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Feasibility Study of small scale production based on additive manufacturing technologies

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Abstract:
Along the last years, the complexity of products has been growing progressively, while the product development life-cycle tended to be reduced. In addition to that, additive manufacturing technologies increased their role in the product development process, resulting in reduction of errors and products release time. In spite of these benefits, the main application of these technologies is still focused on initial phases of projects and results in high costs of parts and low volumes. On the other hand, although conventional produtivity processes results in low costs and high volumes, the investiment related to these processes are high and the implementation time are long. For that reason, the main goal of this work is to investigate the possibility of application of additive manufacturing technologies for small and medium scale production. Along this work, the main direct and indirect processes which are used for small and medium scale production were studied and a numerical cost model were developed for each one. In order to compare the benefits and disvantages among the processes, 3 parts were selected and analysed through such models. By the end, the main cost, payback; amortization and takt time were identified and the most suitable process was found in accordance with annual part demand.

Key words: *Additive manufacturing, medium scale production, network production, flexible manufacturing systems*

1. INTRODUCTION

Over the last several years, the application of additive manufacturing (AM) processes has been steadily growing up as consequence of the advantages provided by it sort of process. In contrast with the benefits of these technologies, the main application is still focused on prototypes and special parts, as such medical devices (GIBSON *et al.*, 2002; GIBSON *et al.*, 2010; CUNICO e CARVALHO, 2013b; a). In parallel to those facts, the current production strategies are based on rapid or definitive tooling, resulting in high capital investments. As consequence, small scale production investments tend not to be justified or the payback time is too long (RUFFO *et al.*, 2006).

For that reason, the main goal of this work is to present a proposal of small scale production which is based on additive manufacture technologies. As result, it is expected that the analysis and comparison of the current manufacturing process (injection moulding) versus 3 other additive manufacturing options indicates the solution that is more suitable for small scale production.

In order to analyse the feasibility of additive manufacturing technologies as an effective production way, we established the injection moulding as the reference process in addition to studying 4 scenarios where the annual part demand, time demand, parts size and investment were the variables and the lead time, part cost, investments cost and pay-back period were the responses.

In all the studied scenarios, we defined and indicated numerical models for the part cost estimation, where the definition of the main components of cost, lead time and minimal stock help to identify the feasibility of each scenario according to the part demand.

In the first scenario, it was analysed the production feasibility of an injection moulding process where the injector machine and tooling costs were considering as amortised capital investment. In this scenario, besides the analysis of feasibility, we have also presented an estimation model for the part, tooling and overhead costs, being useful for the process selection and the part cost estimation at the beginning of projects.

In the second scenario, we investigated the feasibility of additive manufacturing services for production, where the costs related to production overhead and tooling are ignored. In this scenario, it is also important to see that besides the lead time and inventory dimensioning play a fundamental role in this business segment, these parameters might determine the feasibility of a new product release.

In the third and fourth scenarios, we analysed two different production strategies where additive manufacturing technologies are considered. In both cases, the acquisition of equipment was considered in the investment and part cost estimation. At the end, all the scenarios were compared in order to identify suitability the production strategy for small and medium scale strategies.

In addition to the feasibility analysis of small scale production products, this work can also be a very useful tool for customised or tailor-made business segments, where the feasibility of new products is hardly achieved and the product cost tend to be extremely high.

2. PRODUCTION ESTIMATION MODELS

In order to investigate and compare the part cost of parts which are made in conventional injected mould and additive manufacturing techniques, we selected the main components of the part cost and created estimation cost models of these components.

In general way, the main part cost components can be classified in direct and indirect costs, as shown in Figure 1 (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; ASIEDU e GU, 1998; FAGADE e KAZMER, 2000; ROSATO e ROSATO, 2000; NIAZI *et al.*, 2006; RUFFO *et al.*, 2006). Nevertheless, as the main goal of this work is to compare different production scenarios, we excluded the administrative overhead from the analysis.

In this way, it is possible to see that the direct cost is related to the material which is directed used to fabricate the part, while the indirect costs concern the process time, labour, investments and are amortised by the volume of fabricated parts.

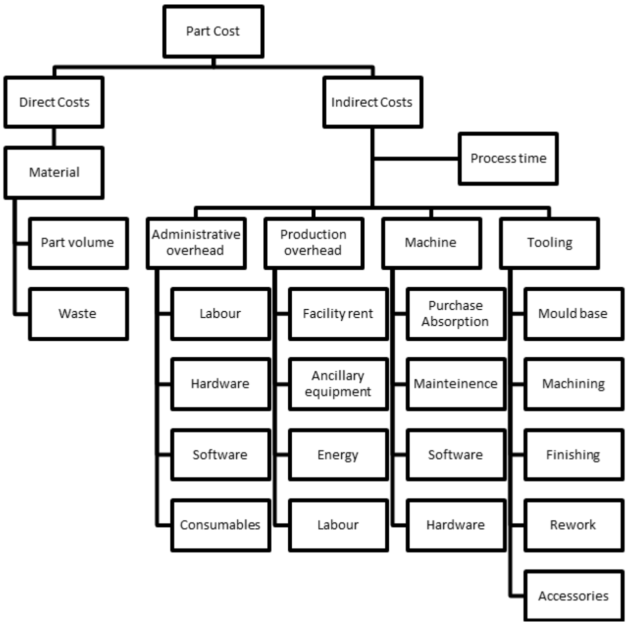

Figure 1 – Representation of the main part cost components

For this study, the main cost components that have influence in the part cost were analysed, as such direct cost ($C_{direct\_\cos t}$), tooling cost ($C_{tooling}$), machine cost ($C_{machine}$) and production overhead cost ($C_{overhead}$). Therefore, the part cost (C_{part}) might be defined as:

$$C_{part} = C_{direct} + C_{tooling} + C_{overhead} + C_{machine} \quad \textbf{(1)}$$

In addition to the analysis of part cost, it was also analysed the feasibility of the production scenarios with respect to demand and lead time. In fact, this is an important parameter to be analysed because it indicates whether the productive way is feasible, in addition to indicating the minimal stock which is necessary for each annual demand and the part demand time.

For the definition of part demand time, we assumed that the annual demand is distributed homogeneously along the year. Therefore, it was possible to see that the part demand time might be characterised by:

$$t_{demand} = \frac{60 \cdot N_{working\_days} \cdot N_{daily\_journey}}{N_{annual}} \quad \textbf{(2)}$$

In general way, the stock flow might be analysed by the variation of delivery parts ($N_{delivery}$) per lead time (t_{lead}) and demand parts (N_{demand}) per demand time (t_{demand}), as shown in Eq. (3)

$$Stock = N_{delivery} \cdot round_{down}\left(\frac{t}{t_{lead}}\right) - N_{demand} \cdot round_{down}\left(\frac{t}{t_{demand}}\right) \quad (3)$$

Therefore, if we assume that the demand time is equal to the delivery time per part, it is possible to estimate the minimal inventory which is needed to attend production through the maximum of stock curve in addition to the safety stock.

2.1. INJECTION MOULDING

In order to identify the total cost of an injected part, we applied an estimation cost model to identify the tooling cost, while the machine cost was obtained by quotation. The part direct cost was estimated through the part volume and the raw material cost was identified by low volume quotation.

DIRECT COST

The direct cost of part is related to the quantity of material which is necessary to fabricate the part, where the volume of part (V_{part}), the specific weight of material ($\rho_{part\_material}$), the raw material coefficient ($k_{part\_material}$) and the material waste (C_{waste}) define the direct cost part (C_{direct}).

$$C_{direct} = V_{part} \cdot \rho_{part\_material} \cdot k_{part\_material} + C_{waste} \quad (4)$$

TOOLING COST

For the estimation of tooling cost, we applied Boothroyd and Dewhurst's method, which concern in the estimation of operational and direct costs which are necessary to build a cold runner mould (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; ASIEDU e GU, 1998; FAGADE e KAZMER, 2000; ROSATO e ROSATO, 2000; WANG *et al.*, 2003; CAMPO, 2006; NIAZI *et al.*, 2006; FONSECA *et al.*, 2007; KAZMER, 2012). In this model, the main inputs which are used to identify the total cost of injection mould are the volume of part and number of cavities.

For this estimation, it is possible to separate the total cost of mould ($C_{moulding\_tool}$) in three main components: Cavities cost ($C_{cavities}$), mould base costs (C_{mould_base}) and customisation costs ($C_{customisation}$), as presented in Eq. (5) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

$$C_{moulding\_tool} = C_{cavities} + C_{mould\_base} + C_{customisation} \quad (5)$$

For the specification of cavities cost, it is established the individual cost of each mould cavity ($C_{cavitiy}$) multiplied by the number of cavities ($n_{cavities}$) and a discount factor ($f_{cavity\_discount}$), as it is possible to see in Eq. (6). In this study, we ignored the discount factor per cavity in addition to establishing that the number of cavities should be limited to 5. This restriction in the number of cavities was defined because the mould was design to low production volumes (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$C_{cavities} = (C_{cavitiy} \cdot n_{cavities}) \cdot f_{cavity\_discount} \quad (6)$$

With respect to the cavity set cost, it is possible to identify that the main cost components are related to cavity material ($C_{cavitiy\_material}$), cavity machining ($C_{cavitiy\_machining}$) and cavity finishing ($C_{cavitiy\_finishing}$), as shown in Eq. (7) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$C_{cavitiy} = C_{cavitiy\_material} + C_{cavitiy\_machining} + C_{cavitiy\_finishing} \quad (7)$$

The cavity material is mainly defined by the maximum dimensions of part (L_{part} -length, W_{part} -width, and H_{part} -height), where the material cost coefficient ($k_{cavitiy\_material}$) and specific weight of cavity material ($\rho_{cavitiy\_material}$) in addition to cavity volume ($V_{cavitiy\_material}$). This estimation can be seen in Eq. (8) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$C_{cavitiy\_material} = V_{cavitiy\_material} \cdot \rho_{cavitiy\_material} \cdot k_{cavitiy\_material} \tag{8}$$

Where:

$$V_{cavitiy\_material} = L_{cavitiy} \cdot W_{cavitiy} \cdot H_{cavitiy} \tag{9}$$

And,

$$L_{cavitiy} = L_{part} + \max[0.1 \cdot L_{part}, H_{part}] \tag{10}$$

$$W_{cavitiy} = W_{part} + \max[0.1 \cdot W_{part}, H_{part}] \tag{11}$$

$$H_{cavitiy} = \max[0.057, 2 \cdot H_{part}] \tag{12}$$

For the estimation of cavity machining cost, it is necessary to identify the machining labour rate ($R_{machining\_rate}$) and the time which is necessary to fabricate the cavity ($t_{cavitiy\_machining}$), as presented in Eq. (13) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$C_{cavitiy\_machining} = t_{cavitiy\_machining} \cdot R_{machining\_rate} \tag{13}$$

The estimation of machining time is characterised by the machining time of cavity volume ($t_{cavitiy\_volume}$) and cavity surface ($t_{cavitiy\_surface}$), where factor of part complexity ($f_{cavity\_complexity}$), machining efficiency ($f_{machining\_efficiency}$) and machinability ($f_{machining}$) are also included in the model, Eq. (14). In spite of the effect of this factors effect on the time estimation, we established that the efficiency of machining is high and the complexity of part was low, resulting in those factors being equal to 1 (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$t_{cavitiy\_machining} = \left(\frac{t_{cavitiy\_volume} + t_{cavitiy\_surface}}{f_{machining\_efficiency}} \right) \cdot f_{machining} \cdot f_{cavity\_complexity} \tag{14}$$

In addition, the estimation of the cavity volume machining time can be identified by the volumetric mould material removal rate, Eq. (15) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$t_{cavitiy\_volume} = \frac{V_{cavitiy\_material}}{R_{material\_volume}} = \frac{V_{cavity\_material}}{h_{pass} \cdot 0.7 \cdot d_{rough}} \cdot \frac{H_{cavity\_volume}}{h_{pass}} \cdot \frac{1}{R_{speed}} \tag{15}$$

Where:

h_{pass} is the removal depth of rough machining

d_{rough} is the diameter of rough machining tool

H_{cavity_volume} is the height of cavity

R_{speed} is the feed rate of rough machining

V_{cavity_volume} is the volume of cavity

$R_{material\_volume}$ is the rate of volumetric removal of material per time

$t_{cavitiy\_volume}$ is the necessary time to machine the volume of cavity

On the other hand, the estimation of surface cavity machining time can also be characterised by the surface area of cavity ($A_{cavity\_material}$), finishing tool diameter ($d_{finishing}$) and feed rate (F_{speed}), as presented in Eq. (16).

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$$t_{cavitiy\_surface} = \frac{A_{cavitiy\_material}}{R_{material\_volume}} = \frac{A_{cavity\_material}}{0.5 \cdot d_{finishing}} \cdot \frac{1}{F_{speed}} \quad \textbf{(16)}$$

With respect to mould base cost and customization costs, we defined that these cost are respectively 15% and 150% of cavities cost.

As the tooling cost is considered a capital investment, the contribution of tooling for the part cost is amortised by the volume of parts which is fabricated. Therefore, the total tooling cost might be defined as a function of moulding tool cost ($C_{moulding\_tool}$), depreciation factor (f_d) and annual parts amount (N), as shown in (17) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

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$$C_{tooling} = \frac{C_{moulding\_tool}}{N} \cdot f_d \quad \textbf{(17)}$$

PRODUCTION OVERHEAD COST

With reference to the estimation of basic production overhead costs (Eq. (30)), we defined manufacturing batch time (t_{batch}), manufacturing rate ($R_{manufacturing\_rate}$) and the amount of parts per batch (N_{batch}) as the main cost components (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000; RUFFO *et al.*, 2006).

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$$C_{overhead} = \frac{t_{batch} \cdot R_{manufacturing\_rate}}{N_{batch}} \quad \textbf{(18)}$$

For the determination of total batch time, we defined that the main components that contribute for the batch are the direct moulding cycle time ($t_{moulding\_cycle}$) and setup time (t_{setup}), as represented in Eq. (19). In general, it was also considered that the cycle time is around 30s, as the injected parts moulding cycle commonly varies from 15 to 120 seconds (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000).

$$t_{batch} = \frac{t_{moulding\_cycle} \cdot N_{Batch}}{n_{cavities}} + t_{setup} \quad \textbf{(19)}$$

In addition, the manufacturing rate is related to the cost rate of machine operation ($R_{machine}$) and labour (R_{labour}), as it is possible to be seen in:

$$R_{manufacturing\_rate} = R_{labour} + R_{machine} \quad \textbf{(20)}$$

MACHINE COST

With respect to the machine and equipment acquisition ($C_{machine}$), it was considered that the total cost of equipment ($C_{equipment}$) is amortised by the amount of parts which is fabricated during a payback period of time ($T_{payback}$). In this case, the total amount of parts is defined by the annual demand of parts (N_{annual}) multiplied by the payback period, as it is possible to be seen in Eq. (36) (REES, 1996; CHATAIN e DOBRACZYNSKI, 1997; FAGADE e KAZMER, 2000; ROSATO e ROSATO, 2000; KAZMER, 2012).

$$C_{machine} = \frac{C_{equipment}}{N_{annual} \cdot T_{payback}} \tag{21}$$

In addition, one of the most commonly methods for equipment specification was the clamp tonnage method, which identify the machine clamp force through the number of cavities, projected area, mould size and shot capacity.

For the determination of shot capacity ($Shot_{capacity}$), we can use the weight of part (Wt_{part}), number of cavities ($n_{cavities}$) and sprue and runner factor (SRF) (ROSATO e ROSATO, 2000; KAZMER, 2012).

$$Shot_{capacity}(g) = \frac{Wt_{part}(g) \cdot n_{cavities} \cdot SRF \cdot 16(oz) \cdot 1.5}{454(g/lb)} \cdot 28.37(\text{g/oz}) \tag{22}$$

For hot runner mould systems, SRF is equal to 1, while for cool runner systems SRF is characterised by :

$$SRF = \frac{1.5}{(Wt_{part})^{0.5}} + 1 \tag{23}$$

It is also possible to identify the melt capacity of machine through:

$$Melt_{capacity}(g) = \frac{Shot_{capacity}(g) \cdot 30}{t_{Cycle}(s)} \tag{24}$$

Through this parameter, it is possible to identify the clamp force of machine in a preliminary way according to the Figure 2.

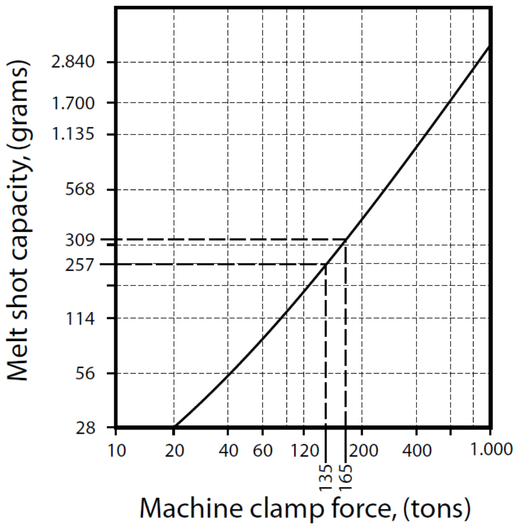


Figure 2 – Machine shot capacity versus machine clamp force (ROSATO e ROSATO, 2000)

On the other hand, it is also possible to estimate the machine clamp force through the wall thickness method. In this method, the clamp force (F_{clamp}) is found by the projected area of runner and cavities ($A_{projected}$) and a wall thickness factor, which can be seen in the Eq. (25).

$$F_{clamp}(t) = A_{projected} \cdot f_{wall\_thickness} \quad \textbf{(25)}$$

Table 1 – Investigation matrix of additive manufacturing services

wall thickness (in)	Wall thickness factor (t/in²)
0.020-0.062	6-5
0.062-0.125	5-4
0.125-0.250	4-3

As consequence, the general estimation of machine cost might be estimated by the update regression of (BOOTHROYD e DEWHURST, 1988):

$$C_{equipment} = 16000 + 430 \cdot F_{clamp}(t) \quad \textbf{(26)}$$

2.2. ADDITIVE MANUFACTURING SERVICES

For the study of additive manufacturing services as productivity way, we have also considered that the tooling cost, machine cost and production overhead were null, while the direct cost remained the responsible component of part cost. It is important to note that there are other costs inherent to this kind of scenario, as such logistics, stock and quality. Nevertheless, these costs were ignored in this study in order to create a comparison criterion among the studied scenarios (RUFFO *et al.*, 2006).

In order to identify the cost estimation of additive manufacturing services, it was requested quotation of 3 dimension parts, 3 technologies, and 4 part quantities in order to be obtained a statistical regression and the cost estimation formulation. The investigation matrix used to analysed the service cost estimation can be seen in Table 2, where it is related the part quantity per order, main dimensions of analysed parts and fabrication technology.

Table 2 – Investigation matrix of additive manufacturing services

		Part maximum dimensions				
Technology	description	L (mm)	W(mm)	h(mm)	vol (mm³)	quantity
SLA	part 1	8	8	15	960	1
						5
						10
						50
	Part2	30	30	15	13500	1
						5
						10
						50
	Part3	60	60	15	54000	1
						5
						10
						50
SLS	part 1	8	8	15	960	1
						5
						10
						50
	Part2	30	30	15	13500	1
						5
						10
						50
	Part3	60	60	15	54000	1
						5
						10
						50
FDM	part 1	8	8	15	960	1
						5
						10
						50
	Part2	30	30	15	13500	1
						5
						10
						50
	Part3	60	60	15	54000	1
						5
						10
						50

In addition to being identified the regression equation for each technology and the part cost estimation model, it was also determined the minimal stock volume which would be needed to attend annual part demand. Therefore, the feasibility of this productivity concept might be evaluated.

It was also find that the lead time was a based on service time that the bureaux provide (t_{batch}) and the shipping time ($t_{shipping}$), as presented in Eq.:(27). Therefore, the minimal inventory might be estimate in accordance with the maximum value of Eq. (3).

$$t_{lead} = t_{batch} + t_{shipping} \qquad \textbf{(27)}$$

2.3. ADDITIVE MANUFACTURING PRODUCTION

For the generalised cost estimation of additive manufacturing parts, it was analysed the direct cost and production overhead as a function of part size, building area, parts demand and batch volume. Therefore, the part cost (C_{part}) might be characterised two conditions: single part batch and optimised batch. In spite of both conditions being defined by Eq. (28), the overhead cost is amortised by the number of parts per batch, resulting in part cost differences (ASIEDU e GU, 1998; HOPKINSON e DICKENS, 2001; HOPKINSON e DICKNES, 2003; RUFFO *et al.*, 2006).

$$C_{part} = C_{direct} + C_{overhead} + C_{machine} \qquad \textbf{(28)}$$

In this study, the estimation of direct cost was mainly determined by the cost of material, whose main components are the raw material cost coefficient ($k_{part\_material}$), material density ($\rho_{part\_material}$), part volume (V_{part}) and waste material (C_{waste}), as shown in Eq. (29). In addition, we have also considered that the waste material is 10% of part material because of the support material, errors, purges routine, among others.

$$C_{direct} = V_{part} \cdot \rho_{part\_material} \cdot k_{part\_material} + C_{waste} \quad \textbf{(29)}$$

In this case, it is important to note that the part volume consider a solid strategy, being ignored either weave infill, pattern infill, low density or airgap strategies (GIBSON *et al.*, 2002; GIBSON *et al.*, 2010).

With reference to production overhead costs (Eq. (30)), we defined manufacturing batch time (t_{batch}), manufacturing rate ($R_{manufacturing\_rate}$) and the amount of parts per batch (N_{batch}) as the main cost components. It is important to be highlighted that although additive manufacturing processes do not result in amortised tooling cost, the operational cost is amortised by the number of parts which is produced in each batch. As consequence, the maximum amortisation is restricted by the building area of machine.

$$C_{overhead} = \frac{t_{batch} \cdot R_{manufacturing\_rate}}{N_{batch}} \quad \textbf{(30)}$$

In this case, the determination of the maximum number of parts which are possible to be produced in each batch was established by the maximum dimensions of part (L_{part} and W_{part}), building area ($L_{building\_area}$ and $W_{building\_area}$) and the minimal distance between parts (s), resulting in:

$$N_{\max\_batch} = round_{down}\left(\frac{L_{building\_area}}{L_{part} + s}\right) \cdot round_{down}\left(\frac{W_{building\_area}}{W_{part} + s}\right) \quad \textbf{(31)}$$

It is also important to note that this equation ignores the possibility of building several parts along z axis, resulting in a bidirectional part building matrix.

For the determination of total batch time, we defined that the main components that contribute for the batch are the direct manufacturing time ($t_{manufacturing}$), setup time (t_{setup}) and post-processing time ($t_{post-processing}$), as represented:

$$t_{lead} = t_{batch} = t_{manufacturing} + t_{setup} + t_{post-processing} \quad \textbf{(32)}$$

We have also defined that the manufacturing time is a result of the building layer height (H_{layer}), part height (H_{part}), part length (L_{part}), part width (W_{part}), number of parts per batch (N_{batch}), raster feed rate (F_{raster}), delay time per change of layer (t_{layer_delay}) and the tool diameter (d), as shown in Eq. (33). In this case, the tool diameter might represent either nozzle diameter, bead width or laser beam diameter, while the part infill strategy was considered solid.

$$t_{manufacturing} = \frac{H_{part}}{H_{layer}} \cdot \frac{(L_{part} \cdot W_{part})}{d} \cdot \frac{N_{batch}}{F_{raster}} + t_{layer\_delay} \quad \textbf{(33)}$$

Additionally, we can also define the average lead time (t_{part}) per part as:

$$t_{part} = \frac{t_{batch}}{N_{batch}} \quad \textbf{(34)}$$

On the other hand, the manufacturing rate ($R_{manufacturing\_rate}$) was defined to be mainly compounded by the operational time-machine cost rate ($R_{machine}$), energy cost rate (R_{energy}) and labour cost rate (R_{labour}), as presented in Eq. (35).

$$R_{manufacturing\_rate} = R_{machine} + R_{energy} + R_{labour} \quad \textbf{(35)}$$

By the end, the last component of part cost is related to the machine and equipment acquisition ($C_{machine}$). As this cost is a capital investment, the total cost of equipment ($C_{equipment}$) is amortised by the amount of parts which is fabricated during a payback period of time ($T_{payback}$). In this case, the total amount of parts is defined by the annual demand of parts (N_{annual}) multiplied by the payback period, as it is possible to be seen in Eq. (36).

$$C_{machine} = \frac{C_{equipment}}{N_{annual} \cdot T_{payback}} \quad \textbf{(36)}$$

With respect to the equipment cost, we identified the approximated cost of the main professional additive manufacturing machines which presented building area superior to 300x300x300mm. In this case, we considered the FDM, SLA and SLS as the main technologies to be analysed in this scenario.

2.4. LOW COST ADDITIVE MANUFACTURING IN NETWORK

On the other hand, the last scenario which we analysed in this work concerns the use of low cost additive manufacturing technologies as an effective way of production. In contrast with the previous scenario, this proposal is marked by the use of low cost machines, which are also known as 3d printer.

In general way, the main difference between the cost estimation model of this proposal and the additive manufacturing scenario is related to the possibility of simultaneous batches in addition to machine cost reduction. As consequence, it was possible to find that the production overhead and machine costs were the most affected component in the model.

Adjusting the previous model to the number of machines ($N_{machines}$), it can be seen that the machine cost is:

$$C_{machine} = \frac{C_{individual\_machine} \cdot N_{machines}}{N_{annual} \cdot T_{payback}} \quad \textbf{(37)}$$

For this scenario, we identified the approximated cost of the main low cost additive manufacturing machines which presented building area up to 150x150x150mm. In this case, we considered only the FDM, SLA technologies.

And the labour cost rate might be amortised by the number of machines which one worker can manage ($N_{machine\_labour}$). In Eq. (38), it is possible to see the formulation of this cost rate as a function of number of machines used in network ($N_{machines}$), number of managed machines per worker ($N_{machine\_labour}$) and cost of worker per hour (C_{labour}).

$$R_{labour} = \frac{N_{machines}}{N_{machine\_labour}} \cdot C_{labour} \quad \textbf{(38)}$$

In addition, it was also possible to find the variation of batch lead time and the average part lead time for more than one batch as a function of the number of machines which is used in network ($N_{machines}$), as presented in Eq. (39) and Eq.: (40). On the other hand, the lead time for the first batch is equal to the batch time.

$$t_{lead} = \frac{t_{batch}}{N_{machines}} \quad \textbf{(39)}$$

$$t_{part} = \frac{t_{batch} + \dfrac{t_{batch}}{N_{machines}}}{N_{batch} \cdot N_{machines}} \quad \textbf{(40)}$$

3. RESULTS AND DISCUSSIONS

3.1. INJECTION MOULDING

With respect to the results of this study, it was possible to characterise the cost of part as a function of annual part demand in addition to production strategy. In order to be possible to compare all the 4 studied scenarios, we established 3 main sizes of parts to be analysed: 8x8x15mm; 30x30x15mm and 60x60x15mm.

For the cost estimation of moulded parts, we considered that the number of cavities should be equal to 4, which is an indicated value for low scale production. The main parameters which were used in this analysis can be seen in Table 3, where the total cost of material, machine and tooling is also presented for each one of the 3 part sizes.

Table 3 – Parameters for cost estimation of injection moulding parts

		Part size 1	Part size 2	Part size 3
	Description	**Value**	**Value**	**Value**
Material cost	Max Lenght (mm)	8,00	30,00	60,00
	Max Width (mm)	8,00	30,00	60,00
	max Height (mm)	15,00	15,00	15,00
	Cavity ρ (g/cm3)	1,05	1,05	1,05
	Material cost factor ($/kg)	4	4	4
	Part weight (g)	1,008	14,175	56,7
	Volume (cm3)	0,96	13,5	54
	Part material Cost ($)	**0,004**	**0,057**	**0,227**
Production overhead	injection cycle time (min)	0,63	1,03	2,30
	Setup time (min)	30,00	30,00	30,00
	number of parts per batch	100,00	100,00	100,00
	Production time cost ($/h)	50,00	50,00	50,00
	Production batch overhead cost ($)	**0,55**	**0,88**	**1,94**
Total Tooling cost	number of cavities	4,00	4,00	4,00
	complexity	moderate	moderate	moderate
	part weight (g)	1,01	14,18	56,70
	projected area (in2)	0,44	6,14	24,55
	Mold cost ($)	**5000,00**	**5000,00**	**20000,00**
Total Machine Cost	part weight (g)	1,01	14,18	56,70
	cavities	4,00	4,00	4,00
	SRF	2,49	1,40	1,20
	Shot capacity	15,08	118,91	407,90
	cycle (s)	37,81	61,52	138,06
	melt Capacity	23,93	115,99	177,27
	Clamp force (t)	0,54	53,64	89,00
	Machine cost ($)	**16230,43**	**39066,42**	**54269,09**

It is also important to note that the number of parts per batch directly interfere in the production overhead cost, as it is possible to see in Figure 3. In this figure, we can indicate the saturation of cost for batch sizes which are superior to 100 parts. For that reason, we selected the batch size equal to 100 parts to perform the cost analysis.

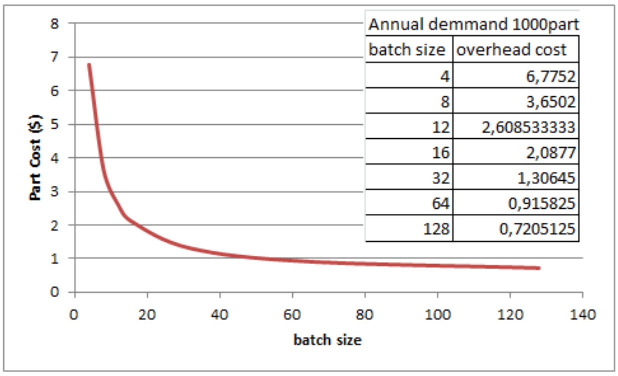


Figure 3 – Effect of batch size for the production overhead cost

As result of this cost analysis, it was possible to identify the variation of injection moulding part cost as a function of annual part demand, as shown in Figure 4. In this figure, we can also see the cost of the 3 part sizes in addition to the needed capital investment for each one. In this case, besides the investment has varied from $16,000.00 to $65,000.00, the amortisation cost happens in exponential proportion. Therefore, if the $16.00 was considered a suitable part cost, the annual demand that justified the injection moulding production would be 1000, 3000, 5000 parts for each one of part sizes.

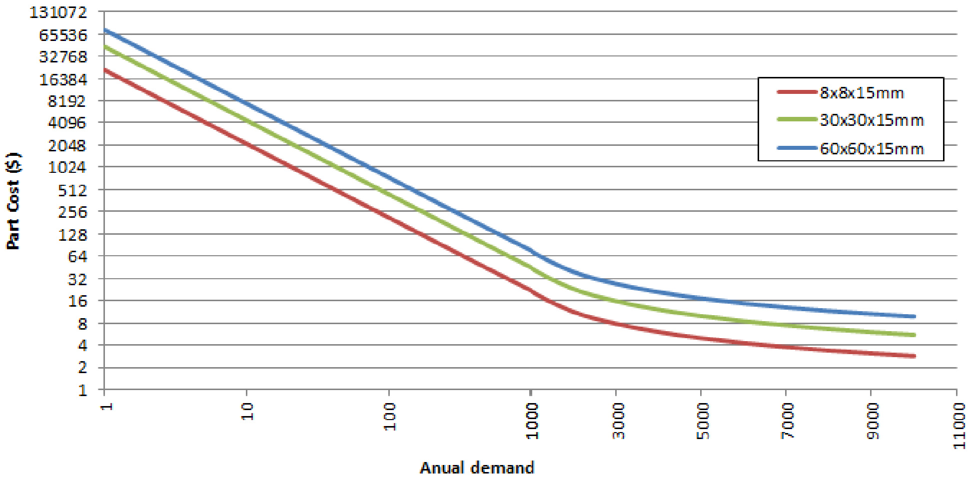


Figure 4 – Injection moulding part cost versus annual part demand

As the injection cycle defines the main lead time of parts, we can see the variation of demand and lead time for the parts, as shown in Figure 6. In this figure, it is possible to see that all the 3 analysed parts resulted in the lead time lower than the demand time. As consequence, it indicates that the machine tend to present idleness for annual part demand inferior to 200000 parts/year.

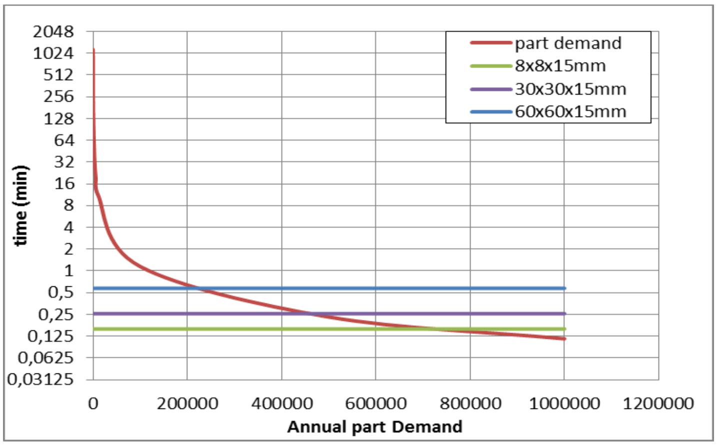


Figure 5 – Delivery and demand time as a function of annual part demand

In addition, if only one idle injection moulding machine were considered, the minimal inventory for 200000parts/year demand and no safety stock would be 26.

3.2. ADDITIVE MANUFACTURING SERVICES

In the second analysed scenario, we investigated the feasibility of additive manufacturing services as production way. In this study, we identified the tendency of cost which is related to parts as a function of number of parts per order or batch, as it is possible to be seen in Figure 6.

In this figure, the diagrams of part cost as a function of number of parts per order or batch were presented in addition to a general diagram which compile the maximum, minimum and mean values of all the three analysed technologies.

It is possible to see that the cost tends to be saturated in 50 parts batch sizes, while the size of parts proportionally increases the part cost. For the FDM technology, values varied between $75.00 and $25.00 for 50 parts batch size, while the value remained near to $200.00 for a single part batch size.

On the other hand, SLA part cost varied from $125.00 to $275.00 for one part batch size and from $17.00 to $50.00 for 50 parts batch size. It is also possible to establish as a general rule that SLA parts with main dimensions from 8 to 60 and 15mm of height mm tend to cost $30.00.

For the SLS technology it was observed similar cost behaviour, where the cost varied according to the part size from $75.00 to $200.00 for a single part batch size. While for 50 parts batch size, the variation of cost was found between $11.00 and $75.00.

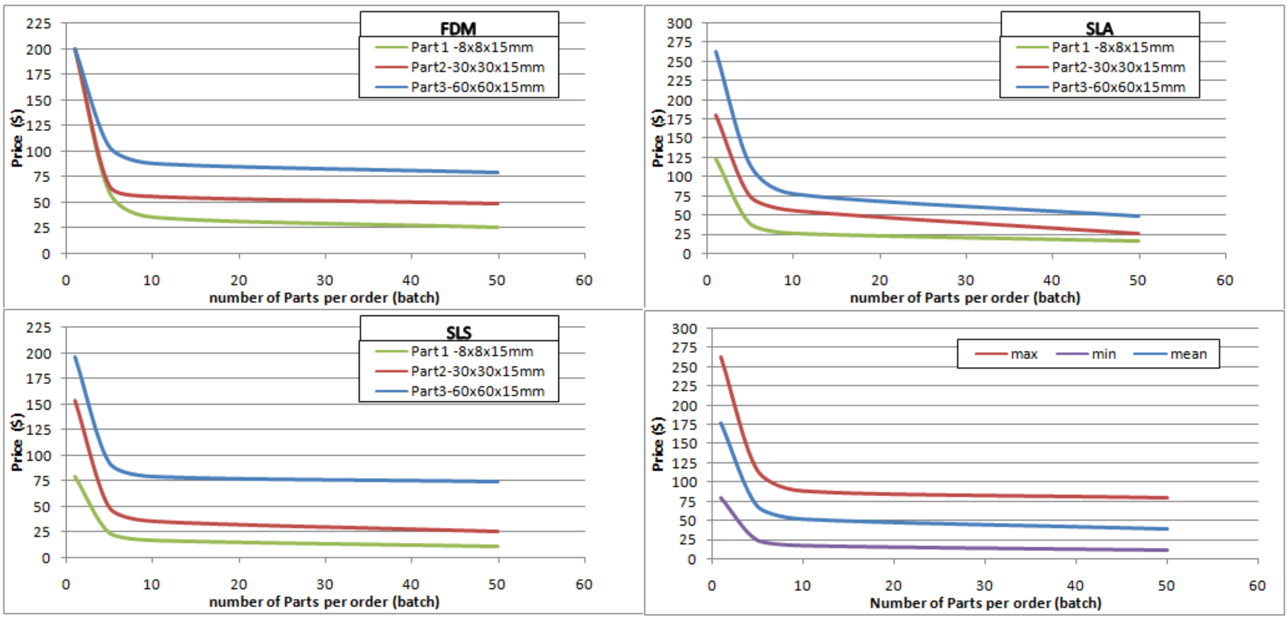


Figure 6 – Diagrams of part cost estimation as a function of the number of parts per order for SLA, FDM and SLS technologies

Another important point that was also seen in this study is related to stock analysis. It was observed that the delivery time for additive manufacturing services is around 7 working days. Therefore, the delivery time per part is approximately 68 hours. In addition, Figure 7 presents the correlation of demand and delivery part time as a function of annual part demand.

In this figure, it is possible to see that use of additive manufacturing services is feasible to be applied for annual part demand inferior to 1715 in terms of lead time.

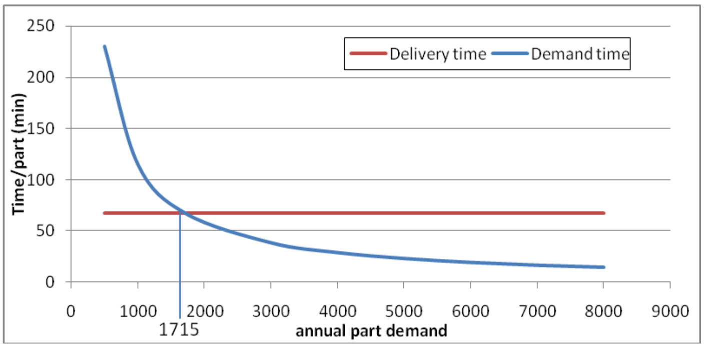


Figure 7 – Delivery and demand time as a function of annual part demand

With respect to stock analysis, the minimal stock with no safety stock should be equal to 50 parts, if an annual part demand of 1715 and a batch size equal to 50 were considered.

3.3. ADDITIVE MANUFACTURING PRODUCTION

For the Additive manufacturing production scenario, we estimate the part cost for 3 part sizes and 3 technologies, as it is possible to be seen in Table 4. It is important to note that the machine cost is a quotation average and reflect the magnitude cost of each technology.

In this table it is also exposed the maximum number of parts that might be produced by batch according to a building area equal to 300x300x300mm.

Table 4 –Parameters for Cost estimation of additive manufacturing parts

		Part size 1	Part size 2	Part size 3
	Description	Value	Value	Value
Material cost	Max Lenght (mm)	8,00	30,00	60,00
	Max Width (mm)	8,00	30,00	60,00
	max Height (mm)	15,00	15,00	15,00
	Volume (cm3)	0,96	13,5	54
	material density (g/cm³)	1,05		
	raw material cost rate ($/kg)	45		
	Part material Cost ($)	**0,05**	**0,29**	**0,64**
Production Overhead cost	layer height (mm)	0,1		
	Raster speed (mm/min)	2500		
	raster diam (mm)	0,5		
	space between parts (mm)	2		
	building Lenght (mm)	300		
	building Width(mm)	300		
	Building Height(mm)	300		
	Max parts / batch	900	81	16
	Machine time cost ($/h)	30		
	Production batch overhead cost	**$ 3,80**	**$ 21,50**	**$ 45,00**
Machine Cost	**SLA Cost**	**$ 150.000,00**		
	FDM Cost	**$ 50.000,00**		
	SLS Cost	**$ 250.000,00**		

Another point that is also important to note is related to the batch size, as presented in Figure 8. It is possible to see the tendency of cost saturation for batch sizes superior to 5 parts. In this figure, the variation of overhead cost as a function of part size is also presented, where the variation of cost is found between $4.00 and $45.00.

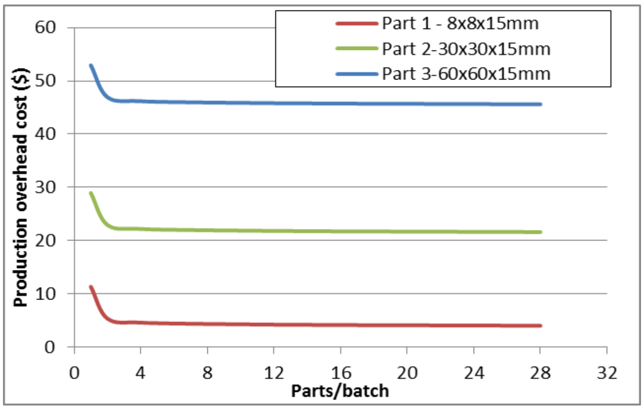


Figure 8 – Effect of batch size for the production overhead cost of additive manufacturing production

In addition, as the final part cost of additive manufacturing production was influenced by the amortised value of machine, we identified the variation of this cost as a function of machine technology and annual part demand, as presented in Figure 9. According this figure, it is possible to see that the part cost tendency is around $25.00 for annual part demand superior to 10000 parts with dimension equal to 30x30x15mm.

It is also presented that for this same annual part demand, the part cost of 8x8x15mm parts tend to $4.00 and 60x60x15mm parts tend to $48.00.

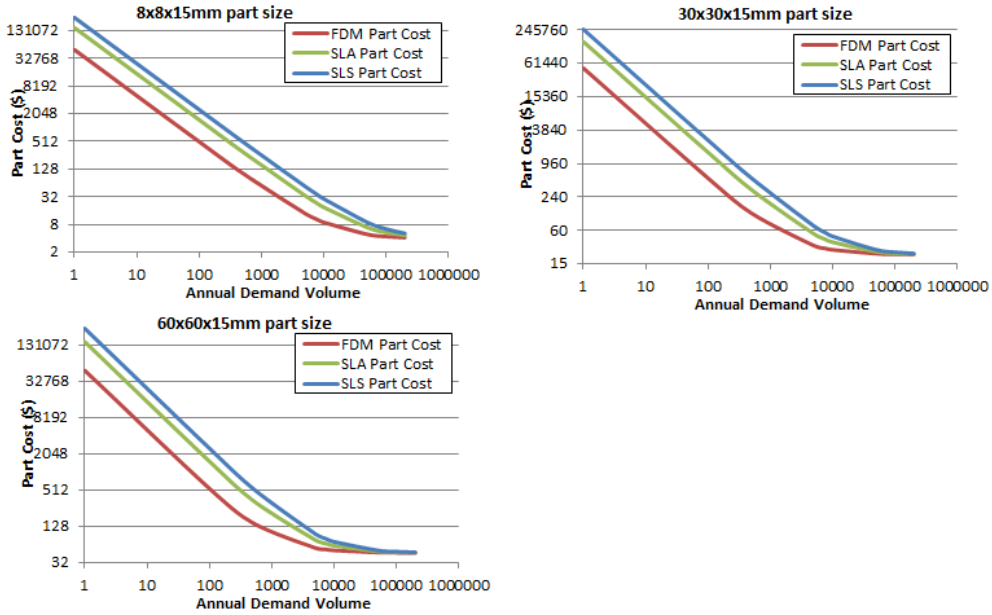


Figure 9 – Diagrams of part cost estimation as a function of the annual parts demand for SLA, FDM and SLS technologies

With respect to the timing analysis, we have also estimated the maximum manufacturing time per batch according to the part size. In contrast, Figure 10 presents the comparison between the lead time and demand time as a function of annual part demand. In this figure, it might be indicated the manufacturing feasibility with accordance with annual part demand. In this way, the maximum annual part demand that can be provided by additive manufacturing production in the studied conditions might be 1255 parts with 60x60x15mm, 2668 parts with 30x30x15mm and 15000 parts with 8x8x15mm.

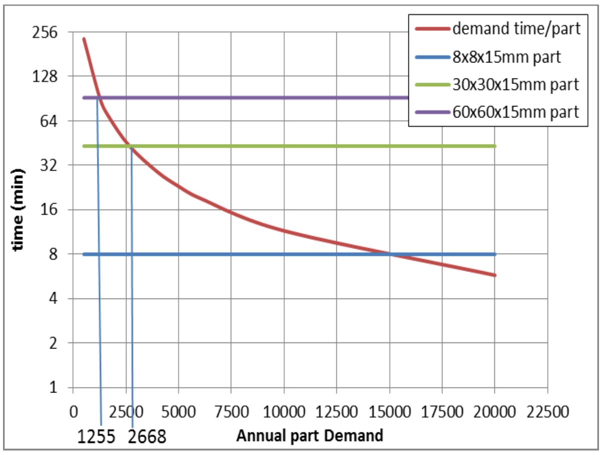


Figure 10 –Demand time and part lead time as a function of the annual parts demand

With respect to stock analysis, the minimal stock with no safety stock should be equal to 16 parts for 60x60x15mm part sizes, 81 part for 30x30x15mm part size and 900 part for 8x8x15mm part size, as it is possible to be seen in Figure 11. In this analysis, the maximum annual part demand for each part size was considered according to the presented before.

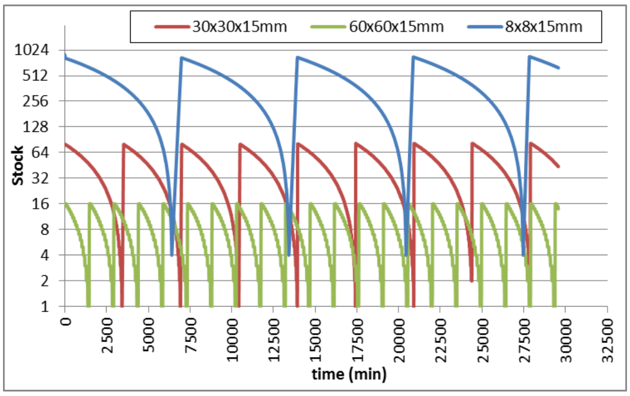


Figure 11 –Stock flow of Additive manufacturing production as a function of part size

3.4. LOW COST ADDITIVE MANUFACTURING IN NETWORK

Now for the last scenario, we analysed the feasibility of production which used low cost additive manufacturing machine in a network arrangement. In this case, the main parameters which were used can be seen in Table 5, where the machine cost and the building area dimensions are the main difference from the previous scenario. It is important to note that in this table, the production overhead cost considers only one machine in the estimation. Otherwise, the production overhead cost tends to decrease in accordance with the number of machines in the network arrangement.

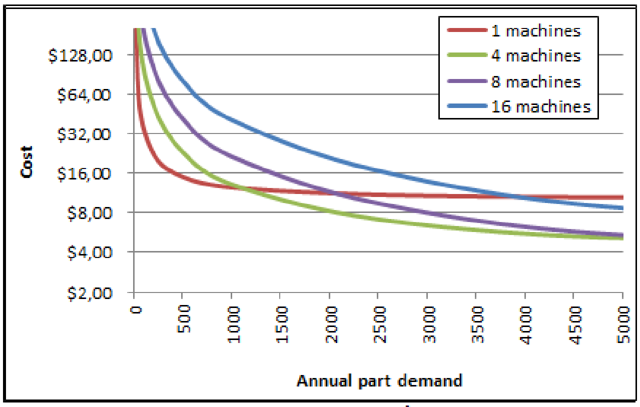
It is also possible to see that in comparison with professional additive manufacturing equipment, low cost equipment implied on an extremely high production overhead cost for large parts. It probably occurs because of the low raster speed and the long manufacturing time.

Table 5 –Parameters for Cost estimation of low cost network additive manufacturing

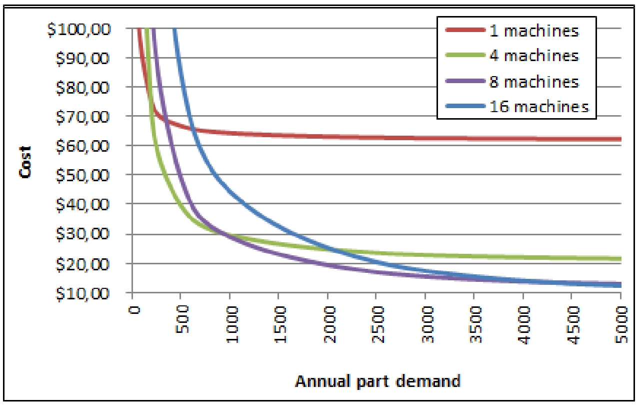
		Part size 1	Part size 2	Part size 3
	Description	Value	Value	Value
Material cost	Max Lenght (mm)	8,00	30,00	60,00
	Max Width (mm)	8,00	30,00	60,00
	max Height (mm)	15,00	15,00	15,00
	Volume (cm3)	0,96	13,5	54
	material density (g/cr	1,05		
	raw material cost rate	45		
	Part material Cost ($)	**0,05**	**0,29**	**0,64**
Production Overhead cost	layer height (mm)	0,1		
	Raster speed (mm/mi	1000		
	raster diam (mm)	0,5		
	space between parts	2		
	building Lenght (mm)	150		
	building Width(mm)	150		
	Building Height(mm)	150		
	Max parts / batch	225	16	4
	Machine time cost ($/	30		
	batch overhead cost	**$ 9,94**	**$ 61,55**	**$ 132,70**
	Machine cost unit	**$ 2.500,00**		

Regarding Figure 12, it is possible to see the part cost as a function of number of machine in network and annual part demand. This figure indicates the decrease of part cost according to the rise of machine number in production network. It is also possible to evidence that the application of network arrangement make possible to reduce the part cost of 60x60x15mm in almost 7 times.

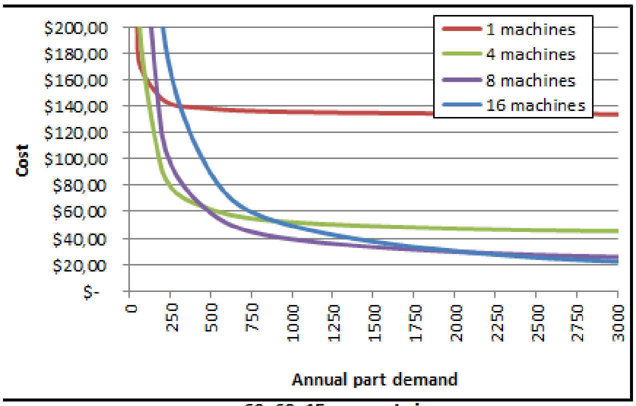
Otherwise, the increase of machines into the network arrangement is not indicated for very small demand. At this way, fabrication of very small parts (8x8x15m) with a single machine tends to be more interesting for annual demand which is found below 1000 parts, while the small parts (60x60x15mm) seems to be more suitable to be fabricated in a network when an annual demand is higher than 200 parts/year.



8x8x15mm part size



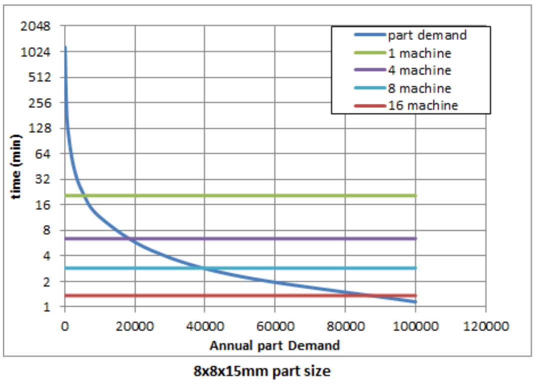
30x30x15mm part size

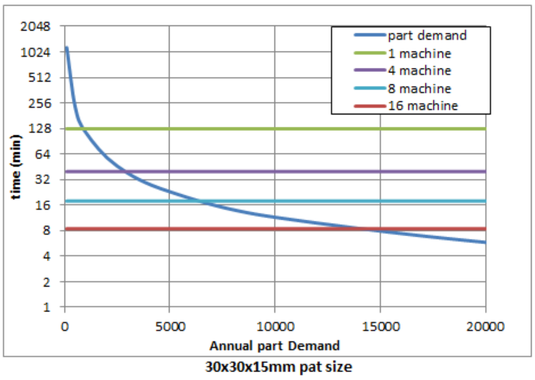


60x60x15mm part size

Figure 12 – Diagrams of part cost estimation as a function of the annual parts demand for the number of low cost machines

In Figure 13, it is presented the correlation between demand time as a function of annual part demand and the lead time which is provided by 1, 4, 8 and 16 machines in the network arrangement in addition to exposing the effect of part size for the lead and demand time. With these diagrams, it is possible to identify the production way feasibility range, where the intersection between demand and lead time marks the maximum annual demand that the production network can support.





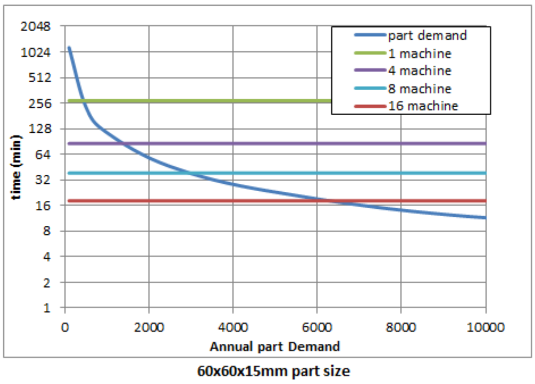


Figure 13 – Demand time and part lead time as a function of the annual parts demand and number of machines

On the other hand, the analysis of part lead time has shown to be strongly influenced by the number of machines in the arrangement. In this case, the maximum annual demand of 60x60x15mm part size that might be attended by the production way varied from 450 to 6000 parts/year if the number of machines in the arrangement would be increased from 1 to 16 machines. In addition, for 8x8x15mm and 30x30x15mm part size, this number would respectively be raise to 80000 and 15000parts/year.

With respect to the minimal stock considering no safety stock, this scenario implied on an inventory size equal to 4 parts for 60x60x15mm part size, 16 for 30x30x15mm part size and 255 for 8x8x15mm part size.

3.5. PRODUCTION STRATEGY COMPARISON

Comparing the results of the analysed scenarios, it was possible to identify the main differences among the scenarios in term of cost. In this analysis, it was also possible to see which production way is more suitable for each annual part demand.

In order to compare the four scenarios, we identified the part cost of each process as a function of annual demand and part size, as represented in Figure 14. In this figure, it is possible to see that the most indicated production way for 30x30x15mm parts size and annual demand inferior to 1000 parts/year might be additive manufacturing services. On the other hand, for annual demand between 1000 and 3000 parts/year, the recommended production way should be additive manufacturing in a 8 machine network arrangement. In this case, it was also evidenced that injection moulding was the most indicated for annual demand superior to 3000 parts/year.

For 8x8x15mm part size, it was indicated that additive manufacturing services is the most indicated production way until 2000 parts/year, in addition to the network arrangement was seen to be equivalent to injection moulding part cost.

In contrast with this, it was found that additive manufacturing services was the most indicated for 60x60x15mm part size with annual demand inferior to 500parts/year. While the low cost additive manufacturing in 8 machine network arrangement was evidenced to be the most suitable for annual demand between 500 and 3000parts/year. For superior values of annual demand, the most indicated process was proved to be injection moulding production.

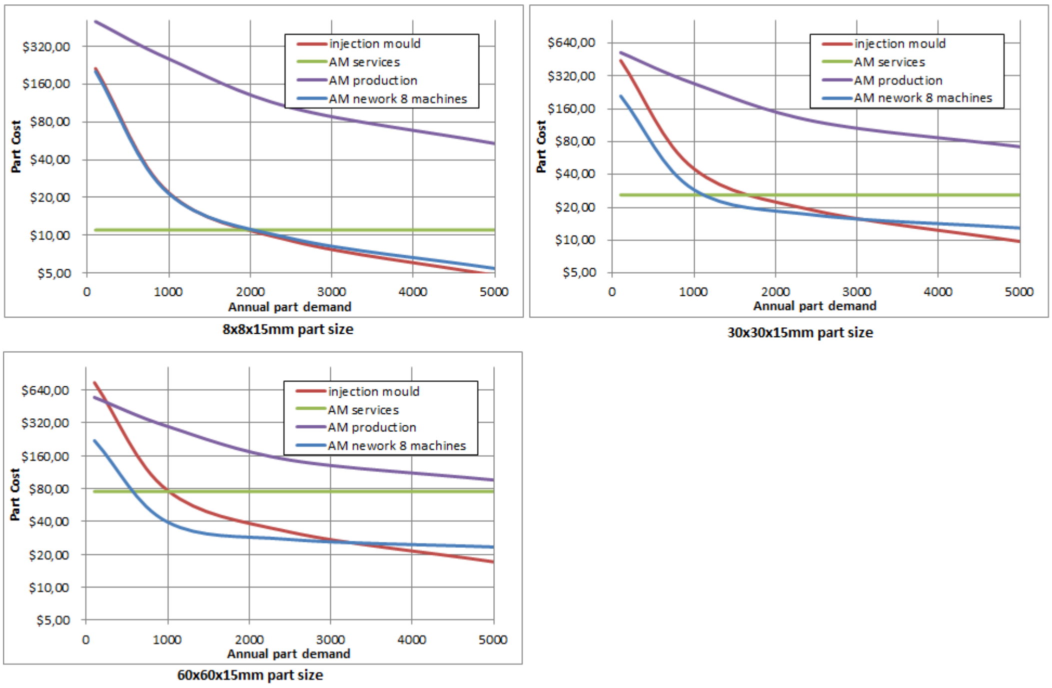


Figure 14 –Part cost as a function of annual demand for injection moulding, additive manufacturing services, additive manufacturing production and low cost additive manufacturing in network arrangement

In addition, the part demand time as a function of annual demand was also compared in Figure 15, where all the production scenarios were shown to be feasible in term of lead time for 8x8x15mm part size and annual demand inferior to 5000part/year.

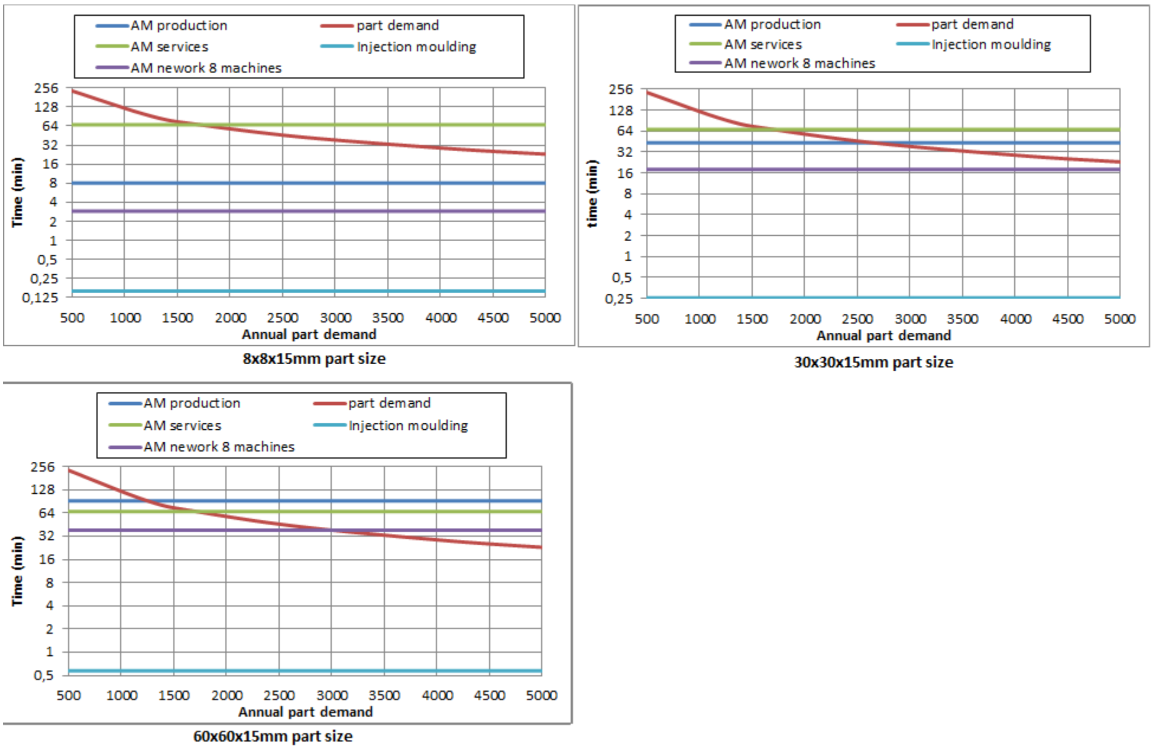


Figure 15 –Part demand time as a function of annual demand for injection moulding, additive manufacturing services, additive manufacturing production and low cost additive manufacturing in network arrangement

Otherwise, the lead time of 30x30x15mm part size of additive manufacturing services was indicated to attend to 1500parts/year, while additive manufacturing production was to 2500parts/year. For this part size, both injection moulding and low cost additive manufacturing in 8 machines network arrangement were found to support to annual demand superior to 5000parts/year.

By the end, as the lead time of 60x60x15mm part size tend to be longer than smaller parts, the additive manufacturing production was found to attend to 1250parts/year, while additive manufacturing services was to 1500parts/year. Additionally, low cost additive manufacturing with 8 machines in a network arrangement was identified to support to 3000parts/year. For this part size, the only process that was found to attend to the demand time for annual demand superior to 3000parts/year was the injection moulding.

With respect to the minimal inventory, we can see in Figure 16 that injection moulding result in the smallest inventory for small parts, while the additive manufacturing with 8 machines in a network arrangement does for medium size parts. Moreover, although injection moulding and additive manufacturing services were found to imply in a constant inventory size for different part sizes the average of inventory size was marked to remain below 50 parts. In other words, no significant benefits in using additive manufacturing were seen for low scale production in comparison with conventional processes.

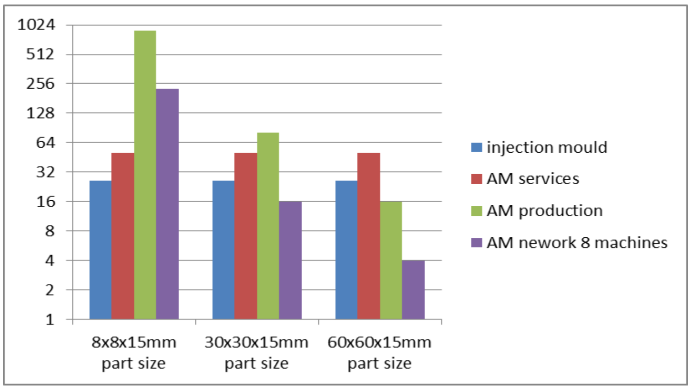


Figure 16 –Minimal inventory for the maximum productivity

4. CONCLUSIONS

In this work, it was possible to see the main differences among injection moulding, additive manufacturing services, additive manufacturing with large professional machines and additive manufacturing with low cost machines in a network arrangement.

In addition, estimated cost numerical models of each one of the analysed processes were developed and identified the main components that contribute for the part cost.

It was possible to evidence the feasibility range of each one of the analysed processes as a function of annual demand besides being indicated the most suitable processes in accordance with the demand range.

For very small demand, the most indicated production way which was found is additive manufacturing services even though it results in a high part cost. In contrast, low cost AM machines in a network arrangement were shown to be the most recommended for annual demand between 500 and 3000parts/year. It might indicate that this range of demand which was poorly covered may be attended by this proposed production way so that new business can also be created as consequence of this.

With respect to the lead time analyses, it was evidenced that injection moulding attend all the analysed part sizes for annual demand superior to 5000parts/year, while the additive manufacturing services was up to 1500parts/year. On the other hand, additive manufacturing with 8 machines in a network arrangement was found to attend to annual demand superior to 5000parts/year for 8x8x15mm and 30x30x15mm part size and annual demand is limited to 3000parts/year for 60x60x15mm part size.

5. ACKNOWLEDGMENTS

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