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An Activity-Based Costing Model for Additive Manufacturing

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Abstract. Additive Manufacturing (AM) has received a high interest in various applications, especially Powder Bed Fusion (PBF) technology. As for any industrial process, cost is one of the most important key performance indicators where good estimation and management have a direct impact on the competitiveness of the enterprise. Therefore, a detailed analysis of the current AM processes cost is essential. This paper has two main contributions, firstly, a critical analysis of the existing cost models in PBF, and metal-based material AM technologies by illustrating their main cost drivers and formulas. Secondly, an Activity-Based Costing (ABC) model is proposed with the aim to cover all important characteristics of AM process. The main cost drivers in AM process are exploited in this model to support the quotation of new product at earlier stages of AM project negotiation. The proposed costing model is part of a global knowledge-based framework for decision aid in AM project.

Keywords: Cost model, Cost estimation, Cost drivers, Activity based costing, Additive manufacturing.

1 Introduction

One of the main challenges for decision maker at early stages of AM project is estimating the cost, since it is usually a key point of negotiation [1,2,3,4]. Good cost estimation has a direct bearing on the competitiveness of a business of an enterprise because overestimation can result in loss of a business and goodwill market, and underestimation may lead toward financial losses in enterprise [5]. Thus, cost estimation Frameworks / models have an important role internally and externally when providing the quotation [6,7]. Estimating the cost is a challenging task which needs a big amount of manufacturing data and knowledge connected to various design and manufacturing aspects: such as material, support, used machine, post-processing, and so on. Face to this complexity, there is recently a high demand of decision support tools and models able to identify the suitable strategy to optimize the global cost while keeping the same level of quality [8]. According to the Solid Freeform Fabrication (SFF) symposium held in Austin in 2014 [9], most of the experts agreed that future Additive Manufacturing (AM) systems should address functional metallic/multi-material and large-scale parts, allowing low operating cost, speed, and energy consumption. So, understanding the key factors impacting the cost of AM process is necessary for ef-

fective deployment and future uptake of high-quality standards [1]. Indeed, a detailed analysis of the current manufacturing cost and evaluation of the expected improvements reveal a cost reduction potential of about 60% in the next 5 years [10], which will significantly advance the market of AM.

In consequence, the costs incurred by AM attract the interest for different stakeholders (i.e., end users, technology developers, AM service providers, investors, etc.). Careful examining of additive manufacturing costs is important to compare additive manufacturing processes with traditional processes, and to identify the main cost drivers used at various steps of the additive manufacturing process [11].

Powder Bed Fusion (PBF) is one of the complex AM processes where thermal energy selectively fuses regions of powder bed to produce parts [12]. Generally, the process consists of: A thin layer of powder is spread by levelling roller or recoating blade, where a moving energy source (laser beam in case of Laser PBF machines that passes through a system of lenses and reflected by a mirror, used to control the laser beam spot movement on the X, Y planner, onto the platform surface [14]) melts or sinters the powder into successive cross-sections based on the CAD file. The platform goes down in a specific pitch based on the layer thickness, then the powder is spread for another layer over the solidified layer, to build the next one, until building a complete 3D component. The process may take place in a high vacuum chamber to avoid oxidation issues of metallic powders at high temperature, thus the build chamber is frequently filled with inert gases, argon in most cases [14]. Examples of PBF process are selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM) that uses electron beam as an energy source [15].

Despite the significant progress and technology advancement that have been made by PBF, performance in terms of speed, accuracy, process control and cost effectiveness still need to be improved [13]. This paper has two main contributions. The first one is a critical analysis of the existing cost estimation models in AM, focusing on the ones that are related to metallic materials, and PBF technologies. Then, based on this analysis, the second one is a cost model using Activity-Based Costing (ABC) approach, proposed for PBF laser-based technologies and metal materials, with the ambition to cover some limits of the existing AM cost estimation models. Also, this study represents the main associated cost drivers within the PBF technology process chain. The next section presents a detailed analysis of literature with the aim to identify the main cost drivers and most significant cost models. Then, section 3 sets up the main foundations of the proposed costing framework, while section 4 gives a brief illustration about the application of this framework in an industrial case study.

2 Literature Survey

2.1 Cost classification techniques

Cost is the amount that has to be paid to obtain an end product or service regardless of how much the company has gained or lost [16]. According to the Association for

Advancement of Cost Engineering [17], cost estimation intends to determine the quantity and predict the costs of constructing a facility, manufacturing goods, or delivering a service. However, there are a wide range of classifications regarding cost estimation [3] based on several aspects like; approach type, granularity level, tools used, and even the application phase. According to Kadir et al. [18], different views of cost models could be categorized into different perspectives depending on the role of the person handling the cost issues like:

Manufacturing perspective: (Task-based classification techniques) includes several phases of product development and manufacturing tasks, it can be grouped into design-oriented (e.g., part design, process planning), or process-oriented that covers cost elements in the production phase, direct and indirect costs (e.g., pre-processing, production (build job), and post processing).

Management perspective: (Level-based techniques) covers a wide range of product costs that are associated with product lifecycle costing, design to cost reduction, remanufacturing and value engineering of the product. These techniques are divided into process-level (costs associated with production, similar to task-based), and system-level (that covers all costs throughout the product life cycle like; maintenance, inventory, etc.).

Financial/accounting perspective: (Method-based) uses a classical classification techniques of cost models based on the used methods and factors. These techniques are categorized into Qualitative (Intuitive techniques, Analogical techniques), and Quantitative (Parametric techniques, Analytical techniques) [5].

Intuitive techniques are primarily dependent on past experience (expert knowledge), where this experience can be applied either directly, or using different decision support systems, like (rules, decision tress, case-based, etc.) [5]. This approach is suitable at early stages like design, and conceptual stage [3]. Analogical techniques are based on the concept of deriving an estimate from actual information regarding similar real product [2], using historical cost data of products with known cost. Such techniques, like Regression analysis and Neural Networks, have the ability to define a relationship between variables and cost.

The Parametric techniques focus on the characteristics of the product without describing it completely [19] by using the cost estimation relationship that can be presented in mathematical equations, with variables that are associated effectively with cost drivers. The Analytical techniques separate a product into several units, operations, and activities, also the resources consumed during the product life cycle. They express the cost as a summation of all these components [5]. It is further classified into different categories (e.g., Operation-based, Feature-based, Tolerance-based, Activity-based, Break-down approach). These are easy and effective methods to apply.

2.2 Cost estimation models in AM

The intent of this section is to scrutinize the most relevant cost models defined about the AM "*focusing on the ones that are related to metallic materials, and Powder Bed Fusion PBF technologies more specifically*". In order to get an overview of the current propositions for cost estimation of AM, in particular the main cost drivers

and the used techniques, as well as classify them according to management perspective, described previously, as shown in Table 1.

Process-level cost models

Schroder et al. [20] used Time-driven ABC for the development of a business model which evaluates the process cost of AM technologies (FDM, SLA, SLS, EBM). Thus, their proposition of cost model is consolidated based on detailed sub-activities, and an overall of 77 input values are needed for a detailed cost calculation divided into process and order specific information's. Another Time-Driven ABC process-level cost model in AM is proposed by Barclift et al. [21]. They provide cost modelling for PBF by expanding the work of [22], and also defining a new financial depreciation model for reused metal powders using Sum-of-the-years digits depreciation. Their study concludes that the fixed material cost undervalued the cost of build jobs within a range of 13% and 75% for virgin Ti64 powder. The uncertainties in this model are the exact number of reuses permitted for each material alloy, also other cost elements related to quality assurance processes are not included. The work proposed by Cunningham et al. [1] incorporates the full process chain for Wire-Arc Additive Manufacturing (WAAM) in order to create a detailed cost model. The key cost drivers are identified using sensitivity analysis. The results of this work state that WAAM has a significant potential as cost-effective manufacturing approach compared to other AM technologies. Moreover, Facchini et al. [10], provide a cost model to compare the process cost due to production of batch of aerospace parts, adopting both WAAM and traditional machining technologies. Their proposition is using a parametric approach based on computational algorithms, taking into consideration overall manufacturing costs and Non-recurring Engineering NRE costs, which refer to the one-time cost to research, design, develop and test due to production of new parts. Four performance indicators of the process are identified to evaluate the cost of each phase of the process (e.g., setup, building job, part removal, etc.). Ruffo et al. [2] have proposed a cost model based on a parametric approach (as an analytical function identifies the cost estimation relationships) and an engineering approach (to find overall costs by the sum of elementary components used in each step of the production process) in the case of LS (Laser Sintering) manufacturing, as the relationships found are approximations based on statistics. The scope of this cost model is limited to the production process, including material cost as an indirect cost and (overheads, maintenance, capital equipment depreciation, labor, software, and hardware) costs as indirect costs assigned to the components on a machine working-time basis. So, this cost model has to be extended to cover a wider range of AM process chain.

The analogical approach was used in Rudolph et al. [23], and Chan et al. [24]. Rudolph et al. [23] develop an automated self-learning calculation cost model for SLM implemented within a web-based platform. The customer is able to upload the part geometrical data via online form. Then, the key characteristics (volume, surface and dimensions) are identified to obtain an offer calculation. Linear Regression is used to predict the capacity utilization and the build height in order to estimate build and material costs. The work is only focusing on a cost calculation of the build process including material and manufacturing costs. Chan et al. [24] propose a cost estimation

framework using machine learning algorithms for dynamic clustering, LASSO and Elastic Net Regressions, so the production cost associated with a new job can be estimated based on similar cases in the past. Cost estimation process starts with extracting and calculating 17 different types of features from the process information in G-code which is generated from the submitted STL file. Those features are then forming the feature vector which will be used as an input of the predictive model. In this study there are some missing links to make effective cost estimation framework, where some cost elements like post-processing, labor cost, and overhead are not included.

System-level cost models

Lindeman et al. [25] aim to provide a deep understanding of AM product lifecycle cost structure for laser-based technologies. The proposed tool is divided into two segments, the first maybe filled by engineer, and the second segment for experienced AM user. It used analytical network process method, multi criteria part classification, then Time-driven activity-based costing as a general method for the calculation, and a good means for allocating cause-based costs to allow the comparison of additive and traditional manufacturing methods. It also, evaluates the relevant factors for specific product, process, warehousing, and capital issues. The cost model is difficult to be implemented in industrial context because of the lack of knowledge about the processes and difficulties for companies to incorporate the lifecycle coasting approach.

Kamps et al. [26] carried out qualitative cost analysis incorporating life cycle assessment (LCA) on laser beam melting process. Two integrated models were suggested for cost and life cycle assessment in cradle-to-gate framework focusing on the industrial process sequence. An excel-based cost model is developed for cost calculation as well as build-up duration and argon demand based on company and machine specific data. Whereas the LCA model is based on key assumptions that simplify the model without threaten the calculation outcome significantly. The model needs more experimental measures to improve its accuracy. The results were based for gear production and only few costs were measured.

Table 1. Comparison of main AM cost models

Cost model	Main cost Drivers	System-level	Process-level	Used method/approach
Schroder et al. [20]	CAD preparation cost, operating cost (preparation process), material cost, machine cost, labour cost (production), post-processing cost, quality control process cost, administrative cost		✓	ABC (Time-Driven-ABC)
Rudolph et al. [23]	CAD preparation cost, set-up cost, operating cost, labour cost (production), production overhead, pricing mode cost, material cost, part removal cost, treatment		✓	Analytical, and analogical “linear regression”

	cost, post-processing overhead			
Chan et al. [24]	Material cost, machine cost, production cost		✓	Analogical "ML algorithms, Net regression"
Barclift et al. [21]	CAD preparation cost, operating cost (preparation process), set up cost, labour cost, material cost, machine cost, depreciation cost (powder feedstock), part removal cost, substrate process cost, post-processing cost		✓	ABC (Time-Driven)
Lindeman et al. [25]	Inventory cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, post-processing cost, part removal cost, production overhead, logistic cost, quality control cost	✓	✓	ABC (time-driven)
Facchini et al. [10]	CAD preparation cost, operating cost (preparation process), setup cost, labour cost, material cost, part removal cost		✓	Parametric (computational algorithm)
Kamps et al. [26]	CAD preparation cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, maintenance cost, electrical cost, gas cost, energy cost, production overhead, post-processing cost, part removal cost	✓	✓	Intuitive, Analogical LCA life cycle assessment
Cunningham et al. [1]	Operating cost (preparation process), setup cost, material cost, machine cost, labour cost (production), part removal cost, post-processing cost, quality control cost, tooling cost, treatment cost		✓	ABC (time-driven)
Ruffo et al. [2]	Material cost, machine cost, production cost (build job), overhead cost		✓	Parametric, and Engineering approaches

In summary, it is necessary to mention that each of the existing cost models has advantages and disadvantages, but no model meets all criteria satisfactorily, these criteria, among others: simplicity, genericity. For instance, part of the proposed models is limited to AM build process, while others are complex and difficult to implement. So, there is a need for a generic and simple cost model that covers cost elements in different phases of AM process and can be adopted in industrial practices.

3 Proposed cost estimation framework: an ABC approach

3.1 ABC method

Activity Based Costing ABC approach has been selected to be used, since it has gained the recognition as an easy and effective method, with better information for controlling capacity cost [16]. The cost estimation is prepared from the cost incurred by activities during manufacturing of the product [5]. ABC could provide the structuring support (the activity) to keep non-financial information such as defect rates (quality), throughput rates (effectiveness of the industrial process) and delivery time [7, 27]. It may help the companies to improve product design and manufacturing process, as well as classifying the activities to value-added and non-value added.

The following steps demonstrate the implementation of the ABC approach [28]; it starts with identifying the cost centers connected to the directly used resources, including human resources (designer, labour, etc.), and equipment/ machines. Then it analyzes the overall cost (like overhead costs) associated with these cost centers, and it calculates their cost driver's rate. After that it is necessary to assign resources to each cost center, and to determine cost center rates based in the resource cost drivers. Later, the method allows identifying the activities that take place in the product development process, and defining activity driver(s) for each one. Finally, the achievement is finding the total cost of each activity based on the cost-centre resources for each activity, using cost center rate multiplied by the amount of the drivers consumed by each activity (see Fig.1).

3.2 Main Cost Drivers

The activities of the PBF production process chain were identified according to the major production processes involved that represent the scope of this cost model. One of the main purposes of cost modeling is to identify the factors affecting the cost during various processes of AM which are called cost drivers. Thus, before starting with the equations of the cost model, the main cost drivers within the process chain - that are needed in order to estimate the product cost - are illustrated in Fig. 2.

It is also important to consider the various interdependent aspects like; product characteristics, customer specifications, machine/ material types, and manufacturing process parameters, in terms of their correlation with the main cost drivers therefore to increase the robustness of cost investigation.

Build time is one of the most essential factors to estimate the cost of AM. Certain machine/ material combination have strong impact on build time. Also, part characteristics, and requirements (part volume, part features, part quality), and manufacturing parameters (hatching and contour percentage, layer thickness, scanning speed, build height, support required) affect the build time. The estimation of build time is beyond the scope of this paper. However, several software packages exist for estimating the build time like (Materialise-Magics, EOSprint, AddUp Manager, etc.). Besides, several works have been caried out for estimating the build time using Machine learning techniques like [29, 30, 31].

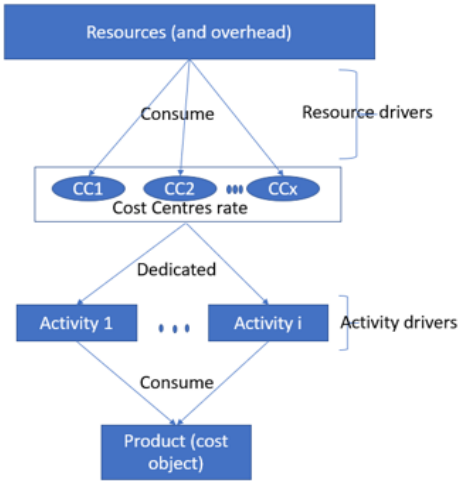


Fig. 1. Activity-Based Costing approach implementation, adapted from [28]

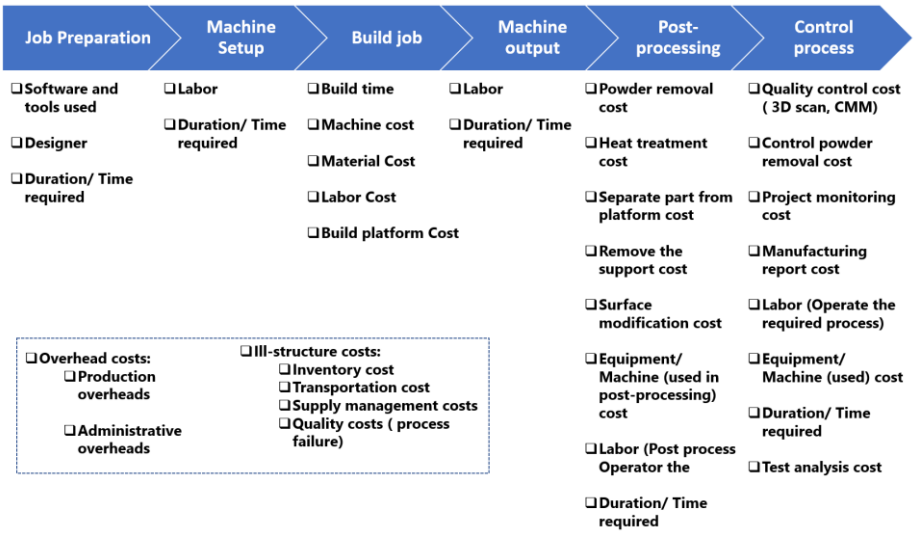


Fig. 2. Main Cost Drivers in PBF process chain

Machine/ equipment cost is also to be taken into account, especially AM machine cost due to the high purchase price of AM machines. This cost is indicated as hourly rate for running the machine (cost/hour). It is based on the purchase price of AM system, service year, and other maintenance expenses associated with such system. Specific machine component like build platform has a separate cost because in some cases, it might have a significant effect on the cost of AM products, this type of cost is based on the dimension “mainly the thickness” of the platform, platform material type, and platform state if it is new or has been already used before for several builds.

Material cost has to be considered carefully because the cost of AM metal material is significantly high compared to raw material used for traditional manufacturing. Two things have to be considered in determining this cost. On one hand, the material price per kilogram which is based on the material type, material supplier, and material state (new or reused). On the other hand, the quantity of the consumed material which is related to the total volume of part, other test parts "that might be included in the build job", support structure, number of parts, and the material waste that includes both material loss during the build process and trapped material within build parts.

Labor cost is related to the labor needed to execute a task or activity (designer, AM operator, post-processing operator, etc.) such as job preparations, machine output, post-processing, and control process. This cost is indicated as an hourly rate cost.

Post-processing and quality control costs may take up to 50% of the final product cost [25]. They both depend on the customer requirements, part characteristics, customer activity sector (function of the product), required labor, used technique, used machine/ equipment, and the duration/ time needed for the activity, which are the most related factors for these costs. Post-processing costs are the sum up of all necessary post-processing operations after AM machine output, (e.g., powder removal, separation of the part from the platform, support removal, machining process, and heat treatment, etc.). On the other hand, quality control cost is the cost of different steps needed to assure and evaluate the various aspects to achieve part quality, and product requirements (e.g., 3D scan, CMM, Tomography, Microstructural evaluation, Metallurgical test, etc.). Indeed, it is substantial to mention that these processes have to be considered beforehand the manufacturing. In specific situations, some of these processes are carried out by subcontractors.

Overhead costs are assigned to the operations of AM system and categorized into: Production overheads, like building rent, support equipment, or energy costs; Administrative overheads that are related to computer equipment, communication, and software license costs. Some cost models (e.g., [25, 2]), have included overhead costs as indirect costs along the machine cost, by taking the annualized overhead costs over the machine working time per year. Ill-structured costs are the hidden costs in the supply chain [11] such as, inventory, transportation, supply chain management (purchasing, operation, distribution, integration), and quality (in terms of process failure during machine operation and part rejection) costs. These costs are difficult to consider and not well understood due to the limited knowledge and data in the accounting practices [9]. However, AM has a positive potentiality in reducing these costs compared to conventional manufacturing technologies, because of its ability to manufacture parts on demand, produce an entire product in the same build at once, and reduce the link in supply chain by bringing the manufacturers closer to consumers.

3.3 Cost calculation for AM

In this section part of the proposed cost model equations are presented. The estimation of AM final product cost is carried out by identifying at first the main needed activities to realize the product, then the cost centers associated with these activities and their drivers. In most of the activities the main drivers are the duration/ time re-

quired to achieve the activity. So, this cost estimation model could be also included as a Time-Driven ABC.

$$\text{CAD/CAM preparation cost} = T_{\text{CAD/CAD prep}} * (C_{\text{Designer}} + C_{\text{WS}}) \quad (1)$$

$T_{\text{CAD/CAD prep}}$: the time required for creating support, simulation, etc. (h)
C_{Designer}: The Designer hourly rate (€/h)
C_{WS}: The cost rate of using workstation (including software and computer) €/h

$$\text{Machine set-up cost} = (T_{\text{setup}} + T_{\text{mat.change}}) * C_{\text{op}} \quad (2)$$

T_{setup}: the time required to prepare and setup the build job (h)
$T_{\text{mat.change}}$: the time required to change the material and clean dispenser (h)
C_{op}: AM operator hourly rate (€/h)

$$\text{Build job cost} = C_{\text{Build machine}} + C_{\text{production-stop}} \quad (3)$$

$$C_{\text{Build machine}} = T_{\text{Build}} * C_{\text{AM-Machine}} \quad (4)$$

$C_{\text{Build machine}}$: the cost for operating AM machine (€)
$C_{\text{production-stop}}$: the cost of stopping the production (not failures), but to fill the dispenser, empty the re-coater (mainly related to manual tasks) (€)
T_{Build}: the time for building the entire job for specific project (h)
$C_{\text{AM-Machine}}$: AM machine hourly rate (€/h)

$$C_{\text{Build material}} = M_{\text{material}} * C_{\text{material}} \quad (5)$$

$$M_{\text{material}} = (V_{\text{Build}} * P_{\text{melted-density}}) + M_{\text{waste}} \quad (6)$$

$C_{\text{Build material}}$: the cost of used powder in AM builds job process (€)
M_{material}: mass of used material in build job (kg)
C_{material}: the commercial price of the used powder (€/kg)
V_{Build}: total build volume for specific project (mm3)
$P_{\text{melted-density}}$: powder melted density (around “Powder density/0.6”) (kg/mm3)
M_{waste}: powder loss during AM builds job (kg)

$$\text{Machine output cost} = T_{\text{rem}} * C_{\text{op}} \quad (7)$$

T_{rem}: the total time required to remove the entire build, and cleaning (h)

$$\text{Powder removal cost} = T_{\text{PR}} * (C_{\text{op}} + C_{\text{PR machine}}) \quad (8)$$

T_{PR}: the time required for automatic powder removing (h)
$C_{\text{PR machine}}$: hourly cost rate for powder removing machine or equipment (€/h)

$$C_{\text{PR (Material trapped)}} = M_{\text{material PR}} * C_{\text{material}} \quad (9)$$

$C_{\text{PR (Material trapped)}}$: the cost of powder lost during the powder removal process, which is the trapped powder within the build parts (€)
$M_{\text{material PR}}$: mass of lost powder during powder removing process (kg)

$$\text{Separate parts from platform} = (C_{\text{Sep mach}} * T_{\text{Sep mach}}) + (C_{\text{Sep op}} * T_{\text{Sep op}}) \quad (10)$$

$C_{\text{Sep mach}}$: hourly rate cost for the used machine (e.g., EDM, Saw) (€/h)
$T_{\text{Sep mach}}$: the time/ duration for the separation machine (h)
$C_{\text{Sep op}}$: hourly rate cost for the separation process operator (€/h)
$T_{\text{Sep op}}$: the time/ duration for the operator (input, remove, monitor) (h)

Other costs related to post-process activities are also included in the cost estimation model like; heat treatment, support removal, surface finishing, and machining. They are mainly based on the time/ duration to realize the activity, post-process operator hourly rate, and used machine/ equipment cost rate. Different quality control activities are included as well, parts of these equations are presented below in (11,12, and 13).

$$\text{Project Monitoring cost} = T_{\text{follow up}} * C_{\text{project leader}} \quad (11)$$

$T_{\text{follow up}}$: the total time needed to trace and monitor specific project (h)
$C_{\text{project leader}}$: project leader hourly rate (€/h)

$$\text{Creating Manufacturing Report cost} = T_{\text{M.rep}} * C_{\text{project leader}} \quad (12)$$

$T_{\text{M.rep}}$: total time required to create the manufacturing report (based on the level of this report, and customer specifications) (h)

$$\text{Control Check} = T_{\text{QC}} * (C_{\text{QC tool}} + C_{\text{QC op}}) \quad (13)$$

T_{QC}: time required to realize the control check (h)
$C_{\text{QC tool}}$: hourly rate for the used tool/ or machine (e.g., 3D scan, CMM) (€/h)
$C_{\text{QC op}}$: quality control operator hourly rate (€/h)

Thus, the final equation to estimate the cost of a product is shown below;

$$\text{Final Product cost} = \text{Total material cost} + \text{B. Platform cost} + \sum\text{Activity cost} \quad (14)$$

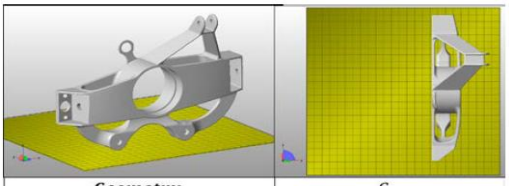
$$\text{Total material cost} = C_{\text{Build material}} + C_{\text{PR (Material trapped)}} + C_{\text{Psq}} \quad (15)$$

Total material cost: the total material required for a specific project (€)
B. Platform cost: the cost for using a specific build platform (€)
C_{Psq}: the cost of the powder sample needed for powder test analysis, if required (€)
$\sum$Activity cost: the summation of the required activities costs (€)

4 Case Study

To illustrate the application of the proposed cost model, one part designed and produced by laser-based PBF has been selected from [21], see Fig.3. This part was built using EOS Titanium Ti64 material, and manufactured by EOS M280 DMLS machine. The cost will be estimated following the carried-out process presented in [21]; the process starts with CAD/CAM preparation by importing the STL file into Materialise Magics software, and Machine setup for the build job, then AM process. Once the

build job is completed the entire build is removed. Next, heat treatment and wire EDM (subcontracted processes) are applied. Finally, the required post-processing in terms of support removal and other mechanical process are carried out by the operator. Using the cost model constants from [21], the costs for producing the part are estimated using the proposed cost model equations, and compared with the ones estimated in [21], as presented in Table 2. The costs are different in both machine setup, and machine output activities because in the proposed model the machine hourly rate cost is not included in these activities, only operator cost rate is included. Material cost includes the fused material to build the part (based on build volume), as well as the powder loss during the build process and the trapped powder inside the build (we assume the same quantity of powder loss from [21]).



$Geometry$	G_1
N_i	1
$V_{part}\ (cm^3)$	175
$V_{supports}\ (cm^3)$	412
$V_{total}(cm^3)$	587
$A_{con}(cm^2)$	69
$Bounding\ Box\ (mm)$	74 x 218 x 172

Fig. 3. Automotive Upright, source [21]

Table 2. Compare the estimated costs

Cost Elements	Estimated costs ($)	Costs from [21] ($)
CAD/CAM Preparation cost	630	630
Machine Setup cost	550	850
Build job (C Build machine) cost	3850	3850
Machine output	330	510
Heat Treatment cost	Stress- relief "Subcontracted" 350	350
Separate parts from platform cost	Wire EDM "Subcontracted" 200	200
Post Process cost	480	480
Material cost	2652	2652

5 Discussion and limitation

In comparison with the current propositions for cost estimation in AM (as shown in Table 1), this model is considered as a process level cost model, using ABC approach,

in which it has been developed based on an exhaustive review of these propositions, as well as several discussions with the industrial partners. This is done in order to overcome the missing cost elements in previous cost models, and to present the main AM cost drivers as well as their correlation with customer specifications and product characteristics.

The cost model equations cover a wider range of cost elements within AM process chain. In the previous models, the costs for following and creating the manufacturing report for a specific project were not mentioned. In reality, these costs might be significant for complex projects that required, for example, a number of subcontracted activities. Other costs were also highlighted in this paper which are related to control check process (e.g., 3D scan), and to the needed test analysis such as: powder test, metallurgical test, tensile test, etc. The cost for the used build platform was also included since it can vary based on its dimensions and material type. For instance, in some project the customer asks for a specific build platform. Moreover, in this model the quantity of the consumed material was based on several aspects along the part volume such as: the associated test parts, powder loss within the build process, powder trapped inside the part channels, and the powder quantity used of test analysis in some cases.

The cost estimation model could serve as a basic element in two important applications. First it can be adopted in real industrial practices and linked to expert knowledge using different approaches (e.g., rule-based) to support the estimation of cost at early stages. Second, it can be used to track the incurred cost of each activity and its related factors toward a full cost traceability model.

On the contrary, this cost model did not consider the state of the used powder (if it is new, recycled, or mixed). Therefore, the material price is treated as an input for the model, based on the commercial selling price from the supplier regardless the state of the powder. In addition, the model is limited to PBF metal laser-based application. However, the use of this cost model in different applications could be achieved after some updates and modifications. Finally, Costs for build failure and re-design or engineering of pre-existing part were not captured in this model.

6 Conclusion and Perspective

In this work several cost models in the field of AM have been reviewed, and a cost model using Activity-Based Costing approach is developed. At first, the main Cost Drivers within the PBF process chain have been presented and explained. After that, generic cost estimation equations using ABC are proposed that cover several cost elements like post process, quality control and assurance processes, test analysis process, powder loss, build platform, etc. A case study was presented using Ti64 material part produced by EOS M280 DMLS, in order to clarify the employment of cost model equations. The cost model has been tested with one of our industrial partners in order to estimate the cost based on customer specifications, using developed Business Rules (know-how knowledge) that link customer specifications and product characteristics to cost model inputs and main cost drivers. The proposed cost model is a key step on

an ongoing work concerning the development of a knowledge-based decision aid system dedicated to support the whole value chain associated to additive manufacturing project. Several future improvements on this model could be carried out, by further investigation of overhead and Il-structured costs (such as those associated with build failure, build rent, energy consumption, and administrative overhead), on the other hand extending the model by considering other associated costs with product lifecycle from product concept until the disposal of the product.

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