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ORIGINAL ARTICLE

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 they are not developed enough yet. In the last decade, 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. The aim of this study is to develop a cost model that evaluates process costs of AM for relevant technologies such as stereolithography, selective laser sintering and electron beam melting when integrated in a general production process. The integration of AM on the shop floor is proved 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 and it is put in evidence how this model overcomes the previous problem of estimation.

Keywords Additive manufacturing · Additive manufacturing cost model

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1 State of the art

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 additive manufacturing (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' [2]. The idea to create solid objects layer by layer comes from Hull [20] who obtained a patent for production of 3D objects using stereo-lithography.

Prototyping was the first application of this new technology. From the beginning of this technology, it is possible to identify 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 [19].

Over time, the mechanical performances of the AM-produced objects grew as witnessed by many sources. In 2016, many papers appeared about the theme of the fatigue [21] and cracking [12]; always in 2016, Ma [26] studied the effects of heat treatments on the mechanical performances of the products from an AM process and Wang [46] studied the mechanical properties of objects in stainless steel produced with AM, referring especially to the Poisson modules. Moreover, in 2014, List [25] studied the mechanical properties of objects realised in Inconel material using an Electron Beam Melting (EBM) machine and Park [35] studied the mechanical properties (such as fatigue resistance, vacancies, roughness) of objects realised in lattice using an AM machine. Other proofs of the mechanical property qualities come from other studies in the recent years such as the study about the material resistance quality of the objects realised with AM [47], about the process design and relative results obtainable using direct laser sintering [43, 44] and about the mechanical properties of metallic products with honeycomb structures realised using AM [48]).

In the years before the triennium (2014–2016), many papers appeared about the application of the AM for other materials different form the plastic one. The first that started to speak about the AM using different materials was Kruth [23], followed Mazumdar [29]. In the following decade, until our days, many authors underlined the possibility to use the AM for other kinds of materials. Baufeld used the AM for the production of some parts in titanium alloys [6], like also Bartkowiak did always in the following year [5]. In the same years, Murr with his research group studied the mechanical properties of the aluminium alloy parts realised using the AM [30] and of other metal materials in the following years [31, 32]. In the last years, Travitzky [45] studied the properties of the ceramic materials realised using AM and Quan studied the mechanical properties of carbon fibre parts realised using the new technology.

A paper by [24] 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, even if the scheduling problem of this kind of machine is referred to the single machine scheduling problem [17, 34].

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.

Several cost models have been proposed in the past [15, 16]. 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 (HD) [19] 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.

$$\begin{aligned}\text{Total cost per part} = {} & \text{Machine cost per part} \\ & + \text{Labour cost per part} \\ & + \text{Material cost per part} \qquad (1)\end{aligned}$$

The proposed model provides a first approximation of the production costs. The work was realised 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. [40] 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 the indirect costs depend on the duration of the process:

$$\text{Cost of a build} = \text{Direct costs} + \text{Indirect costs} \tag{2}$$

Build time estimation is performed using an empirical estimation algorithm for the SLS process [41]. This approach is correct only in the case of production of several copies of the same geometry.

In their subsequent work [39], Ruffo defined a new approach to calculate the cost per part in the case of mixed production of different parts in the same build chamber. They proposed three ways to calculate the unit cost of the parts: the first based on the part 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 and his research group ([7, 9]) were the first to examine the economic and energetic aspects and also the time necessary to realise the AM construction. The highlights of his work are enumerated below:

- Activity-based cost estimator of the type devised by [40]
- 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:

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

where

$\dot{C}_{\text{Indirect}}$	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]
$P_{\text{Raw material}}$	Price per kilogram 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:

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

where

T_{Job}	Fixed time consumption per build [h/build]
n	Number of layers [−]
T_{Layer}	Fixed time consumption per layer [h/layer]
$T_{\text{Voxel } xyz}$	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 baseline level of energy consumption throughout the build:

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

where

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

Lindemann [24] 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.

[37, 38] 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

Rickenbacher's [37, 38] cost model is based on the generic cost model by Alexander et al. [1]. The cost of the single part (P_i) is obtained by summing the costs of the seven process steps which as defined below:

$$C_{\text{tot}}(P_i) = C_{\text{Prep}}(P_i) + C_{\text{Buildjob}}(P_i) + C_{\text{Setup}}(P_i) + C_{\text{Build}}(P_i) + C_{\text{Removal}}(P_i) + C_{\text{Substrate}}(P_i) + C_{\text{Postp}}(P_i) \quad (6)$$

where

$C_{\text{tot}}(P_i)$	Total manufacturing costs [€]
P_i	Part with ith geometry [−]
$C_{\text{Prep}}(P_i)$	Cost for preparing geometry data (orientation and support structures) [€]
$C_{\text{Buildjob}}(P_i)$	Cost for build job assembly [€]
$C_{\text{Setup}}(P_i)$	Machine setup costs [€]
$C_{\text{Build}}(P_i)$	Cost for building up the part [€]
$C_{\text{Removal}}(P_i)$	Cost for removing the part from the SLM machine [€]
$C_{\text{Substrate}}(P_i)$	Cost to separate parts from substrate plate [€]
$C_{\text{Postp}}(P_i)$	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 Sect. 3.1.6, 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.
- A simple and effective algorithm to allocate the time fraction of the total build time to each part is realised.
- 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. [42] is the last model to be analysed. To develop their business model, Schröder et al. [42] 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 and 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 realise 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 realise polycarbonate and polypropylene objects. Subsequently, energy costs were inserted between overhead costs [40]. Because of the higher energy consumption necessary to realise metallic objects, it was essential to take into account this cost item: [7] analysed the theme and inserted energy between direct costs.

Older cost models do not consider any post-processing steps [7, 19, 40]. However, [24, 37, 38, 42] 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) [3]. 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 [4, 18] and material removal costs [28]. For this reason, we consider it appropriate to define a production model that includes the post-processing cost of AM [14, 27].

Among all the cost models analysed, only [37–39] 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 of the main models analysed, shown in Table 1, can lay the foundations to define and build a new cost model that will help solve the open issues analysed here.

2 Cost analysis model introduction

The AM process includes several activities characterised 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 Mixed Production Cost Allocation Model for Additive Manufacturing (MiProCAMAM). Before analysing MiProCAMAM, we list its highlights as follows:

Table 1 strengths and weakness of the models analysed

Model	Strengths	Weaknesses
[19]	First approximation of the production costs	Roughness of the model; only some costs are considered; lacking of post-processing costs
[40]	ABC application	Empirical time estimator; only some costs are considered; lacking of post-processing costs
[39]	Calculation of a mixed production for a single build job	Roughness of the model; only some costs are considered; only one criterion to split the indirect cost between several geometries; lacking of post processing costs; cost allocation between different geometries is not solved
[9]	Time estimator not empirical; energetic aspects are considered in the cost model; it is possible to see for the first time the importance of the build; chamber saturation; the importance of the geometries and of the shape complexity arose as a problem of the break-even approaches	No considerations about the production issues, only some costs are considered; lacking of post-processing costs; cost allocation between different geometries is not solved
[24]	Event-driven process chains; post-processing costs are considered	Cost allocation between different geometries is not solved
[37, 38]	Total cost model based on ABC	Cost allocation between different geometries is not solved
[42]	Impact of different geometries on the cost allocation is considered	Total cost involving also the indirect enterprise costs is considered in the industrial full cost of a part

- The structure and the coating time allocation algorithm of the type proposed by Rickenbacher [37, 38] 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. [9] is the starting point for our work.
- Models including pre- and post-process 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. These costs can be added later basing on the traditional costing models for these operations.
- 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 [37, 38] 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, five process steps:

- Preparation
- Build job
- Setup
- Building
- Removal

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

3 Model formulation

Let us introduce the new model presented here. In Fig. 1, 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.

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 [37, 38]; moreover, several authors proposed methods to approximate the building time [13, 36, 41]. 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.

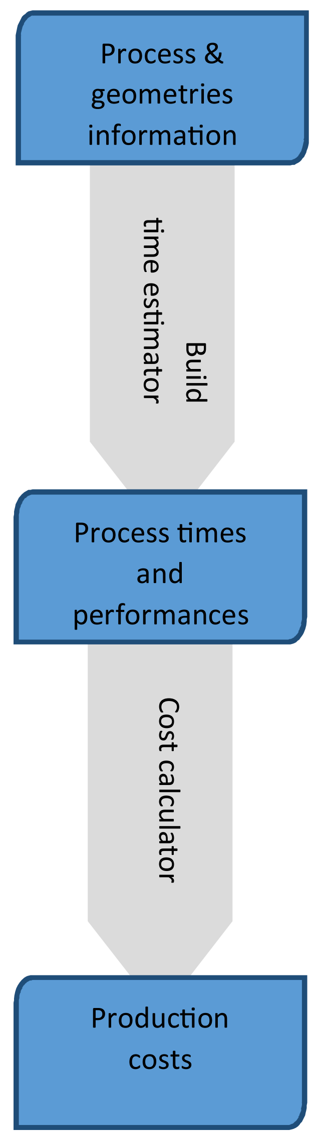

Fig. 1 MiProCAMAM structure

3.1 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

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

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 [33] 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 [22]. 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:

$$T_{\mathrm{real}} = \frac{T_{\mathrm{theoretical}}}{\mathrm{OEE}} \quad (8)$$

Previous formulation is valid also for the 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.

3.1.1 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:

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

where

W . up	Warm-up time [h]
W . up . build	Build warm-up time [h]
G_i	ith geometry [−]
V	Volume of the geometry [cm^3]
N_i	Quantity of part with the ith geometry [−]

3.1.2 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 [10]. Although regression is an approximation of recorded data, we decided to use Baumers et al.'s 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.

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

where

Scanning	Scanning time [h]
G_i	ith 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

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

where

N_L	Number of layers [−]
G_i	ith 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]

3.1.3 Coating time

For the definition of Coating (G_i), see Sect. 3.1.6.

3.1.4 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 realised. 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'.

3.1.5 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 realised: 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 is to use the following algorithm developed by Rickenbacher et al. [37, 38]:

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

3.1.6 Coating time allocation

In their paper, [37, 38] 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' [10] 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. An example in Fig. 2 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$_k$

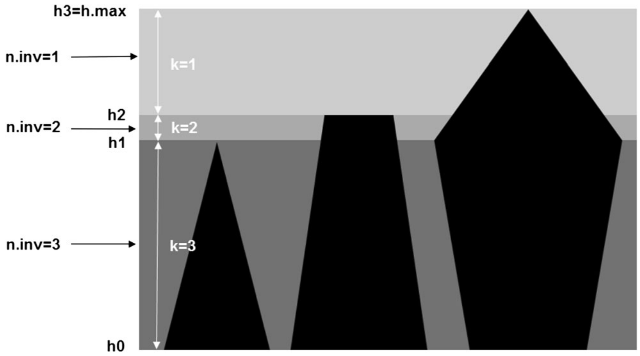

Fig. 2 Simultaneous build-up of multiple parts with different heights (adapted from Rickenbacher)

and the number of parts, for each geometry, present in the *k*-class.

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

$$\text{Coating.ratio}_k = \text{Coating.build}^{*} \frac{h_k - h_{k-1}}{h_{\text{max}}} \tag{14}$$

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

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 the coating ratio for each class of different heights [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 [−]

3.1.7 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 realise once the building phase is completed. In some cases, it could be necessary to realise further post-processing work, such as thermal treatments or material removal. Rickenbacher et al. [37, 38] 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:

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

where

C	Completion time [days]
G_i	ith 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	jth post-processing working
N_{ws}	Number of work shifts per day [−/day]
H_{ws}	Number of hours for each work shifts [h]

4 Cost calculator

4.1 Total manufacturing cost

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

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

where

C_{tot}

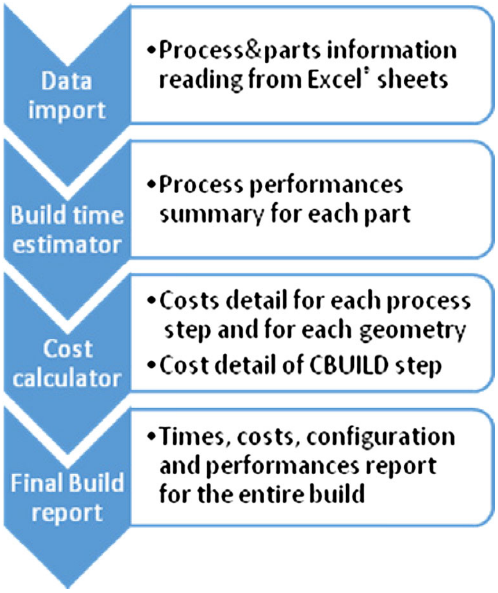

Fig. 3 Tool structure

	Total manufacturing cost of each part with the *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 the *i*th geometry [€/part]
C_{removal}	Cost for removing the part with the *i*th geometry from the machine chamber [€/part]

4.2 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:

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

where

C_{prep}	Cost for preparing geometry data (orientation, support structures, etc.) [€/part]
G_i	*i*th geometry [−]
$C_{\mathrm{op.pre}}$	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 the *i*th geometry [−]

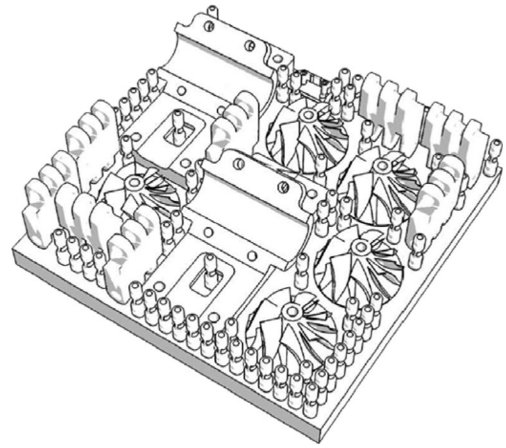

Fig. 4 Full build configuration, basket parts (image source: [7])

4.3 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 part volume like the allocation criteria:

Fig. 5 Venturi pipe (image source: [7])

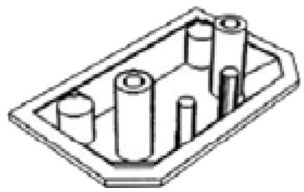

Fig. 6 End cap (image source: [7])

$$C_{\text{buildjob}}(G_i) = T_{\text{buildjob}}{}^{*}\left(C_{\text{op.pre}} + C_{PC}\right)^{*} \frac{V(G_i)}{\sum_i V(G_i)^{*} N_i} \quad (19)$$

where

C_{buildjob}	Cost for build job assembly [€/part]
G_i	ith geometry [−]
T_{buildjob}	Time required for build job assembly [h]
$C_{\text{op . pre}}$	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 the ith geometry [−]

4.4 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 part volume like the allocation criteria:

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

where

C_{setup}	Machine setup costs [€/part]
G_i	ith geometry [−]
$C_{\text{op . mach}}$	Machine operator's hourly rate [€/h]
C_{mach}	Machine cost per hour [€/h]
T_{setup}	Time required for machine setup [h]
$F_{\text{mat . ch}}$	Factor to model the frequency of material changes [−]
$T_{\text{mat . ch}}$	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 the ith geometry [−]

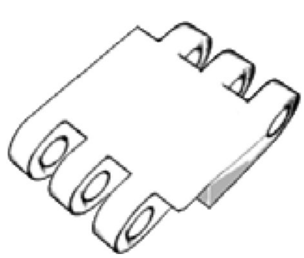

Fig. 7 Belt link (image source: [7])

Fig. 8 Turbine wheel (image source: [7])

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 ($F_{\text{mat . ch}}$) 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:

$$C_{\text{machine}} = \frac{\text{Machine cost}}{h^{*}upt} \quad (21)$$

where

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

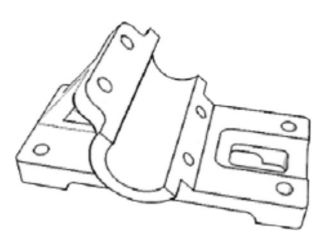

Fig. 9 Bearing block (image source: [7])

Table 2 Build time estimator output

'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. [mm^2]'	[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]

4.5 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.

$$C_{\text{build}}(G_i) = T_{\text{build}}(G_i)^*\left(C_{\text{mach}} + C_{\text{inertgas}}{}^*\text{Gas}_{\text{cons}} + C_{\text{energy}}{}^*P_{\text{cons}}{}^*K_u\right) + M(G_i)^*\left(C_{\text{material}}{}^*W_f\right) \quad (22)$$

where

C_{build} Cost for building up a part with the ith geometry [€/part]
G_i ith 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 [−]

4.6 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

Table 3 Cost calculator 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 4 Building costs detail (CBUILD)

'CBUILD_DETAIL [€...'	'vent. pipe'	'end cap'	'belt link'	'lturb. wheel'	'bear. black'
'BUILD ID'	[1.00]	[1.00]	[1.00]	[1.00]	[1.00]
'PART ID'	[2.00]	[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]

handling in a protective gas environment. The allocation criteria of this cost is based on part volume:

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

where

C_{removal}	Cost for removing the part with the ith geometry from the machine chamber [€/part]
G_i	ith geometry [−]
T_{removal}	Time required for removing parts from the machine chamber [h]
$C_{\text{op.mach}}$	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 the ith geometry [−]
F_{inertgas}	Factor to model extra effort required for handling in protective gas environment [−]

Table 5 Build report

'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]

5 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 regarding machine, material, object geometries, labour costs, etc. The Matlab® scripts, which represent the calculation and output area of the model, are composed by four sections (see Fig. 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*

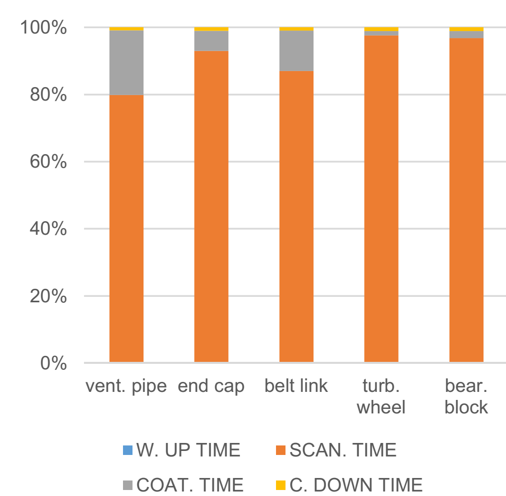

Fig. 10 Time consumption for each part

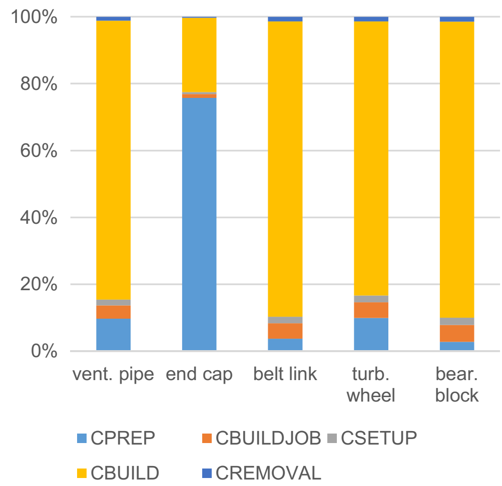

Fig. 11 Cost composition for each part

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.

5.1 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:

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

5.2 Capacity utilization

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

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

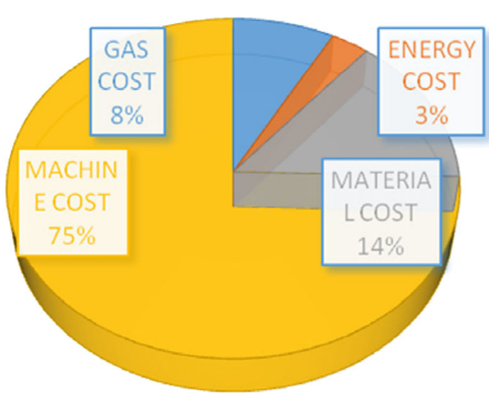

Fig. 12 CBUILD detail

5.3 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 [8], is useful to consider the effect of the height occupied in the chamber of the machine:

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

5.4 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:

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

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.

6 Results

In order to validate MiProCAMAM in a mixed production case, we will use information provided by Baumers in his doctoral thesis [7]. In the B01 experiment (Figs. 4, 5, 6, 7, 8 and 9), he built contemporary 85 stainless steel objects using an EOS EOSINT M 270 machine:

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

The output of the Build time estimator script (Table 2) shows a report of the geometric characteristics, quantity and time consumption phases for each geometry.

The output of the Cost calculator script (Table 3) shows a cost detail for each of the five process steps defined and for each geometry. Furthermore, in the tables we report a detail of the active building step (CBUILD row in Tables 3 and 4).

Table 5 shows a report of characteristics, times, costs and performances of the entire build.

AM processes are characterised by fixed time consumption elements for each build: warm-up, coating and cool-down. Also, Preparation, Build job assembly, Setup and Removal

Table 6 Cost comparison for [7]—B01 experiment

		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%

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 h); 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.

Table 7 Cost structure comparison

Baumers	MiProCAMAM
Direct costs • Material • Energy	Preparation • Operator • PC
Indirect costs • Production overhead • Rent, building area costs • Administration	Build job assembly • Operator • PC
Overhead • Hardware • Software • Consumables • Labour costs • Machine costs • DMLS Machine • Wire erosion machine	Setup • Operator • Machine • F. inert gas • F. material change
	Building • Machine • Gas • Energy • Material • Waste factor
	Removal • Operator • Machine • F. inert gas

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 minimise production costs through optimizing utilization of deposited layers.

In Fig. 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.

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

Table 6 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 7.

Even if the cost items included in our CBUILD (gas, energy, material and machine) step are not the same as included in the [11] cost model, it is nevertheless possible to compare MiProCAMAM with the Baumers' one. In fact, in Table 6 they are 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 (Table 7).

7 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 cost analysis, for each step and for each geometry, allows identification of factors that are the most cost-influencing.

The aim of this paper was 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 system performances as separate from the production systems in which they work: OEE, production mix, completion time, etc., are not taken into account.

MiProCAMAM goes over these limitations; in fact, a step forward is the definition of the completion time and its relation with the OEE. 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.

Moreover, MiProCAMAM allows for a better understanding of AM performances in terms of costs, which are modified from the older formulations, in terms of referral to the real instances of production.

After the description of all the results achieved by this method, it is possible to conclude that the paper achieved its initial aim, i.e. to build a cost model that goes over the previous models' limitations and give the possibility to initiate a new step in the management facets of AM, i.e. the optimization of the scheduling for AM machines.

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