Joint Special Interest Group meeting between euspen and ASPE
Dimensional Accuracy and Surface Finish in Additive Manufacturing,
KU Leuven, BE, October 2017
www.euspen.eu

Cost estimation of a specifically designed direct light processing (DLP) additive manufacturing machine for precision printing

Alessandro Charalambis[1], Ali Davoudinejad[1], Guido Tosello[1] and David Bue Pedersen[1]

[1] *Department of Mechanical Engineering, Technical University of Denmark, Building 427A, Produktionstorvet, 2800 Kgs. Lyngby, Denmark*

Abstract
Additive Manufacturing (AM) refers to a portfolio of novel manufacturing technologies based on a layer-by-layer fabrication method. The market and industrial application of additive manufacturing technologies as an established manufacturing process have increased exponentially in the last years creating new opportunities for manufacturers in a variety of industrial sectors. AM is an essential prototyping technique for product design and development that is used in many different fields. However, the suitability of AM applications in actual production in an industrial context needs to be determined. This study, presents a cost estimation model for precision printing with a specifically designed Digital Light Processing (DLP) AM machine built and validated at the Technical University of Denmark. The model presented in this study can be easily adapted and applied to estimate within a high level of confidence the cost of any part manufactured with the mentioned 3D printing technology.

Keywords: Additive manufacturing, cost estimation, digital light processing, precision printing

1. Introduction

The aim of this research is to propose a method to estimate with a good confidence level the cost of a part manufactured by additive manufacturing (AM). More specifically, this study will focus on the use of Digital Light Processing (DLP) technology for precision manufacturing of miniaturized parts. DLP is a vat-photopolymerization technology [1] that selectively solidify layer-by-layer the part by application of a UV-light to a photo-sensitive polymer. Figure 1 shows the part that is used as application case study for this cost model: a cuboid with a dimension of $12 \times 12 \times 4\ mm^3$ and equipped with different sets of micro-features on its surface.

The historic use of AM has been for prototyping, fabrication of functional parts and parts to be tested for design purposes [2]. One of the reasons among others that circumscribed the use of 3D printing to rapid prototyping is also due to the often expensive manufacturing process that makes AM cost effective for small production series [2]–[4]. The key success of AM application as production technology in industrial context on a "comprehensive and realist cost justification for its use" [2].

Previous cost models and economic considerations for AM have relied on the concept of substituting IM or other conventional manufacturing processes with AM for fabrication of parts [5]–[7]. Rather than applying AM to replace conventional manufacturing processes, this study attempts to propose a cost estimation model for AM that is employed to support such processes. Moreover, a cost estimation model for DLP technology has not yet been discussed or presented in available literature [8] hence it acquires a particular interest to propose such cost estimation model.

2. Methodology

The investigated application case study considers the fabrication of the part shown in Figure 1 on a DLP machine that has been developed and built at the Technical University of Denmark. The cost model presented in this study is the result of a parametric cost modelling that included a conspicuous number of parameters used as input for the cost model.

Three main steps have been followed in the development of the present cost model for DLP:

a) Identification of the main cost components that affect the cost per part;
b) Development of the mathematical relationship between the process parameters;
c) Allocation of overheads costs to the model.

The methodology applied to this cost model can be adapted to other 3D printing technology. However, the parameters that have been used and modelled as well as some key considerations are limited to DLP technology. The assumptions stated and considered for DLP hold also for AM technologies belonging to the vat-photopolymerization processes.

This cost model can be applied and used to estimate the cost of other parts as long as they fulfil the constraints of maximum part dimension given by the machine building envelope and the use of light-activated resin material.

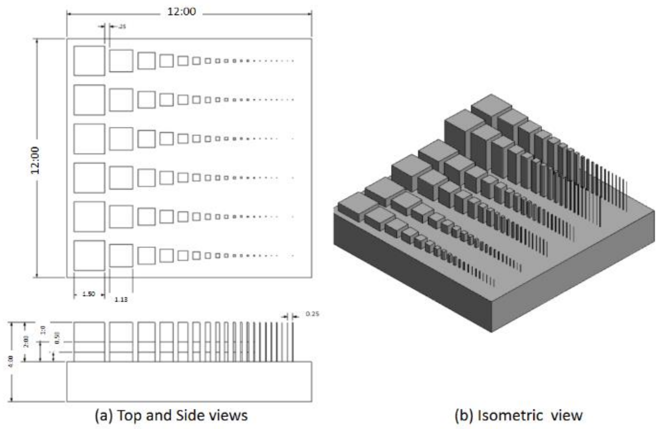

Figure 1. Drawing of the test part (a) Top & side views and (b) Isometric view (dimensions in mm)

2.1. DLP cost model

The investigated cost model has been developed for DLP that was chosen as it is one of the most accurate AM technology available in the market [2], [10]. The cost model presented in this study is applied to a DLP machine that is equipped with a vat filled with a light-activated resin, a horizontal platform holding the part and moving vertically for printing each layer. The part geometry is projected layer by layer in the vat where the part selectively solidifies following the photopolymerization process.

The process of DLP involves mainly three steps starting from pre-processing activities, moving the fabrication process and ending with post-processing activities. Pre-processing activities involve:

a) determination and selection of material;
b) definition of layer thickness of the part, printing parameters, build style, verification of the STL file and resolution of any errors;
c) choice of part orientation taking into consideration the trade-off between surface quality and building speed;
d) definition and generation of support structures if necessary.

The second step is the fabrication of the part where a top-down layer-by-layer manufacturing process is carried out. Lastly, post-processing activities includes:

a) clean the part from liquid resin;
b) remove support material;
c) dry the part;
d) post curing into a UV light oven;
e) sanding, grinding or machining as needed to achieve the desired level of surface finish and/or for the fitting purpose.

It follows that the cost of a part manufactured with DLP technology can be calculated considering the effect of five main cost elements: pre-processing cost, material cost, processing cost, post-processing cost, and overheads cost as show in the following equation.

$$C_{DLP} = C_{pp} + C_{pr} + C_m + C^{pp} + C_{ov} \quad (1)$$

C_{DLP} is the unit cost for parts fabricated on the DLP machine ($€/part$), C_{pp} the unit cost for pre-processing ($€/part$), C_{pr} the unit cost for manufacturing a part ($€/part$), C_m the unit cost for material ($€/part$), C^{pp} the unit cost for post-processing ($€/part$), and C_O the unit cost of overheads ($€/part$). Each cost component will be further described and broke down in the following equations.

Equation (2) describes the cost for pre-processing activities that is affected among others by the part size, desired level of surface finish to achieve, material selection, and part orientation.

$$C_{pp} = \frac{C_{Op}}{N} \times T_{SW} \quad (2)$$

The hourly operator cost including overheads is defined as C_{Op}(€/hour), N is the number of parts that can be printed in the same build and it depends on the size of the building envelope and the part orientation chosen. T_{SW} (hour) is the time used to setup the print job and chose the initial setting.

In order to estimate the cost to print a part it is considered a simple mathematical relation between the machine cost per hour and the time spent to build a part as shown in Eq. (3):

$$C_{\mathrm{Pr}} = C_h^M \times \frac{T_B}{N} \quad (3)$$

where C_h^M is the hourly cost of the DLP machine (€/hour), T_B is the printing time (hour). It is important to highlight that it is possible to incur in some errors during the printing of a part hence it is chosen to account for possible failures in the building through the use of the factor δ = [5% , 20%]. Previous studies show that errors during the printing process can be linked with the experience of the operator that is handling the machine [11]. It was then chose to set the build error at 5% for an experienced operator and 20% for operators that do not have a high degree of experience with DLP. The error factor delta is introduced in the building time as follow: $T_B = T_B/(1-\delta)$. Considering that N parts can be built in the same build, the time to complete the build is distributed over the number of parts manufactured simultaneously. Equation (4) describes the mathematical expression used to calculate the hourly cost of the machine.

$$C_h^M = \frac{C_I}{Y} \times \frac{1}{\sigma \times H} \quad (4)$$

C_I is the investment cost in the machine (€), Y is the machine lifetime (year), σ is a factor attributed to the machine utilization (%), and H is the total number of hours the machine can work in a year (hour/year). It is noticeable to be highlighted that the present model is applied to a specifically designed DLP additive manufacturing machine that has been manufactured at the Department of Mechanical Engineering of the Technical University of Denmark. Therefore, its use has been limited for production linked with research studies. As a consequence it was then chose to use in the cost estimation model an utilization equal to 57% as discussed in [6].

Cost for the material used in the printing process is estimated starting with the price of material per litre and multiplied for the total volume of the part in the build as shown in the equation below.

$$C_m = C_{lt}^m \times V_b \quad (5)$$

C_{lt}^m is the cost of material per litre used (€/lt) and V_b is the total volume of the build that includes the volume of a part, support structures and material wasted during the printing process. Based on observation, the total volume filled by the part in the vat is around 70% of the total volume used in the build. Therefore, the total volume used in the build, V_b can be estimated applying Eq. (6a, 6b).

$$V = V_{part} + V_{support} + V_{waste} \quad (6a)$$

$$V = \frac{V_{part}}{0.7} \quad (6b)$$

$V_{support}$ is the volume used for support structures in the build (litre), V_{waste} is the amount of material that is waste (litre).

Equation (7) breaks down the cost for post-processing activities, which includes removal of support material, post-curing, dry, and machining the part.

$$C^{pp} = \frac{C_{Op} \times T^{pp}}{N} \quad (7)$$

The time to post-process the part T^{pp} (hour) is the sum of the time to remove support material T_{SR}, time to post-cure T_{pc}, time to dry the part T_{pd} and the time required to machine the part T_{Mc} as shown in Eq. (8):

$$T^{pp} = T_{SR} + \alpha \times (T_{pc} + T_{pd} + T_{Mc}) \quad (8)$$

Since the post-processing activities can be applied to more than one part at the same time, the total time used for post-processing is distributed over the number of parts that are printed in the same build, N. Moreover, to account for the time the operator is required to post-process DLP parts, the factor α (%) is used.

The last cost component considered in this estimating model is the cost for overheads. Previous cost models [12] neglected the overhead cost by assuming that their contribution is less than 1% of the total unit cost. However, a more recent cost model [6] that was built based on the model of [12] discussed the importance of overheads cost that account for a 10% of the total unit cost. Therefore, it is chosen to have an accurate estimation of the cost of a part manufactured with DLP and overheads cost are introduced in the following equation:

$$C_{ov} = \frac{C_{el} + C_{Sr} + C_{Me}}{N} \quad (9)$$

The cost for electricity usage C_{el} (€/part) is calculated considering the amount of electricity consumed by the machine E (KWh), the cost per kilowatt of electricity consumed C_e (€/KW) and divided by the number of parts manufactured in a hour P (part/hour) as shown in Eq. (10).

$$C_{el} = \frac{E \times C_e}{P} \quad (10)$$

It follows that the cost to rent the facility C_{Sr} (€/part) is estimated by multiplying the amount of space used by the machine S (m^2) and the cost for square meter used C_s (€/m^2) and divide the whole by the number of hours the machine works in a year $(H \times \sigma)$, which is multiplied by the amount of parts manufactured in a hour P. Equation 11 summarizes what just described.

$$C_{sr} = \frac{S \times C_s}{\sigma \times H} \times P \quad (11)$$

Lastly, the maintenance cost C_{Me} (€/part) is usually charged as a service cost from the machine manufacturer and equal to 10% of the machine purchase price. The yearly maintenance cost C_{Me}^{y} (€/year) is then distributed over the hours the machine works in a year $(\sigma \times H)$ and multiplied by the number of parts per hour H. Equation (12) show the mathematical equation used to estimate the maintenance cost per part.

$$C_{Me} = \frac{C_{Me}^{y} \times P}{\sigma \times H} \quad (12)$$

3. Results

The cost model described and introduced in the previous section has been adapted and used to calculate the cost for the part shown in Figure 1. The results of the present cost estimation model are summarized in Table 1, which breaks down each cost component and parameter of the model by using specific values.

As it is possible to notice, for some parameter is challenging to find a unique value as there are many different configurations that can lead to several scenarios and results. Therefore, it was chosen to use a range of values to introduce a minimum and maximum value that a parameter can have and that was considered in the present cost model. Consequently, variables that are dependent on parameters having more than one value, inevitably result in more than two values (e.g. pre-processing cost).

It is of particular interest to notice that manufacturing a part with dimensions of $12 \times 12 \times 4\,mm^3$ on the studied DLP machine can lead to a minimum cost per part of 13,48€ and up to 50,82€. One of the main advantages that this DLP machine is the level of accuracy down to 1 µm resolution in the z-stage, a fast building process. Moreover, it is important to consider that in this application case is chosen to set a utilization rate of the machine equal to 57% of the total amount of time available. A higher utilization rate, equal to 80-90% would decrease the production cost and make the unit cost even lower than already achievable. A high utilization level is feasible to be met for AM applications in industrial contexts where manufacturers heavily rely on AM machines for its application to different purposes (e.g. prototyping, functional parts, spare parts, jigs & fixtures, small production series,…).

Another interesting consideration that is possible to draw from the cost per part resulting from the cost estimation model, is the high cost of human labour related activities. A breakdown of the cost components and their analysis shows that pre-processing cost, which requires an operator for the whole time, is the largest source of components because of the high cost of labour related activities. However, in the previous cost model for AM carried out by Ruffo et al. [6] the cost per hour of an operator in a western European country amounts to 14 €/hour. It would then have a huge impact on the cost per part leading to a minimum unit cost of 3,95€ and a maximum of 11,80€. In this case, a decrease of 79% in the hourly operating cost would not only reduce the unit cost per part by around 70%. However, the five cost components of DLP would have a much more balanced cost split meaning that labour related activities would not account for such larger split of the unit cost compared to the other activities.

Table 1. Detailed cost breakdown for DLP manufactured parts

Description (unit)	Value
Parts per build (*N*)	[1; 2]
Operator cost (*€/hour*)	67,20
Setup time (*min*)	[15; 20]
Pre-processing cost (€)	***[8,40; 11,20; 16,80; 22,40]***
Purchase machine (€)	36.000,00
Depreciation time (*year*)	[2; 3]
Utilization (*%*)	57
Hours per year (*hour*)	8760
Machine cost per hour (*€/hour*)	[2,40; 3,60]
Time to build (*min*)	30
Printing failure (*%*)	5
Production cost (€/part)	***[0,63; 0,95; 1,26; 1,90]***
Productivity (part/hour)	[2; 4]
Cost of material (*€/lt*)	65
Part volume (*cm*^{3})	0,32
Volume of the build (*lt*)	$[5 \times 10^{-4}; 9 \times 10^{-4}]$
Material cost (€)	***0,03***
Support removal (*min*)	[5; 15]
Post curing time (*min*)	[5; 15]
Drying time (*min*)	[5; 15]
Machining time (*min*)	[5; 15]
Manual labour in post-processing (*%*)	[10; 20]
Post-processing time (*hour*)	$[\frac{1}{2};1]$
Post-processing cost (€)	***[3,64; 4,48; 7,28; 8,96; 10,92; 13,44; 21,84; 26,88]***
Maintenance cost per year (€/year)	400
Maintenance cost per hour (€/hour)	0,08
Maintenance cost per part (€/part)	[0,16; 0,32]
Machine electricity consumption (kWh)	0,25
Cost of electricity (€/kWh)	0,091
Cost of electricity per part (€/part)	[0,01; 0,005]
Cost for sqm of space per year (€/m^2)	17
Space used by the machine (m^2)	10
Cost of space per part (€/part)	[0,07; 0,14]
Overhead cost per part (€/part)	***[0,24; 0,47]***
Cost per part (€/part)	***[13,48; 14,32; 23,25; 25,77; 26,25; 27,93; 45,78; 50,82]***

4. Conclusion

The present research contributes to the field of AM by proposing a cost estimation method that can be applied on DLP technology. More specifically, the cost estimation model for DLP can be easily adapted to the fabrication of different parts in size, material, and level of complexity as long as those parts have been manufactured with DLP.

Creating a method to estimate the cost of a part manufactured with DLP technology has a great potential in the continuously evolving field of AM. In an industrial context, many decisions are driven by the cost advantages that a technology or solution can offer. Therefore, estimating with a good level of confidence the cost of a part manufactured with an AM technology has the opportunity to offer a tool to use in management-based decisions that involve AM.

This study demonstrated that promising opportunities for DLP production of parts both in terms of process capability and costs. This cost estimation model represents a source of novelty in introducing a new tool to foster the adoption of DLP technology. Previous research in the realm of cost modelling for AM have focused on other AM technologies and on the economic aspects of replacing conventional manufacturing processes with AM. With the present cost model, the objective is to reflect with a reliable cost estimation of a part manufactured with DLP for its use as direct manufacturing technology or as support technology to conventional manufacturing processes.

References

[1] ASTM International, "Standard Terminology for Additive Manufacturing Technologies – General Principles – Terminology," Iso/Astm 52900, vol. **i**, pp. 1–9, 2015.

[2] Wohlers Associates, "Wohlers Report 2017 - 3D Printing and Additive Manufacturing State of the Industry," 2017.

[3] D. L. Cohen, "Fostering Mainstream Adoption of Industrial 3D Printing: Understanding the Benefits and Promoting Organizational Readiness," *3D Print. Addit. Manuf.*, vol. **1**, no. 2, pp. 62–69, 2014.

[4] T. Hofstätter et al., "Comparison of Conventional Injection Mould Inserts to Additively Manufactured Inserts Using Life Cycle Assessment," *Euspen's 16th Int. Conf. Exhib.*, no. **May**, 2016.

[5] M. Franchetti and C. Kress, "An economic analysis comparing the cost feasibility of replacing injection molding processes with emerging additive manufacturing techniques," *Int. J. Adv. Manuf. Technol.*, pp. 2573–2579, 2016.

[6] M. Ruffo, C. Tuck, and R. Hague, "Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. **220**, no. 9, pp. 1417–1427, 2006.

[7] D. S. Thomas and S. W. Gilbert, "Costs and Cost Effectiveness of Additive Manufacturing - A Literature Review and Discussion," *NIST Spec*. Publ., vol. **1176**, 2014.

[8] D. Thomas, "Costs, benefits, and adoption of additive manufacturing: a supply chain perspective," *Int. J. Adv. Manuf. Technol*., pp. 1–20, 2015.

[9] M. Mischkot, H. N. Hansen, and D. B. Pedersen, "Additive manufacturing for the production of inserts for micro injection moulding," in *Euspen's 15th International Conference & Exhibition*, 2015, no. **June**, p. 2.

[10] I. Gibson, D. Rosen, and B. Stucker, Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. *Springer*, 2014.

[11] M. K. Thompson et al., "Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints," *CIRP Ann. - Manuf. Technol*., vol. **65**, no. 2, pp. 737–760, 2016.

[12] N. Hopkinson and P. Dicknes, "Analysis of rapid manufacturing using layer manufacturing processes for production," *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. **217**, no. 1, pp. 31–39, 2003.