
- Bearing block (2 parts).

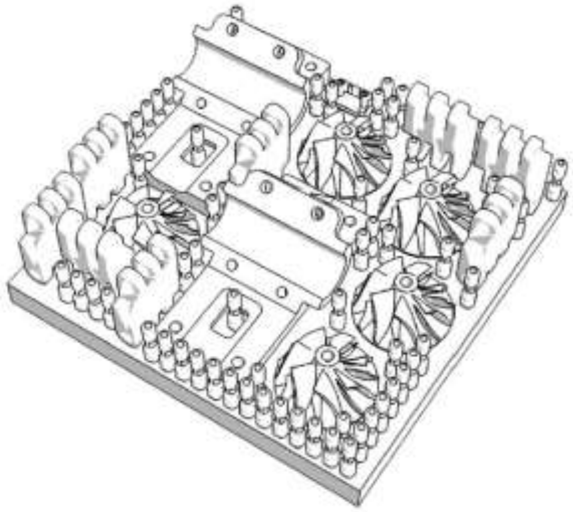


Figure 4: Full build configuration, basket parts (image source: Baumers)

Figure 5: Venturi pipe (image source: Baumers)

Figure 6: End cap (image source: Baumers)

Figure 7: Belt link (image source: Baumers)

Figure 8: Turbine wheel (image source: Baumers)

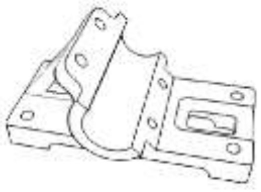
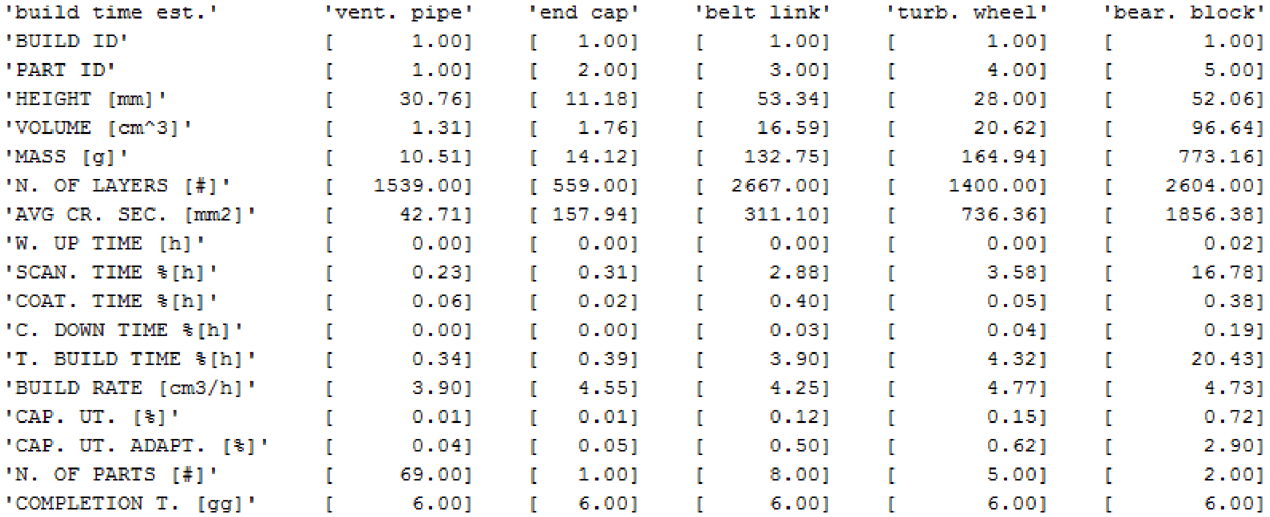


Figure 9: Bearing block (image source: Baumers)

The output of the Build time estimator script (Table 1) shows a report of the geometric characteristics, quantity and time consumption phases for each geometry.

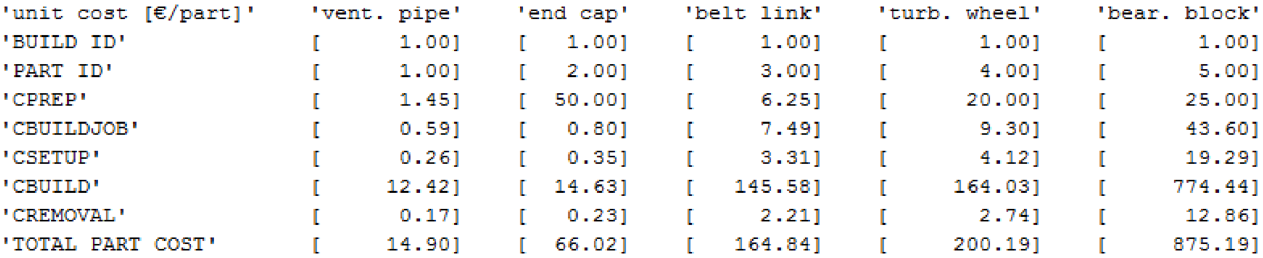
The output of the Cost calculator script (Table 2) shows a cost detail for each of the 5 process steps defined and for each geometry. Furthermore, in Table 3 we report a detail of the active building step (CBUILD row in Table 2).

Table 4 shows a report of characteristics, times, costs and performances of the entire build.



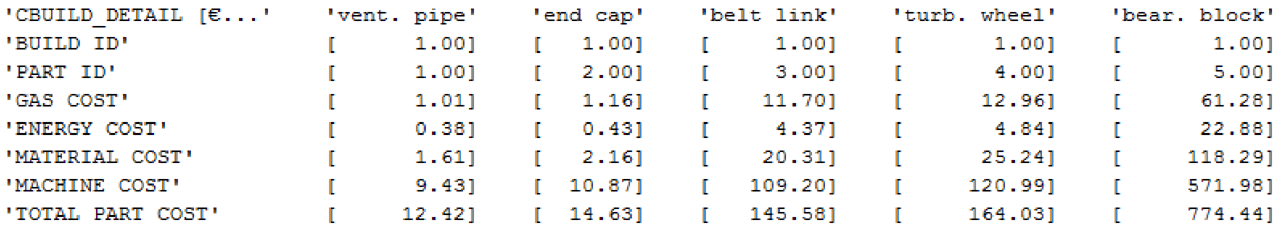
```
'build time est.'          'vent. pipe'    'end cap'    'belt link'     'turb. wheel'     'bear. block'
'BUILD ID'                 [       1.00]   [   1.00]    [      1.00]    [         1.00]   [         1.00]
'PART ID'                  [       1.00]   [   2.00]    [      3.00]    [         4.00]   [         5.00]
'HEIGHT [mm]'              [      30.76]   [  11.18]    [     53.34]    [        28.00]   [        52.06]
'VOLUME [cm^3]'            [       1.31]   [   1.76]    [     16.59]    [        20.62]   [        96.64]
'MASS [g]'                 [      10.51]   [  14.12]    [    132.75]    [       164.94]   [       773.16]
'N. OF LAYERS [#]'         [    1539.00]   [ 559.00]    [   2667.00]    [      1400.00]   [      2604.00]
'AVG CR. SEC. [mm2]'       [      42.71]   [ 157.94]    [    311.10]    [       736.36]   [      1856.38]
'W. UP TIME [h]'           [       0.00]   [   0.00]    [      0.00]    [         0.00]   [         0.02]
'SCAN. TIME %[h]'          [       0.23]   [   0.31]    [      2.88]    [         3.58]   [        16.78]
'COAT. TIME %[h]'          [       0.06]   [   0.02]    [      0.40]    [         0.05]   [         0.38]
'C. DOWN TIME %[h]'        [       0.00]   [   0.00]    [      0.03]    [         0.04]   [         0.19]
'T. BUILD TIME %[h]'       [       0.34]   [   0.39]    [      3.90]    [         4.32]   [        20.43]
'BUILD RATE [cm3/h]'       [       3.90]   [   4.55]    [      4.25]    [         4.77]   [         4.73]
'CAP. UT. [%]'             [       0.01]   [   0.01]    [      0.12]    [         0.15]   [         0.72]
'CAP. UT. ADAPT. [%]'      [       0.04]   [   0.05]    [      0.50]    [         0.62]   [         2.90]
'N. OF PARTS [#]'          [      69.00]   [   1.00]    [      8.00]    [         5.00]   [         2.00]
'COMPLETION T. [gg]'       [       6.00]   [   6.00]    [      6.00]    [         6.00]   [         6.00]
```

Table 1: Build time estimator Output



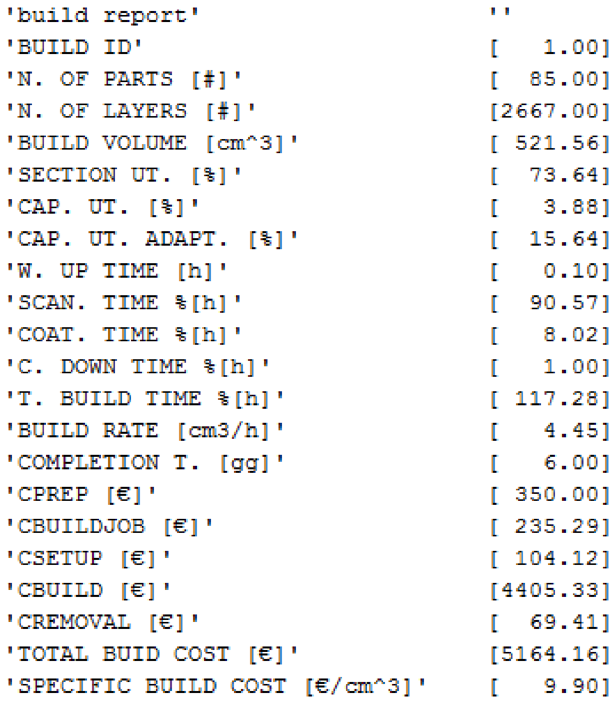
```
'unit cost [€/part]'      'vent. pipe'     'end cap'    'belt link'     'turb. wheel'     'bear. block'
'BUILD ID'                [       1.00]    [   1.00]    [      1.00]    [         1.00]   [         1.00]
'PART ID'                 [       1.00]    [   2.00]    [      3.00]    [         4.00]   [         5.00]
'CPREP'                   [       1.45]    [  50.00]    [      6.25]    [        20.00]   [        25.00]
'CBUILDJOB'               [       0.59]    [   0.80]    [      7.49]    [         9.30]   [        43.60]
'CSETUP'                  [       0.26]    [   0.35]    [      3.31]    [         4.12]   [        19.29]
'CBUILD'                  [      12.42]    [  14.63]    [    145.58]    [       164.03]   [       774.44]
'CREMOVAL'                [       0.17]    [   0.23]    [      2.21]    [         2.74]   [        12.86]
'TOTAL PART COST'         [      14.90]    [  66.02]    [    164.84]    [       200.19]   [       875.19]
```

Table 2: Cost calculator Output



```
'CBUILD_DETAIL [€...'   'vent. pipe'   'end cap'   'belt link'   'turb. wheel'   'bear. block'
'BUILD ID'              [      1.00]   [   1.00]   [      1.00]   [        1.00]   [        1.00]
'PART ID'               [      1.00]   [   2.00]   [      3.00]   [        4.00]   [        5.00]
'GAS COST'              [      1.01]   [   1.16]   [     11.70]   [       12.96]   [       61.28]
'ENERGY COST'           [      0.38]   [   0.43]   [      4.37]   [        4.84]   [       22.88]
'MATERIAL COST'         [      1.61]   [   2.16]   [     20.31]   [       25.24]   [      118.29]
'MACHINE COST'          [      9.43]   [  10.87]   [    109.20]   [      120.99]   [      571.98]
'TOTAL PART COST'       [     12.42]   [  14.63]   [    145.58]   [      164.03]   [      774.44]
```

Table 3: Building costs detail (CBUILD)



```
'build report'                      ''
'BUILD ID'                          [   1.00]
'N. OF PARTS [#]'                   [  85.00]
'N. OF LAYERS [#]'                  [2667.00]
'BUILD VOLUME [cm^3]'               [ 521.56]
'SECTION UT. [%]'                   [  73.64]
'CAP. UT. [%]'                      [   3.88]
'CAP. UT. ADAPT. [%]'               [  15.64]
'W. UP TIME [h]'                    [   0.10]
'SCAN. TIME %[h]'                   [  90.57]
'COAT. TIME %[h]'                   [   8.02]
'C. DOWN TIME %[h]'                 [   1.00]
'T. BUILD TIME %[h]'                [ 117.28]
'BUILD RATE [cm3/h]'                [   4.45]
'COMPLETION T. [gg]'                [   6.00]
'CPREP [€]'                         [ 350.00]
'CBUILDJOB [€]'                     [ 235.29]
'CSETUP [€]'                        [ 104.12]
'CBUILD [€]'                        [4405.33]
'CREMOVAL [€]'                      [  69.41]
'TOTAL BUID COST [€]'               [5164.16]
'SPECIFIC BUILD COST [€/cm^3]'      [   9.90]
```

Table 4: Build report

AM processes are characterized by fixed time consumption elements for each build: warm-up, coating and cool down. Also Preparation, Build job assembly, Setup and Removal costs are fixed elements for each build. With this mind, by increasing the number of parts built concurrently, it is possible to have a lower impact of these fixed cost items simply by dividing them between more objects.

The previous statement is widely accepted in all previous cost models analysed, but we have to underline an important aspect related to AM times. As seen in the previous example, even if high Capacity utilization has a positive impact on production costs, the Total build time is very high (about 117 hours); capacity utilization and total build time are directly related. In a conventional production environment, beyond production costs, it is important to respect the due dates of products. For this reason, filling a machine chamber (maximizing Capacity utilization) could not be the only rule in the Build job assembly step. Companies, in fact, could accept lower performances from the economic point of view, in order to respect the due dates. Furthermore, MiProCAMAM is generally valid at both high and low capacity utilization.

Figure 10 shows a strong impact (more than 80%) of the Scanning time on the Total Build Time, but another important observation is related to Coating time. This fixed time consumption element is related to the height of the objects. For example, above it affects, on average, about 8% of the Total build time. As stated by Rickenbacher et al. the Coating time algorithm ‘suggests optimizing the use of building space by simultaneously building up as much geometries with similar part heights as possible’. This approach is an effective way to minimize production costs through optimizing utilization of deposited layers.

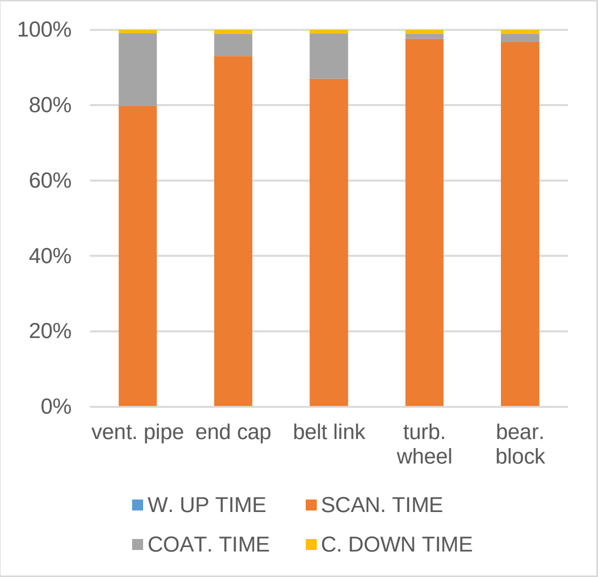


Figure 10: Time consumption for each part

In Figure 11 we can see the high impact of the CBUILD step, except for the ‘end cap’. In this case we observe a strong impact of Preparation costs (about 75%) due to the allocation of the total cost item on a single part. Despite only two parts being produced, bearing blocks are not affected by high preparation costs because their cost is higher than that of the end cap.

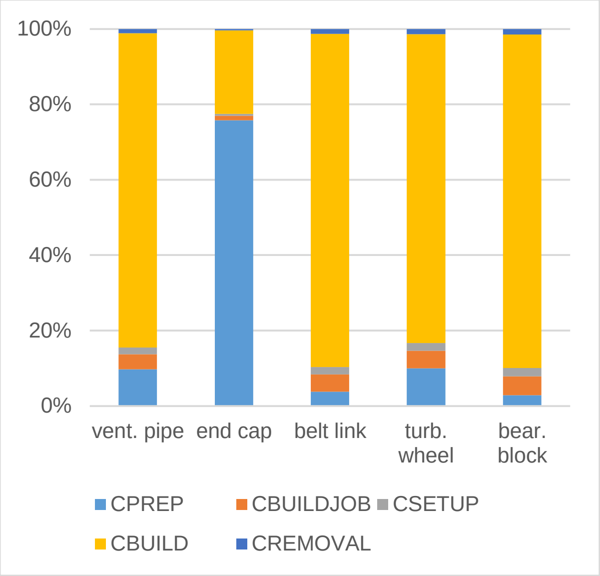


Figure 11: Cost composition for each part

Due to the high Machine hourly cost, the Building step (CBUILD) cost has a large impact on the Total build cost (about 75%). In Figure 12 we report a detail of this cost item: machine cost affects about 75%.

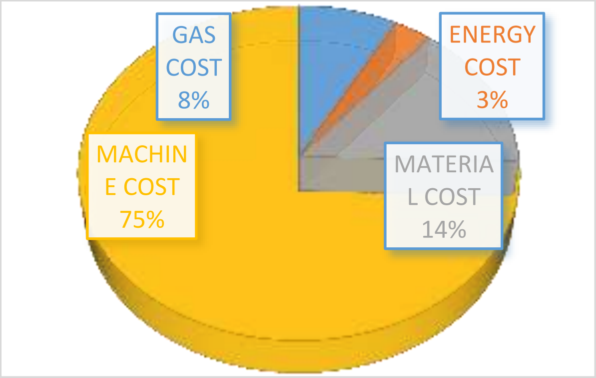


Figure 12: CBUILD detail

Table 5 shows our model unit costs, for each geometry, compared with the Baumers ones. As we can see we have higher unit costs (37% for the entire build) due to Preparation, Build job, Setup and Removal steps, neglected by Baumers. If we consider the active building step (CBUILD), deviations are lower (17%).

To better understand the differences in the cost structure between MiProCAMAM and Baumers' model, a summary of the single cost items considered in both models is shown in Table 6 .

Even if the cost items included in our CBUILD (gas, energy, material and machine) step are not the same as included in the Baumers et al., 2016 cost model, it is nevertheless possible to compare MiProCAMAM with the Baumers' one. In fact, in Table 5 they reported the deviations of each product cost. It is worth noting that we have always had an increase of the costs, due to the fact that MiProCAMAM considers phases not eliminable such as all the pre- and post-processing of the build, the OEE and a different costs allocation policy. So, it is important to see MiProCAMAM as an evolution of the previous ones and not as an alternative to them.

		Venturi pipe	**End cap**	**Belt link**	**Turbine wheel**	**Bearing block**	**Total build**
Total part cost	**Baumers [€]***	7.25	13.35	125.51	155.94	730.96	**3759.63**
	MiProCAMAM [€]	14.90	66.02	164.84	200.19	875.19	**5164.16**
	dev [%]	105%	394%	31%	28%	20%	37%
Building cost	**CBUILD [€]**	12.42	14.63	145.58	164.03	774.44	**4405.28**
	dev [%]	71%	10%	16%	5%	6%	17%

Table 5: Cost comparison for Baumers B01 experiment

*€/£= 0,85608

Baumers	**MiProCAMAM**
Direct costs	**Preparation**
• **Material**	• Operator
• **Energy**	• PC
Indirect Costs	**Build job assembly**
• **Production overhead**	• Operator

• **Rent, building area costs** • **Administration Overhead** • **Hardware** • **Software** • **Consumables** • **Labour costs** • **Machine costs** • **DMLS Machine** • **Wire erosion machine**	• PC
	Setup • Operator • Machine • F. inert gas • F. material change
	Building • Machine • Gas • Energy • Material • Waste factor
	Removal • Operator • Machine • F. inert gas

Table 6: Costs structures comparison

CONCLUSIONS

MiProCAMAM allows for the analysis of production costs, for each step, in the case of building up various geometries simultaneously. This possibility is one of the strengths of AM technologies. Production costs analysis, for each step and for each geometry, allows identification of factors that are the most cost-influencing. MiProCAMAM structure allows adapting to various additive technologies and materials, simply by setting the right process parameters.

As stated in the initial part of this paper, this work aims to define cost models for AM that include strengths of older cost models and avoid their weaknesses. None of the existing cost models analyses AM from an operations management point of view. They measure additive systems performances as separate from the production systems in which they work: OEE, production mix, completion time etc. are not taken into account. For example, the hypothesis of large scale production is made considering the production volume of an AM machine, with no attention to the general market demand. Moreover, the hypothesis of cost reduction by increasing the capacity utilization of the chamber may be in contrast with the delivery time; if a delivery has to be performed, it is not possible to wait for the saturation achievement.

If we want to measure a single process phase, it is correct to consider only the additive processes; however, with an integration point of view of AM in a conventional production system, we think that it is correct to increase the number of aspects to analyse.

One of MiProCAMAM's steps forward is the definition of the completion time. This way we are able to estimate how much time is necessary, for each part, to complete the production evaluating Build job assembly time, Setup time, Total build time and Removal Time. Furthermore, the introduction of Overall Equipment Effectiveness in completion time calculation focuses our attention on a conventional production system environment, taking into account the availability, performance and quality losses.

A weakness of this cost model is related to the a and b parameters used to define the scanning and the coating time. According to Baumers et al., 2013 they can be obtained from a least square regression model on measured building time for several layers. Their values cannot be obtained from the start, but they have to be measured during the process or obtained from historical data.

Defining a cost model is the first step before analysing AM from an operations manager point of view. The next step is to understand cost performances of AM when it works in a conventional production system where we have to, for example, satisfy the market demand and respect delivery time while optimising production costs. In this context we have to analyse the scheduling problem of AM. Furthermore, we need future OEE computations.

MiProCAMAM allows for a better understanding of AM performances in terms of costs and times. Also, the performance indexes cited, OEE and completion time, have an important function because they shift the focus on a wider approach to contextualize AM in a conventional production environment.

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