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Procedia Manufacturing 41 (2019) 280–287

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

8th Manufacturing Engineering Society International Conference

Study and comparison of the different costs' schema associated to geometry, material and processing between 3D printing, injection molding and machining manufacturing technologies

J. Minguella-Canela[a*], S. Morales Planas[b], J.R. Gomà Ayats[a], M.A. de los Santos López[a]

[a] *Centre CIM/Departament d'Enginyeria Mecànica, Universitat Politècnica de Catalunya, Av. Diagonal, 647, 08028 Barcelona, Spain*
[b] *Fluidra S.A., C/Ametllers, 6, 08213 Polinyà, Barcelona, Spain*

Abstract

Cost models to assess and compare the level of expenditure incurred when manufacturing a part by applying different production technologies are of big importance for industrial companies. However, the more precise a cost model is, the more information is needed in order to complete the costs calculation; thus, rising an emergent need for simplified yet accurate enough cost models. Building on a real industrial case study from a company dedicated to the supply of spare parts, the present paper starts proposing a categorisation of products capable of describing the level of added value of a part -being considered as high, average or low. Also, the paper proposes a simplified mathematical model for calculating and comparing parts costing, considering some estimators for geometry, material use and process complexity in the part. The model is applicable to calculate the production costs of a part made via additive manufacturing, injection molding and machining technology. Considering that other product-associated cost factors (such as logistic costs, warehousing, etc.) remain constant, the model can be utilized to compare the different production options and to advise which one would be more cost-effective to be applied. Finally, the cost models are applied to four products of high or average added value from the industrial company analyzed. In this application, the models reveal an acceptable level of cost approximation only in the cases of additive and subtractive manufacturing technologies.

Keywords: Additive manufacturing, 3D printing, costs, modelling, spare parts, machining.

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* Corresponding author. Tel.: (+34) 93 405 42 85
E-mail address: joaquim.minguella@upc.edu

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Peer-review under responsibility of the scientific committee of the 8th Manufacturing Engineering Society International Conference.

1. Introduction

1.1. Cost schemas

Cost schemas are of vital importance in manufacturing decision-making. Most cost schemas normally take into consideration the major cost generating drivers as factors for elaborating the calculations [1]; namely: machinery, raw material, labour and location. Additionally, some cost models more complete can include warehousing and inventory policies [2], leading to more comprehensive estimations that fully describe the value chain implications from the product origin to the point of sale.

1.2. Comparing costs between conventional manufacturing and additive manufacturing technologies

On the one hand, additive manufacturing technologies yield low set-up costs and thus increase the feasibility of manufacturing unitary lots of parts in a costly (and timely) manner. Therefore, cost incurrence is currently a field carefully evaluated due to the great possibilities in switching from producing via conventional technologies such as machining or moulding to the utilisation of additive manufacturing technologies [3,4].

On the other hand, additive manufacturing processes allow the production of parts with complex designs without penalizing the costs associated with manufacturing. On the contrary, in conventional plastic transformation technologies, the complexity of a part always has implications in the form of an increase of the costs of equipment and associated tooling needed.

1.3. Aims and objectives

The aim of the present paper is to formulate a set of simplified costing schemas for calculating the costs incurred in the manufacturing of products via three different sets of technologies (additive manufacturing, injection moulding and subtractive manufacturing). In order to achieve so, a detailed taxonomy analysis of industrial parts will be addressed. Also, the possibility of obtaining fast cost estimations will be of use for establishing comparisons between the different reviewed manufacturing technologies, and thus the results yield will be compared with other cost frames.

2. Parts' analysis of costs in an enterprise context

2.1. Parts in the stock of the case study company

In order to deploy the costing models and its implications targeted in the present paper, and because of the crossed industry-academia insight of the "*Programa de Doctorats Industrials*", the authors have had access to the enterprise product database of the company "*Unistral recambios*", belonging to the group *Fluidra*. *Fluidra* is a group of companies operating in 45 countries world-wide, employing about 4300 people and dedicated to the development of applications for the sustainable use of water [5]. The applications cover many different solution niches, from outdoor swimming pools to indoor wellness spaces, from water handling systems to facility management accessories and from residential needs to commercial or public uses.

At the present time, *Fluidra* has activated more than 20,000 reference codes throughout its history, consisting of different parts manufactured in different production centres and distributed around the world. *Unistral recambios* is the company in the group dedicated to supply spare parts for maintenance and refurbishment of the products sold. At the present time, the stock of the company has a total of 8403 living references in the portfolio –meaning by living that a potential customer could order any of them. For references with low demand and global marketing, the costs per unit of manufacturing with injection moulding technologies are high and create the specific context where it would be of interest to apply other manufacturing strategies -such as additive manufacturing or even subtractive approaches in certain circumstances of orders of "*one-of-a-kind*", "*two-of-a-kind*" or "*very-few-of-a-kind*".

The parts in the product portfolio are divided in several classification descriptors. Two of main importance in the present study are the following:

- *Part type:* Depending on the material and assembly type of the part. Several types of classification are Plastic parts, Electronics, Chemical products, Mechanical sets, etc.
- *Production rationale:* Divided into two categories, depending on the order origin; *Made to Stock* (*MTS*) and *Made to Order* (*MTO*)

2.2. Costing for batch production

One general manufacturing cost framework [6], suitable for calculating the total manufacturing costs of a batch '*j*' for a given part '*i*' ($C_{BATCH,i,j}$) is presented in Eq. 1:

$$C_{BATCH,ij} = C_{EQU,ij} + C_{LAB,ij} + C_{MAT,ij} + C_{STO,ij} \tag{1}$$

Where the addends represent the following cost drivers:

- $C_{EQU,ij}$: is the cost of the machinery and ancillary equipment utilised in the manufacture of the batch '*j*' of product '*i*', taking into account the effective hours of service from the total expected useful life, as well as the costs related to energy consumption
- $C_{LAB,ij}$: is the cost incurred due to the utilisation of the labour force required to manufacture the batch '*j*' of product '*i*'
- $C_{MAT,ij}$: is the cost of the material used in the manufacture of the batch '*j*' of product '*i*'
- $C_{STO,ij}$: is the cost incurred by having to stock the units of part '*i*' that are not sold at the end of the manufacturing process of the batch '*j*'

Concerning manufacturing processes undertaken in an MTS basis, all the parts manufactured in the batch '*j*' will be stocked and will incur in costs of stock. Concerning orders launched in an MTO basis, the number of units manufactured will equal the quantity of the optimal manufacturing batch '*q*'. This quantity might be the same amount of the order received '*k*' or may have an excess of parts, so '$q \geq k > 0$'. In the case of excess of parts, the difference between '*q*' and '*k*' will be stocked and incur in costs of stock.

2.3. The criteria of added value of a part

When considering conventional plastic transformation manufacturing technologies, -being via injection moulding or via machining operations-, the complexity of a part has a direct impact in the associated tooling costs. Therefore, one suitable indicator for the identification of parts with potential geometrical complexity in a company set of data is the unit manufacturing cost of each specific reference (Reference Cost; $C_{REF,i}$).

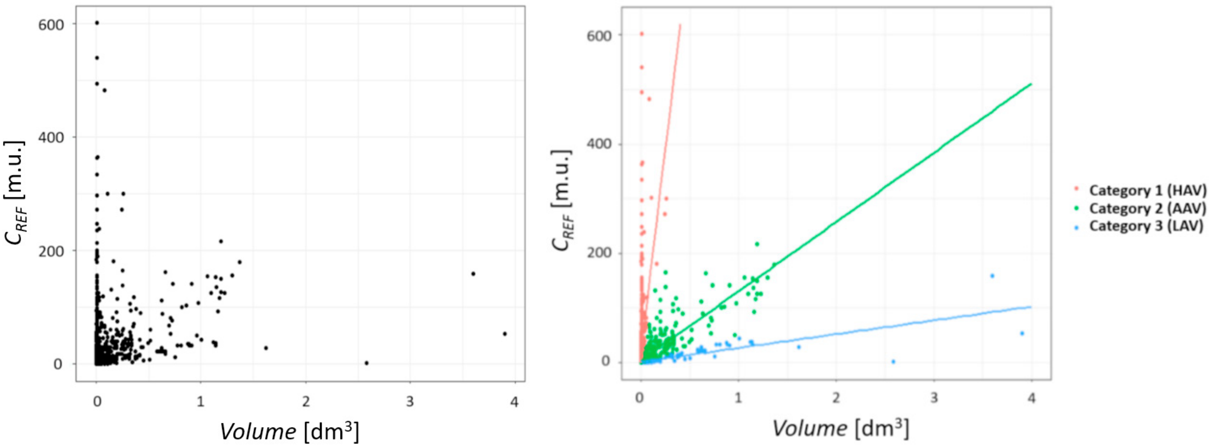
The industrial cost of a reference can be calculated based on the manufacturing cost of a full batch, as shown in Eq. 2, where '*i*' is the particular part reference, '*j*' is the particular batch manufactured, '$C_{BATCH,ji}$' is the cost of manufacturing the batch '*j*' of part '*i*' and '$N_{BATCH,ji}$' is the number of parts '*i*' in the batch '*j*' manufactured:

$$C_{REF,i} = \frac{C_{BATCH,ji}}{N_{BATCH,ji}} \tag{2}$$

As introduced in section 2.2, the manufacturing cost of a batch of products is composed by the addition of the different costs of labour, materials, energy and tooling. Assuming that, when undertaking traditional manufacturing strategies, the cost of tooling will be the most significant one, it can be said that, for a complex design, if the manufacturing costs for the two production systems are compared, the difference between them will always be smaller for a simpler design.

With this rationale, it has been launched a query to the company product database in order to elaborate the dispersion data presented in Fig. 1, which depicts an extraction of 1847 references, consisting of plastic products, manufactured to specific orders (only MTO, and not MTS), with a volume under 4 dm^3 for each part. This set of references represent a 13,7% of the total turnover of the case study company.

As expected by the authors, Fig 1(a) reveals a large density of references that have both low levels of costs (below 100 monetary units) and small volume dimensions (below 0.5 dm^3). However, the study of the entire dotplot chart also reveals three different trends according to the relationship C_{REF} [m.u.] vs. *Volume* [dm^3], which allow clustering the products in three different categories. The first category includes the parts with small volumes but at the same time high costs per part. The second category includes the references whose cost increase in direct relation with parts' volume. Finally, the third category includes references with bigger volumes but with very reduced levels of cost. Fig.1(b) shows the same references plotted in Fig. 1(a), but this time with the products clustered in the three product categories identified.



(a)

(b)

Fig. 1. (a) Dotplot of the unit reference costs (C_{REF}, expressed in monetary units) as function of the envelope volume of a part (Dimensions, expressed in dm^3). (b) Same dotplot but clustering the products in categories 1 (HAV), 2 (AAV) and 3 (LAV).

Indeed, having a close look to the parts clustered in each category, it is possible to identify differentiated groups of products.

- Category 1: Consisting on parts with complex designs, in which, having small part volume (in dm^3), the manufacturing cost is significantly high. This category is formed by, for example, propellers, pump impellers and other parts with intricate geometries.
- Category 2: Consisting on parts that follow a scale-effect trend. In this sense, the larger the plastic part is, the larger are the moulds and tools required to manufacture the part. Larger tooling implies higher manufacturing costs per unit and vice-versa. Some examples of parts in this category are valve components, pump bodies, etc.
- Category 3: Consisting on parts that do not follow a trend of scale. In effect, some of parts in this category have production process highly optimized and very insensible to the effective use of materials. Also, some of these parts have big envelope volumes but with minimum weight, meaning that the use of materials is relatively low. Some examples of products in this category are blow filters, thermoformed filters, etc.

This part segmentation in three categories is useful for qualifying the level of value added of a part in a company. In particular, Category 1 will be recognised as the one for parts with the Highest Added Value (HAV), Category 2 for parts with Average Added Value (AAV) and Category 3 for parts with the Lowest Added Value (LAV). This qualification will be taken into consideration when assessing costs levels and determining different manufacturing strategies. Being capable to apply innovation and new manufacturing solutions that optimize the production costs and the supply chain of these articles will be of the utmost importance for products in Category 1, as these are the products reaching the higher individual reference costs.

3. Simplified mathematical model for comparative parts costing

3.1. Cost drivers and simplified estimators for additive manufacturing

Although the general model presented in *Eq. 1* is a complete model, possible to be applied to calculate costs in additive manufacturing processes, many quotation prescribers prefer to utilise the following parameters as a simplification for obtaining fast estimations of products' costs: (i) Part weight, (ii) part z-dimension and (iii) processing time. These three cost factors cover, in fact, all the cost factors identified in *Eq. 1* except stocking -as presented above: equipment, labour and material costs-.

Additive manufacturing technologies allow the production of parts with complex designs without increasing the costs associated with manufacturing in comparison with a part with the same material content and the same external dimensions. In other words, the cost to manufacture additively a mirror-finish sphere is very similar to the cost of manufacturing a sphere with the same external dimensions and quantity of material but with a fractal design in the surface.

This means that a sensible estimation of the costs incurred by the utilisation of additive manufacturing processes could be obtained by the addition of a function taking into account the contribution of the volume of the part '$f_{AM,t}(V_i)$ ' plus another function taking into account the contribution of the relative size of the part in the layers' direction '$f_{AM,t}(Z_i)$'. Therefore, it is possible to estimate the cost of manufacturing a single part via additive processes ($C_{AM,\,i}$) by utilising the following expression presented in Eq. 3.

$$C_{AM,i} = f_{AM,t}(V_i) + f_{AM,t}(Z_i) \tag{3}$$

Or, deploying the cost factors into specific parameters, as presented in Eq. 4:

$$C_{AM,i} = \alpha_{AM,t} \cdot V_i + \beta_{AM,t} \cdot Z_i \tag{4}$$

Which considers the following parameters and cost factors:

- $\alpha_{AM,t}$*:* is a parameter for a specific additive technology '*t*' that adjusts the influence of the volume of the manufactured part '*i*' in the additive manufacturing cost estimation
- V_i*:* the volume of the part '*i*'
- $\beta_{AM,i}$*:* is a parameter for a specific additive technology '*t*' that adjusts the influence of the maximum height of the manufactured part '*i*' in the additive manufacturing cost estimation
- Z_i*:* the maximum height of the part '*i*' once located in the additive manufacturing construction platform

3.2. Cost drivers and simplified estimators for injection moulding manufacturing

Among the parameters that mostly affect the cost of an injection moulding part are (i) Part weight, (ii) Mould complexity (including the number of cavities, the complexity of the part to be casted) and (iii) Process complexity (including whether it is a hot or cold cast moulding and whether it is an automatic or manual mould).

Following an analogous approximation as undertaken in the case of additive manufacturing processes, this means that a sensible estimation of the costs incurred by the utilisation of injection moulding processes could be obtained by the addition of a function taking into account the contribution of the volume of the part '$f_{IM,Raw}(V_i)$ ' plus another function taking into account the contribution of the complexity of the part '$f_{IM,Part}(S_i)$' and finally another function taking into account the contribution of the complexity of the process '$f_{IM,Proc}(S_i)$' When combining all these functions in a single expression, it is obtained an estimation for '$C_{IM,i}$' as presented in Eq. 5.

$$C_{IM,i} = f_{IM,Raw}(V_i) + f_{IM,Part}(S_i) + f_{IM,Proc}(S_i) \tag{5}$$

Or, deploying the cost factors into specific parameters, as presented in Eq. 6:

$$C_{IM,i} = \alpha_{IM,Raw} \cdot V_i + \gamma_{IM,Part} \cdot S_i + \rho_{IM,Proc} \cdot S_i = \alpha_{IM,Raw} \cdot V_i + \left(\gamma_{IM,Part} + \rho_{IM,Proc}\right) \cdot S_i \tag{6}$$

Which considers the following parameters and cost factors:

- $\alpha_{IM,Raw}$: is a parameter that adjusts the influence of the raw material of the manufactured part 'i' in the injection moulding manufacturing cost estimation
- V_i: the volume of the part 'i'
- $\gamma_{IM,Part}$: is a parameter that adjusts the influence of the mould complexity of the manufactured part 'i' in the injection moulding manufacturing cost estimation
- $\rho_{IM,Proc}$: is a parameter that adjusts the influence of the process complexity of the manufactured part 'i' in the injection moulding manufacturing cost estimation
- S_i: *is* the surface of the part 'i'

3.3. Cost drivers and simplified estimators for machining manufacturing

The general undertaking of a subtractive process to obtain a part contains several paths of a tool-head through the raw material in order to remove the material excess in the places where needed. Generally speaking, some of the tool paths are for rough machining and some others are intended for the surface finishing. Therefore, many quotation prescribers in industrial machining sectors utilise the following parameters as a simplified approximation for obtaining fast estimations of products' costs: (i) Part weight, (ii) Part rough machining time and (iii) Part finishing time. These three cost factors cover somehow all the cost factors identified in Eq. 1 except stocking -as presented above: equipment, labour and material costs-.

With this rationale, and like the previous cases, it is possible to estimate the cost of manufacturing a single part via subtractive manufacturing processes ($C_{SM,\,i}$) by utilising the following expression presented in Eq. 7.

$$C_{SM,i} = f_{SM,Raw}(V_i) + f_{SM,RM}(V_i) + f_{SM,FM}(S_i) \tag{7}$$

Or, deploying the cost factors into specific parameters, as in *Eq. 8*:

$$C_{SM,i} = \alpha_{SM,Raw} \cdot V_i + \delta_{SM,RM} \cdot V_i + \theta_{SM,FM} \cdot S_i = \left(\alpha_{SM,Raw} + \delta_{SM,RM}\right) \cdot V_i + \theta_{SM,FM} \cdot S_i \tag{8}$$

Which takes into account the following parameters and cost factors:

- $\alpha_{SM,Raw}$: is a parameter that adjusts the influence of the raw material of the manufactured part 'i' in the subtractive manufacturing cost estimation
- V_i:*is* the volume of the part 'i'
- $\delta_{SM,RM}$: is a parameter that adjusts the influence of the Rough Machining paths of the manufactured part 'i' in the subtractive manufacturing cost estimation
- $\theta_{SM,FM}$: is a parameter that adjusts the influence of the Finishing Machining paths of the manufactured part 'i' in the subtractive manufacturing cost estimation
- S_i: *is* the external surface of the part 'i'

4. Case study application in four products of the company portfolio

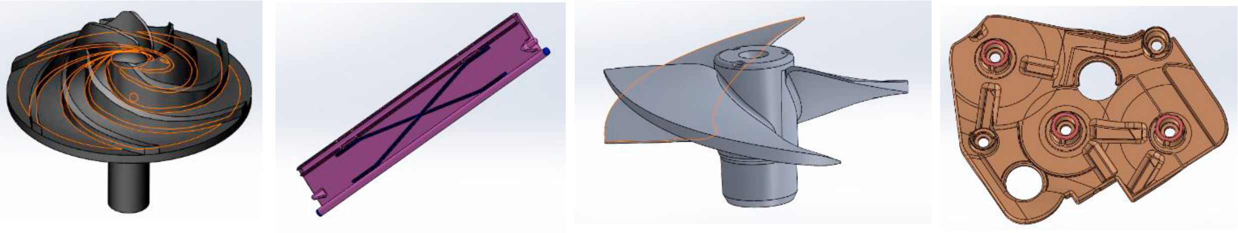
4.1. Parts selection for the evaluation costs by the different models

In order to apply the different simplified cost models and so to find if they have a suitable match with the results yield by the general costing models, four specific parts have been selected; namely: (a) Pump impeller, (b) Filter cover, (c) Propeller and (d) Bearing plate. The four parts are depicted in Fig. 2.

All these parts are currently being manufactured by means of injection moulding. This means that:

- Part (a), with an envelope volume of 0.023 dm^3 and a cost of 90.12 m.u., is an HAV part (Category 1).
- Part (b), with an envelope volume of 0.006 dm^3 and a cost of 62.44 m.u., is an AAV part (Category 2).
- Part (c), with an envelope volume of 0.009 dm^3 and a cost of 65.14 m.u., is an AAV part (Category 2).
- Part (d), with an envelope volume of 0.017 dm^3 and a cost of 113.91 m.u., is an HAV part (Category 1).

As it can be seen in the categorisation of the selected parts, it has not been chosen any part belonging to Category 3 (LAV). This is because, having already a very low-cost level, the parts in Category 3 are the ones that have the lowest impact in the total costs of the company.



(a) (b) (c) (d)

Fig. 2. Parts utilised in the match evaluation of costs estimations by different models: (a) Pump impeller, (b) Filter cover, (c) Propeller and (d) Bearing plate.

4.2. Determination of the costs incurred with the complete costing method

For the four references selected, the manufacturing costs of each part have been calculated utilising the cost model presented in section 2 [6]. For the calculations of the costs incurred in additive manufacturing, the costs levels refer to the utilisation of Multi Jet Fusion technology as technology '*t*'. Table 1 summarises the results of the costs calculated for the four products selected. Also, it is important to mention that given that the geometry of the Propeller would require a 5-axis machining, machining is not considered an applicable process to the manufacturing of Part (c).

Table 1. Determination of the costs incurred with the complete costing method.

	Part (a) – Pump impeller	**Part (b) – Filter cover**	**Part (c) – Propeller**	**Part (d) – Bearing plate**
C_{AM} [m.u.] (N_{BATCH} = 1)	6.97	1.33	2.28	4.27
Optimal batch size for IM	200	150	150	300
C_{IM} [m.u.] (N_{BATCH} = optimal batch size)	90.12	62.44	65.14	113.91
C_{SM} [m.u.] (N_{BATCH} = 1)	130	55	Not Applicable	145

4.3. Estimation of the costs incurred with the simplified costs schemas

In order to utilize the simplified costs schemas, it is necessary to obtain the values required for each of the above-mentioned parameters. Having been done the determination of coefficients by means of multiple linear regression on the scattered set of points proposed by the company inventory, the results are presented in Table 2.

Table 2. Determination of the values of the parameters for the simplified costs schemas.

Parameters for additive manufacturing		**Parameters for injection moulding**		**Parameters for subtractive manufacturing**	
$\alpha_{AM,t}$	$\beta_{AM,t}$	$\alpha_{IM,Raw}$	$\gamma_{IM,Part} + \rho_{IM,Proc}$	$\alpha_{SM,Raw}$	$\delta_{SM,RM} + \vartheta_{SM,FM}$
309.22	-47.85	-2620.96	84.18	1222.92	84.08

Once the parameters are obtained, the manufacturing costs of each part have been calculated utilising the simplified cost models presented in section 3. Again, in the calculations of the costs incurred in additive manufacturing, the costs levels refer to the utilisation of Multi Jet Fusion technology as technology '*t*'. Table 3 summarises the results of the costs calculated for the four products selected.

Table 3. Determination of the costs incurred with the simplified costs schemas.

	Part (a) – Pump impeller	Part (b) – Filter cover	Part (c) – Propeller	Part (d) – Bearing plate
Surface [dm^2]	1.88	0.72	0.77	1.89
Z height [mm]	12.23	8.34	11.69	8.59
C_{AM} [m.u.]	6.52	1.46	2.22	4.85
error [%] for C_{AM}	6.36	9.52	2.47	13.49
C_{IM} [m.u.]	97.97	44.88	41.23	122.12
error [%] for C_{IM}	8.72	28.12	36.71	7.21
C_{SM} [m.u.]	129.95	53.20	Not Applicable	145.70
error [%] for C_{SM}	0.04	3.27	Not Applicable	0.48

5. Conclusions and future work

The access to the company product database makes possible to obtain a large set of data composed by 1847 references, consisting of plastic products, manufactured to specific orders (only MTO, and not MTS) and with an envelope volume under 4 dm^3 for each part. The analysis of these references reveals three different trends that make possible to cluster the products into three different product categories related to the level of added value for each part (HAV, AAV and LAV).

The proposition of a simplified mathematical model for parts costs calculation has been undertaken for (i) additive manufacturing processes, (ii) injection moulding processes and (iii) machining. For each of them, the calculation of the processes parameters is estimated with the filtered product dataset.

Finally, four references are selected, and their manufacturing costs are calculated, first by a general costing method (Hopkinson & Dickens) and secondly with the simplified costs methods presented. The results obtained by the simplified estimators demonstrate a suitable level of approximation to the detailed calculations in the cases of additive manufacturing and subtractive manufacturing, while the fit in the case of injection moulding technologies is still very weak. Therefore, the simplified methods for these two technologies could be used as proper cost estimators in future technology assessments. Moreover, considering that other product-associated cost factors (such as logistic costs, warehousing, etc.) remain constant, these simplified methods could also be used to compare cost levels within different manufacturing technologies and so to decide which strategy would be more cost-effective to be undertaken for the fabrication of a specific part.

Acknowledgements

The authors would like to thank the "*Agència de Gestió d'Ajuts Universitaris i de Recerca*" (AGAUR) of the "*Generalitat de Catalunya*", which cofounded this research under the schema "*Programa de Doctorats Industrials*", with grant number 2015DI29.

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