Systematic proposal to calculate price of prototypes manufactured through rapid prototyping an FDM 3D printer in a university lab

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Abstract

Purpose – The purpose of this paper is to propose a systematic study to formulate the cost of prototypes manufactured through rapid prototyping (RP) an fused deposition modeling (FDM) 3D printer in a university lab.

Design/methodology/approach – The paper has a theoretical-conceptual approach. This approach is carried out by studying and proposing a methodology for calculating the cost of pieces prototyped an FDM 3D printer.

Findings – This work originated from a gap in literature to establish a way to calculate the price of RP pieces from FDM 3D printers in universities' labs, since no similar work has dealt with this RP technology and has not taken into account the costs of post-processing step. The results suggest that the formulation may be used to calculate price of prototyped pieces through FDM 3D printer.

Research limitations/implications – The systematic approach proposed by this research to formulate cost for the RP pieces is initially oriented only to modelling technique by FDM 3D printer. Considerations on operator's and designer's hourly rates are those practiced in Brazil, which may differ from other countries.

Originality/value – The paper's scientific contribution is a specific formulation to calculate price of prototyped pieces through FDM considering the post-processing way, which differs from previous published works. The formulation implies that the execution times and the amount of material used were obtained by internal calculation of the tested machine. This is different from what has been already studied by previous literature which considers an index that encompasses the machine operation cost in function of time. It is aimed that the results obtained here are accurate, since error margins of the process variables are reduced.

Keywords Brazil, Rapid prototypes, Modelling, Production costs

Paper type Conceptual paper

1. Introduction

In the 1980s, a new machine technology appeared that allowed piece modelling from a three-dimensional (3D) model generated in a CAD system. Such machines known as rapid-prototyping (RP) machines, permit one automatically obtains finished physical pieces with any shape and final dimensions with such a complexity and details that conventional machining could not afford. The machines used here promote a higher speed and lower cost in manufacturing prototypes with a time reduction in the product development. Moreover, they reduce risks that belong to the initial phases of the process without competing with the productive resources of the organization.

However, there is a question to the centers responsible for manufacturing pieces using RP machines that is: how to calculate the price of a piece manufactured with RP?

To answer this question, the present work has as its main goal to propose a procedure to the cost formulation for pieces manufactured by RP using fused deposition modeling (FDM) technology.

Some works have already suggested techniques to calculate prototyped pieces (Xu *et al.*, 2000). Nevertheless, they did not have FDM technology. Moreover, their formulas did not include post-processing costs.

This project approaches a theoretical-conceptual issue, as it is found in Filipini (1997). This approach is carried out by studying and proposing a methodology for calculating the cost of pieces prototyped by FDM.

This technique is one of the fewest RP processes available in the market that offers real possibilities of producing solid objects in a different range of materials, including metals and

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composites (Masood, 1996), although Agarwala *et al.* (1996) mention that the ceramics can also be used.

The FDM 3D printing technology was chosen for it is the one that offers the lowest expensive tools (Kochan, 2000), that is, tools that are affordable by small and average enterprises and research centers. Moreover, the research unity chosen, Federal University of Itajubá (UNIFEI), has a RP machine, Dimension SST 768 manufactured by Stratasys. This machine uses FDM technology. For that being so, the cost calculation systematic put forward here is limited to adapt itself to the equipment and technology.

2. Proposed procedure for cost formulation

The definition of costs due to product development process, specifically the process belonging to the FDM, will permit to name and classify cost components. Therefore, it will be possible to make a budget on a prototype generation with the FDM technique.

According to Horngren *et al.* (2007), a product or service costs may be classified as follows:

- *Direct*. All the costs that can directly be attributed to something; they may be related to a consumption rate of material or service using a measurement which is relative to the process.
- *Indirect*. All the costs that do not have a factor or criterion through which the costs may be attributed to products or services, normally in a random way or in an allotment basis.
- *Variable*. All the costs that have changes in their values proportional to the volume produced or to the work pace of the productive system.
- *Fixed*. The nature of these costs is independent of the increase or decrease of the volume produced; it is kept stable within determined limits.

Among these classifications, it is still possible to sub-classify costs in variable direct costs or in fixed direct costs.

The elements which are considered to be part of prototype manufacturing process, through FDM, are classified according to their accounting nature as:

- *Model material filament*: *variable direct cost.* The material consumption varies according to the volume and matter of the model to be manufactured.
- *Machine work per hour*: *variable direct cost.* The prototype manufacturing time depends on geometry specifications as well as on required finishing.
- *Ultrasonic bowl work per hour*: *variable direct cost.* The ultrasonic bowl time depends on both the amount of support material dissolved and the number of parts processed.
- *Energy*: *variable indirect cost.* The energy consumption is in function of the hour load required to the prototype manufacturing and having as its attribution allotment basis, the power needed by each one of the elements belonging to the general process (STL processing, model execution and prototype post-processing).
- *Soap*: *variable direct cost.* The soap volume used for the post-processing stage has a common value and it varies according to both the amount of support material dissolved and the number of parts processed.
- *Labor*: *fixed direct cost.* The labor cost is exclusive to 3D model prototype manufacturing and it does not vary with the increase of mass and volume of manufactured models. In this particular case, the operator and the designer are full-time university technical/administrative staff of the university, whose single job is to supervise the RP process.
- *Supporting material filament*: *variable direct cost.* Similarly to model filament and machine work per hour, the cost of supporting material is proportional to the prototype specifications and dimensions to be manufactured.
- *Maintenance*: *variable indirect cost.* Maintenance may not be attributed directly to the whole process having into account the execution time of each component, since the execution is schedule according to a calendar base. However, it is applied periodically in function the execution hours and it does keep constant among its application.

Xu *et al.* (2000) suggest a specific cost analysis model to RP processes. This model is based on prototype expenses by dividing the manufacturing into three stages: CAD file processing, execution and post-processing.

Xu *et al.* (2000) claim that processing time is basically similar to most processes, except for some cases, for instance, FDM appliance where manufacturing techniques need to process STL with support material output. Material support development, slicing and transformation imply more processing time (T_p) and, therefore, higher cost to the prototype.

This condition is checked within the analysis carried out for the present work and the relation that defines processing cost (C_P) is given by equation (3.1):

$$C_p = \left(\frac{0,2 \times C_{pc}}{W_{at}} + \omega_d + PC_e \times P_{kh} + \frac{0,2 \times C_{sl}}{W_{at}} \right) \times T_p \quad (3.1)$$

where:
C_{pc} – PC cost (US$).
C_{sl} – software license cost (US$).
ω_d – designer's cost per hour with fringe benefits (US$/h).
W_{at} – PC availability time per year (h).
PC_e – PC energy consumption hour rate (kWh/h).
P_{kh} – local average energy specific cost (US$/kWh).
T_p – designer's processing time (h).

The execution cost (C_e) is the sum of the machine running cost and the material cost. Both costs are defined in function of execution time and material consumption, respectively. They are obtained through machine internal calculation. Thus, there is no need to use the timing model proposed by Xu *et al.* (2000), reducing error margins in the calculation of the processing variables.

However, Xu *et al.* (2000) suggest an index generation that encompasses all machine running costs in function of time, given by equation (3.2.1) and that, with the execution time, gives the cost budget which is given by equation (3.2):

$$C_e = T_e \cdot r_f \quad (3.2)$$

$$r_f = (1 + \sigma_{op}) \cdot \omega_o + (1 + \sigma_{mch}) \cdot \frac{P_{mch}}{8{,}760 \cdot T_{mch}} \quad (3.2.1)$$

where:
T_e – model execution time (h).
r_f – machine running cost.
σ_{op} – labor tax per execution hour (percent).
ω_o – operator's hour cost (US$/h).
σ_{mch} – machine tax per execution hour (percent).
P_{mch} – machine price (US$).
T_{mch} – machine amortization time (years).

In the model in Xu et al. (2000), the machine running cost formulation, equation (3.2.1), is based on percentage taxes due to machine running and labor costs. These taxes are not specified and do not allow their component analysis, such as, energy consumption, maintenance and depreciation. According to Martins (2003), the inclusion of these three components is permitted and the calculation of the machine running cost per hour under this new perspective, (r_f'), may be altered based on equation (3.2.2):

$$r_f' = \left((P_e \times P_{kh}) + \frac{0,2 \times P_{mp}}{W_{at}} + \omega_o + \left(\frac{M_m}{W_{at}}\right) \times 12 \right) \quad (3.2.2)$$

where:
- r_f' – machine running cost per hour.
- ω_o – operator's cost per hour with fringe benefits (US\$/h).
- P_e – machine energy consumption rate per hour (kWh/h).
- P_{kh} – local average energy specific cost (US\$/kWh).
- M_m – cost maintenance per month (US\$).
- P_{mp} – machine price (US\$).
- W_{at} – machine availability time per year (h) – (8 h a day, 22 days a month, 12 months a year).

Thus, the execution time is then calculated by equation (3.3):

$$C_e = T_e \cdot r_f' \quad (3.3)$$

The material cost (C_m) calculation, given by equation (3.4), is similar to the one proposed by Martins (2003), where the material, support, and construction costs are function of specific cost per volume:

$$C_m = \frac{(V_m \cdot P_m)}{V_c} + \frac{(V_s \cdot P_s)}{V_c} \quad (3.4)$$

where:
- V_m – model volume utilized (cm^3).
- P_m – specific cost per model material volume (US\$).
- V_s – support volume utilized (cm^3).
- V_c – model/support material volume per cartridge (cm^3).
- P_s – specific cost per support material volume (US\$).

Finally, the post-processing cost (C_{pp}), given by equation (3.5), is the sum of resource costs (products and machine) and the specific cost per hour of operator's labor needed in this stage:

$$C_{pp} = \left((P_{ub} \times P_{kh}) + \frac{0,2 \times P_{bp}}{W_{at}} + \omega_o \right) \times T_{pm} + (S_c \cdot S_r) \quad (3.5)$$

where:
- P_{ub} – energy consumption rate per hour of the ultrasonic bowl (kWh/h).
- P_{kh} – average local energy specific cost (US\$/kWh).
- ω_o – operator's cost per hour with fringe benefits (US\$/h).
- P_{bp} – bowl price (US\$).
- W_{at} – bowl availability time per year (h).
- T_{pm} – model permanence time inside the ultrasonic bowl (h).
- S_c – soap cost per washing time at post-processing (US\$).
- S_r – soap rate per package (percent).

Hence, the prototype final cost may be calculated by equation (3.6):

$$C_{fp} = C_p + C_e + C_m + C_{pp} \quad (3.6)$$

3. Proposed formulation application

This research project stage consisted of data survey related to a prototype manufacturing through RP using FDM to produce one piece (Figure 1). Enough data is collected to be embedded in the proposed formulation.

The chosen piece, a flange, was selected due to its need of different machining processes using traditional technology (turning, piercing and milling). It has a simple geometry though and is used to link the axis to the vehicle wheel in a competition vehicle from Mini-Baja project at UNIFEI. This vehicle is being object of study of many research projects which deal with RP theme.

The chosen piece was drawn in Solid Works, version 2005, and saved in STL format. Afterwards, this design was inserted into the RP machine system Dimension Model SST 768, manufactured by Stratasys. The database, which concerns time and material usage in the RP machine process, was collected by the interface software Catalyst EX, version 1.2, build 2727. According to data provided by this software for each piece, it would be necessary 13.16 h to manufacture the prototype in the solid mode (solid-normal), as well as 493.26 cm^3 of model material plus 19.13 cm^3 of support material.

3.1 Processing cost calculation

Equation (3.1) was used in this stage. In order to calculate the computer cost per hour (C_{pc}), it was considered a desktop computer that is US\$4,000.00 worth, an equipment depreciation rate per year of 20 percent and a PC availability time per year (W_{at}) of 2,112 h. And then, to this amount, one must add this equipment energy consumption rate per hour (average power of 600 W/h or 0.6 kW/h), multiplied by local kW/h cost (US\$0.5/h).

To calculate the software license cost, the same premise was adopted as for the desktop computer. On the other hand, the license of Solidworks was purchased for US\$15,000.00.

To calculate the designer's hourly rate with fringe benefits (ω_d), a salary of US\$500.00 and 2,016 h of labor available per year was considered. The processing time (Tp) to draw the piece was 3.5 h.

Finally, based on this information and using equation (3.1), the processing cost (C_p) is US\$9.26.

3.2 Execution cost calculation

The execution cost was calculated using equation (3.3). Initially, the machine running cost (r_f') is obtained using equation (3.2.2).

To calculate the prototyping machine operator's cost per hour with fringe benefits (ω_o), the same premise was adopted as for the designer's hourly rate.

The machine electrical energy consumption rate per hour (P_e) may be defined in function of the RP machine power. In the case of tested equipment, this power is the order of 1,650 W/h or 1.65 kWh/h, multiplied by the local average specific cost (P_{kh}) of US\$0.50/h.

Data to calculate mensal maintenance cost (M_s) were collected in the enterprise, which supplied the prototyping machine tested and the periodical maintenance service. The monthly contractual value charged for the maintenance service is US\$1,174.10, which covers expenses due to preventive

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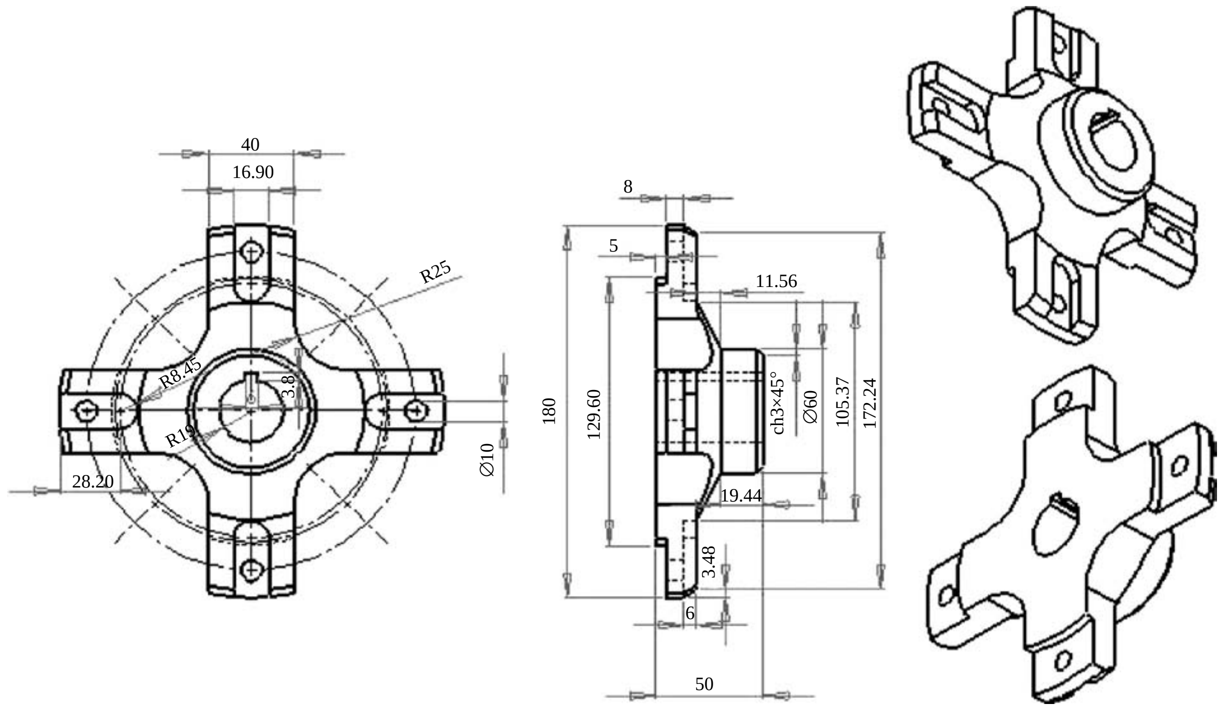
Figure 1 Piece design



execution repairs and any piece replacement. Considering the annual contract and 2,112 h for the availability time for the prototype machine, this item of the equation (3.2.2) is then US$6.67/h. Moreover, there is still the need of small routine maintenance (cleaning, lubricating, injector nozzle clogging and machine condition inspection) performed by the prototyping machine operator himself. This item is considered machine operator's hourly rate with fringe benefits, since the prototype machine operator has to be aware of potencial problems that can occur during the piece processing.

The RP machine tested was bought by US$84,525.00 ($P_{mp}$) and it is available 2,112 h/year (W_{at}). Considering that the machine is depreciated at a rate of 20 percent per year, the machine running cost per hour (r_f') is US$16.05. Thus, the execution cost is given by multiplying r_f' by the model execution time (T_e), which is calculated by the interface software in 13.16 h. Therefore, the execution cost comes to be US$211.16.

3.3 Material cost calculation

Equation (3.4) is used in this stage. Each material cartridge (model and support) has a volume of 922 cm^3 and costs US$600.00. Thus, the specific cost per volume of support material (P_s) and of model material (P_c) is US$0.65/$cm^3$ each.

For the piece tested, the machine interface software of RP Catalyst EX, version 1.2, build 2727, came up that 493.26 cm^3 of model material (V_c) and 19.13 cm^3 of support material (V_s) would be used. Therefore, the material cost (C_m) was US$333.44.

3.4 Post-processing calculation

It is carried out using equation (3.5). The post-processing is performed using an ultrasonic bowl. As it is mentioned in the equipment manual, its energy consumption per hour (P_{us}) is 0.65 kWh and the local average specific cost is US$0.50/h. For each piece tested, the model permanence time inside the ultrasonic bowl (T_{pm}) was 1 h, once the piece geometry features contributed to build the prototyping machine for only one support layer in its basis which eases its own removal.

The operator's cost per hour (ω_o) has already been calculated. The ultrasonic bowl used for cleaning uses in its interior a water and soap solution. The soap used, WaterWorks P400SC, supplied by Stratasys itself, has a high pH factor and each package of 950 g costs US$65.30 ($S_c$). According to the manufacturer, with the correct water volume in the bowl, one-third of the soap in the package must be used (S_r). Thus, the soap cost per solution load in the bowl is US$21.76.

The ultrasonic bowl tested was bought by US$550.00 ($P_{bp}$) and it's available 2,112 h/year (W_{at}).

Inserting these variables into equation (3.5), the post-processing cost (C_{pp}) for the flange in question is US$22.90.

3.5 Prototype manufacturing cost calculation

For the prototype manufacturing final cost (C_{fp}), one must add the processing cost parcels (C_p), the execution cost (C_e), the material cost (C_m) and the post-processing cost (C_{pp}).

In order to facilitate inputting those parcels data, given by equations (3.1), (3.3), (3.4) and (3.5), respectively, an electronic spreadsheet (Table I) was built. Adding up the values for the cost parcels cited previously, or entering the variable values required by the spreadsheet, the FDM's for the flange cost tested in this research are US$572.95 and US$567.50 with and without processing stage, respectively.

It may be true that the university lab needs to offer services to the community. In this case, there are some administrative fees charged by foundations linked to the universities. Those fees must be added up in the final cost. For that being so, the last two lines in the spreadsheet provide the cost corrected by the

Table I Electronic spreadsheet for RP cost

Description	Specific cost
Processing cost	
Designer's cost per hour with fringe benefits (ω_d)	0.54
Desktop computer cost (C_{pc})	4,000.00
Software license cost (C_{sl})	15,000.00
PC energy consumption per hour (kWh) (PC_e)	0.6
Local kWh cost (US$) ($P_{kh}$)	0.5
Equipment availability time per year (h) (W_{at})	2,112
Processing cost (US$) ($C_p$)	9.26
Execution cost	
Operator's cost per hour with fringe benefits (ω_o)	0.54
Prototype machine price (US$) ($P_{mp}$)	84,525.00
RP machine energy consumption per hour (kWh) (P_e)	1.65
Monthly maintenance service cost (M_s)	1,174.10
Average time of routine maintenance (h) (T_{rm})	2.00
Machine operating cost (r')	23.60
Execution cost (US$) ($C_e$)	211.16
Material cost	
Model material cartridge cost (P_m)	600.00
Support material cartridge cost (P_s)	600.00
Model material volume per cartridge (cm^3) (V_c)	922
Support material volume per cartridge (cm^3) (V_c)	922
Material cost (C_m)	333.44
Post-processing cost	
Ultrasonic bowl power (kWh) (P_{ub})	0.65
Ultrasonic bowl price (kWh) (P_{bp})	550.00
Operator's cost per hour with fringe benefits (ω_o)	0.54
Soap coast per package (950 g) (S_c)	65.30
Soap rate per package (S_r)	0.33
Post-processing cost (C_{pp})	22.90
Input data	
Model permanency time inside bowl (h) (T_{pm})	1.00
Designer's processing time (h) (T_p)	1.00
Model volume (cm^3) (V_m)	493.26
Support volume (cm^3) (V_s)	19.13
Model executing time (h) (T_e)	13.16
Prototype total cost	572.50
Prototype cost without processing	567.50
Calculation of prototyped piece sale price	
Administrative fees (%)	20.00
Sale price of complete prototyped piece	692.11
Sale price of piece without processing	681.01

taxes (service sale value) for the whole process situations and without the processing stage (3D piece drawing). In this case, the administrative fee of 20 percent was considered, increasing the cost of the piece prototyped (Figure 2).

4. Discussion and conclusions

In defining the variables used in the proposed formulation, some considerations should be discussed.

In the calculation of the machine running cost per hour (r_f'), in equation (3.2.2), the cost of maintenance was specified according to the type of equipment used as object of study in this research. For the appropriateness of this formulation for other equipments, these values must be adjusted. Although labor for RP industry is not usually related to hourly workers,

Figure 2 Prototyped flange in FDM at UNIFEI

the operator's cost has been well considered, since it is a common practice in Brazil, and it follows the way it was handled in the work of Xu *et al.* (2000).

All equipment is devalued due to time, despite being used or not. Whether a machine is rarely or intensively used throughout the year, there is depreciation due to utilization. The depreciation of machinery is not known with precision, since it is not sold. At this time only, its actual value would be known. For the proposed equation, a depreciation rate of 20 percent per year for the computer, the software license, the prototype machine and the ultrasonic bowl was considered.

The authors consider that this research fulfilled its goal to propose a procedure to calculate RP cost of pieces using the FDM process in a university lab.

It is considered as a scientific contribution of the present work, a specific formulation to calculate prototyped piece costs through FDM and also a post-processing process which differs from other works (Xu *et al.*, 2000; Lan and Ding, 2007). Moreover, the present formulation uses the execution times and the material consumption amount that are obtained by internal calculation of the tested machine. This is quite different what is found in Xu *et al.* (2000), where an index, which encompasses the machine running costs in function of time, is used. Hence, it is considered that the cost formulation proposed by this study offers accurate results since error margins of the process variables are reduced.

The authors encourage future works on the comparison of prototyped pieces using FDM with other prototyping technologies in order to verify differences in finishing quality, dimensional accuracy and mechanical resistance.

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