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Cost estimation for rapid manufacturing – simultaneous production of mixed components using laser sintering

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Abstract: Rapid manufacturing (RM) is a production method able to build components by adding material layer by layer, and it thus allows the elimination of tooling from the production chain. For this reason, RM enables a cost-efficient production of low-volume components favouring the customization strategy. Previous work has been developed on costing methodologies applicable to RM, but it was limited to the scenario of the production of copies of the same part. In reality, RM enables the production of different components simultaneously, and thus a smart mix of components in the same machine can achieve an enhanced cost reduction. This paper details this concept by proposing mathematical models for the assignment of the full production cost into each single product and by validating through a case study. This paper extends previous work on RM costing by adding the scenario of simultaneous production of different parts.

Keywords: rapid prototyping, rapid manufacturing, cost model, mixed production, laser sintering

1 INTRODUCTION

The processes able to build components in an additive manner were originally named rapid prototyping (RP) because they were used to create models for demonstration and visual aids [1]. The typology of the process, which consists in adding material layer by layer to build an object, permits the production of parts without the need of tooling, allowing the manufacture of low-volume products and increased design flexibility [2, 3]. The production of end-use parts using RP techniques is a modern concept named rapid manufacturing (RM) [4, 5]. The basis of RM lies in the direct production of components from a three-dimensional computer-aided design model. RP/RM processes include stereolithography, laser sintering (LS), fused deposition modelling, and three-dimensional printing, among others [6, 7]. LS systems are currently the most widely used for RM applications [7, 8].

From the literature, there are different limitations for current RM systems [9, 10], including:

- (a) material variety and properties;
- (b) process speed;
- (c) dimensional accuracy;
- (d) surface finish;
- (e) repeatability;
- (f) cost effectiveness.

The aim of this work is to develop and enhance the knowledge regarding the economy of RM. In particular, the aim of this paper is to extend the original work of RM cost modelling to the scenario of producing simultaneously different components on the same machine build envelope.

2 LITERATURE REVIEW

There has only been limited work concerning the cost of RM. Grimm [11] studied the hourly cost to run different RP machines and compared the results, but the study was limited to the production of single parts and therefore his assumptions were not extendable to an RM environment.

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The first costing work entirely dedicated to RM was developed in 2003 by Hopkinson and Dickens [12]. The authors calculated the cost of a part, assuming that the machine was producing only copies of the same part and using a constant production time. Their model was used to calculate a first approximation break-even analysis with injection moulding (IM). LS manufacture was compared against IM techniques in order to find when RM was economically viable. Figure 1 is an example of the results of the study conducted by the two authors.

The IM curve decreases because the initial cost of the mould is amortized across the production volume. The RM line is constant, supposing that all indirect costs are charged on every single part, dividing the total indirect cost for the number of parts produced (i.e. machine depreciation in 8 years).

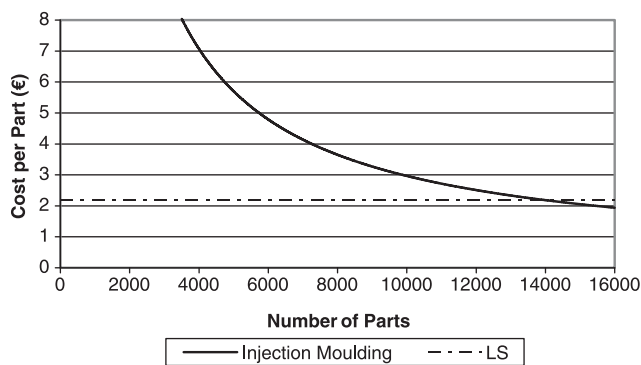


Fig. 1 Example of break-even analysis comparing LS with IM [12]

This model is a good approximation, but only valid where the RM method is making:

- relatively high production volumes;
- copies of the same part.

The first limitation was overtaken by Ruffo *et al.* [13] in 2006, on which work the present study is based. The authors developed a new cost estimator based on a 'full costing' concept, which included labour, material, machine absorption, production, and administrative overheads. The indirect costs were assigned to the components on a machine working time basis using an empirical time estimator for LS [14]. The main outcome of the study was a curve relating the cost per part to the production volume. In contrast to the previous work by Hopkinson and Dickens [12], the curve has a sawtooth shape owing to the filling of the machine bed space, and it is shown in Fig. 2. Specifically, if adding parts to a production set-up does not increase the number of layers (i.e. parts are added next to each other in the horizontal directions), the time and cost of the build is efficient. In contrast, when a new part needs to be placed on a new layer, both time and cost for the build increase dramatically owing to the enlarged build height (which means additional layers for recoating). The same effect is present when the additional part causes the set-up of a new machine bed.

In the study by Ruffo *et al.* [13], the previous cost model [12] was compared with the new model (Fig. 2). The comparison evidenced an underestimation for the old model. The break-even point for the sample part chosen moved from 14 000 parts

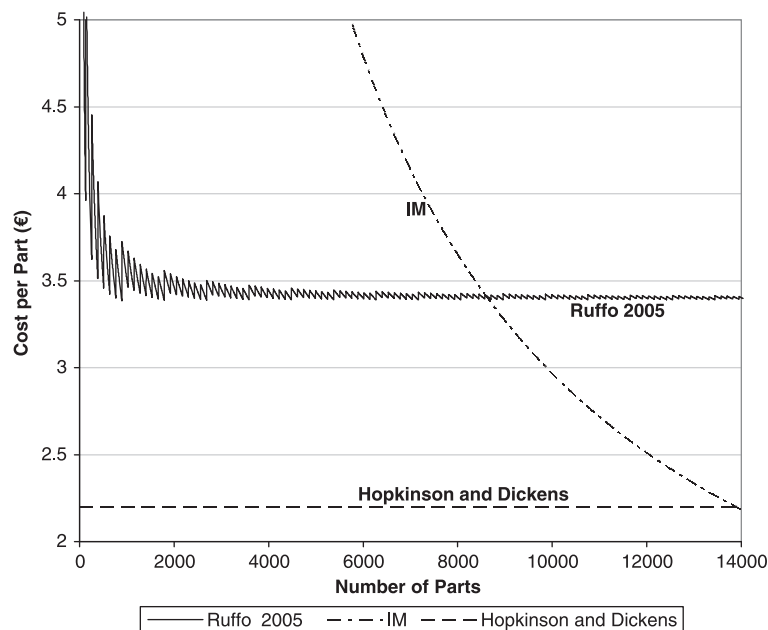


Fig. 2 Cost model comparison of LS and IM [13]

calculated by Hopkinson and Dickens in 2003 to 9000 parts obtained by the new estimator with data up to 2005.

However, the second limitation previously exposed about mixed parts production has not yet been solved. The flexibility of additive techniques allows the production of more than one component at the same time, and the parts in production can be different from one another. For this reason it is possible to define RM as a *parallel* process, where different parts can be built simultaneously. The importance of parallel production should be noted because the smart mixing of components on a single machine bed could lead to a higher build packing ratio and a consequent cost reduction. Therefore, the development of a method for cost calculation of mixed parts in the same build envelope is the aim of this paper.

From now onwards, the term ‘original model’ will be used to identify the cost model of Ruffo *et al.* [13] which is used as the basis of this work. This means that the case studies in this work are developed by using the cost model mentioned, and therefore all the assumptions made in the original model are also used for this study. In particular, it should be recalled that the LS machine used was a 3D Systems Vanguard Model [15] and the material was Duraform PA [16].

3 EXPERIMENTAL METHOD – MODEL FORMULATION

The original cost model [13] is able to output the total cost of manufacture for the entire planned production, $Cost_B$, through the input of simple geometrical data such as the sum of the object volumes and the sum of the bounding box volumes. A summary of the equations constituting the original model follows [13]

$$Cost_B = \frac{\sum \text{indirect_Costs}}{\text{working_time}} t_B + \frac{\text{direct_Cost}}{\text{mass_unit}} m_B \quad (1)$$

where m_B is the mass of the planned production, proportional to the object volumes, and the time to manufacture the entire build

$$t_B = t_{xy} + t_z + t_{HC} \quad (2)$$

is the sum of the three subtimes [14]:

- (a) the time to laser-scan the section and its border in order to sinter the powder, t_{xy} ;
- (b) the time to add layers of powder (recoating time, t_z);
- (c) the time to heat the bed before scanning and to cool down slowly after scanning, adding layers of powder or just waiting time to reach the correct temperature, t_{HC} .

The aim of this study was equitably to split the total cost of manufacture, $Cost_B$, into the different costs

for the different parts, $Cost_P$, in the scenario of mixed components manufacture.

3.1 Existing model: multiples of the same part

When the planned production consists of copies of a single part, the cost per part, $Cost_P$, is intuitively equal to the entire cost of the build, $Cost_B$, divided by the number of parts placed in it, n , as in equation (1)

$$Cost_P = \frac{Cost_B}{n} \quad (3)$$

3.2 Extended model: mixed components for parallel production

The original cost model [13] was built under the idea of activity-based costing (ABC), which is a well-known theory in the literature. Tsai [17] gives a good definition for the costing of different products manufactured together: ‘joint products are produced simultaneously by a common process or series of processes’. In ABC there are different possibilities for allocating costs to joint products; the main ones analysed in the literature are [18, 19]:

- (a) market value method;
- (b) average unit cost method;
- (c) weighted average method;
- (d) quantity unit method.

Similarly, three different mathematical methods for RM cost assignment follow – they are finally compared through a case study.

3.2.1 First assignment method – based on parts volume

A possible estimation is based on the components volume. Once the cost of the entire build is found, the cost of a single part can be calculated as a fraction of the total cost using the ratio between the volume of the part, V_P , and the total volume of production, V_B

$$Cost_{P_i} = \left(\frac{V_{P_i}}{V_B} \right) \times Cost_B \quad (4)$$

where V_B is the volume of the entire build, $Cost_{P_i}$ is the cost of part i , V_{P_i} is the volume of part i , and i is an index going from one to the number of different parts present in the build.

3.2.2 Second method – based on the cost of building a single part

It has been demonstrated that the part volume, considered singularly, is not enough for time and cost estimation purposes [13, 14]. Therefore, a different solution is proposed in order to split the full build cost into the different parts placed on the machine

bed. A coefficient $\gamma \in [0, 1]$ is introduced as a weight; its purpose is to identify the build cost of the part when manufactured alone in the machine bed. This method ensures that both volume and bounding box volume are used for the estimation, following the directives of the original cost model [13]. When calculating the single part cost, the constants referring to machine set-up, warming up, and cooling down [14] are excluded. This is because the single part cost should be a ‘naked’ production cost, depending only on the part size and geometry. Therefore, the coefficient γ includes the variables identifying part size and build time and it works as a weight for the assignment of the full build cost

$$Cost_{p_i} = \frac{\gamma_i \times Cost_B}{n_i} \tag{5}$$

where

$$\gamma_i = \frac{Cost_{p_i}^* \times n_i}{\sum_j (Cost_{p_j}^* \times n_j)} \tag{6}$$

and i is the index of the part under cost calculation, j is the index that refers to all the parts manufactured on the same bed, γ_i is the above-mentioned factor for part i , n_{\square} is the number of parts identified with the subscript (\square), and $Cost_{p_{(\square)}}^*$ is the cost obtained with the original model [13] for the building of the single part (\square), but where the constant t_{HC} is missing from the equations and the time function is reduced to

$$t_B = t_{xy} + t_z \tag{7}$$

This second method is logically correct but introduces a significant error. In the presence of a small part (i.e. small in the x and y directions), the machine bed is partially empty and thus the packing ratio used for calculation is poor – in reality manufacturers set every build with the highest packing ratio possible. This makes the γ -based method very inaccurate because this weight is based on manufacturing conditions very far from the ones used in practice. Figure 3 shows the provenance of the factor

γ_i on the production curve of an automotive component (which will be used in the next section for a case study).

3.2.3 Third method – based on the cost of a part built in high-volume production

In order to overcome the problem described above, an effective solution appears to be the replacement of the cost of the single part, $Cost_{p_i}^*$, with a cost calculated in hypothetical high-volume production using RM. The explanation of the solution proposed is based on the fact that the RM curve tends to stabilize for a high number of parts (see Fig. 2 and/or Fig. 3) and the packing ratio is then optimized. Conceptually, it is possible to extrapolate the cost for the production of an infinite number of parts. In practice, a high part number is used instead, with the condition that this production volume makes the production curve flat, as shown in Fig. 3. It is then reasonable to use the following equations

$$Cost_{p_i} = \frac{\gamma_i^\infty \times Cost_B}{n_i} \tag{8}$$

where

$$\gamma_i^\infty = \frac{Cost_{p_i}^\infty \times n_i}{\sum_j (Cost_{p_j}^\infty \times n_j)} \tag{9}$$

γ_i^∞ is the weight for the assignment of the full build cost, and $Cost_{p_i}^\infty$ is the cost described above for a hypothetical infinite number of manufactured parts i . The use of ‘infinite parts production’ is not credible for engineering problems, and thus its value is set by the cost for high production, where the curve is flat or, at least, has very low oscillations (with a consequent low error – see Fig. 3).

4 RESULTS

In order to determine the efficiency of the three models proposed, a brief case study is analysed. Figure 4

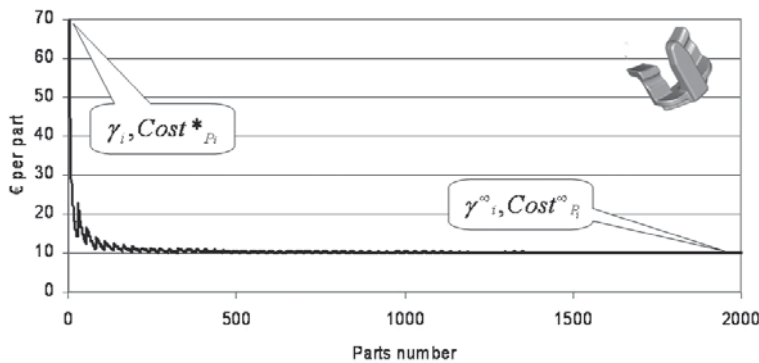


Fig. 3 Graphical aid to understand the source of weights γ_i and γ_i^∞


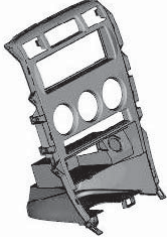
Spring Clip	Centre Console
	
Volume: 19634 mm ³ Bounding box dimensions: X=51.6 mm Y=54.1 mm Z=39.2 mm	Volume: 387821 mm ³ Bounding box dimensions: X=200.7 mm Y=256.9 mm Z=383.5 mm

Fig. 4 Automotive components

Table 1 Comparison between different cost assignments for mixed production

Method	Equation number	Cost per part (€)	
		Console	Spring clip
a) Multiples of the same parts (only consoles first and only spring clips then)	(3)	1637.6	10.0
b) Mixed production			
1st – volume based	(4)	<i>315.8</i>	<u>16.0</u>
2nd – single part cost based	(5)	<i>162.3</i>	<u>17.5</u>
3rd – high volume production based	(8)	<i>1188.7</i>	<u>7.3</u>

shows two automotive components, one of small and one of large physical dimensions (not to scale in the figure).

Their RM production costs were calculated (a) as if produced separately, and (b) as if produced simultaneously in the same machine, and then compared. The maximum number of consoles that can fit the Vanguard machine chamber was two, and 200 small spring clips were added around the consoles in order to fill the build capacity. Costs for RM production were estimated, using the original model [13], as follows:

- (a) €526 752 to build separately 20 000 clips (€199 218) and 200 consoles (€327 533);
- (b) €382 967 to build together the same number of parts in parallel production.

The cost saving is evident for components mixing, as expected; but what is the cost per part for the two components in both scenarios (a) and (b)? Table 1 shows the resulting costs per part using the three different assignment techniques.

In Table 1, the values indicating a cost reduction are shown in bold italic, while the values indicating a cost increase are underlined. Intuitively, only the third model is a fair assignment method. In fact, the first

two methods tend radically to reduce the cost of larger components at the expense of smaller parts. In contrast, the last model equitably splits the cost saving, typical of mixed production, between each component.

5 DISCUSSION

The use of the third cost assignment method, described by equations (8) and (9), can be used graphically to show the advantage of mixed parallel production. A clear example follows for the production of the spring clip described previously.

5.1 Scenario 1 – the machine builds only spring clips

There is a need to build 200 spring clips and a machine is reserved for this work. The spring clip production curve, which relates the cost per part plotted against the production volume, was shown in Fig. 3. Figure 5 shows the same cost curve but focuses on low-volume production, for the building of up to 200 clips.

5.2 Scenario 2 – the machine works in parallel production of mixed components

In this second scenario there is a machine already set up for the manufacture of two consoles – some spring clips can be added to the same build. Figure 6 shows a comparison between the two production curves plotted under the assumptions of scenarios 1 and 2, being respectively curves for copies of the same part and mixed production of consoles and clips.

The continuous curve is the same as that shown in Fig. 5 and refers to the production of only spring clips on the machine bed. The dashed curve has been modelled using equations (8) and (9) for the simultaneous production of two different components on the same machine.

For scenario 2, owing to the absorption of indirect costs on the two different components, the spring clip curve deflection for low volumes is not as steep as in scenario 1. This indicates the advantage of mixing components in the machine bed envelope in order to increase the build density and optimize the build space. Moreover, Fig. 6 confirms that a smart mixing of parts allows the manufacture of one-off components (or very low volumes) without incurring in a high cost, which is typical of the absorption of indirect costs.

It should be noted that the concept of mixing different parts is in common use by RM users. However, the methodology for the cost assignment and the graphical evidence of the advantage obtainable are novelties.

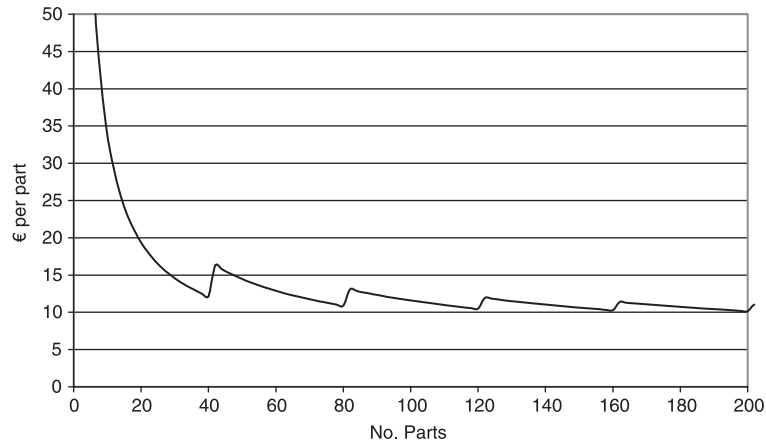


Fig. 5 View of the spring clip production curve for low-volume production levels

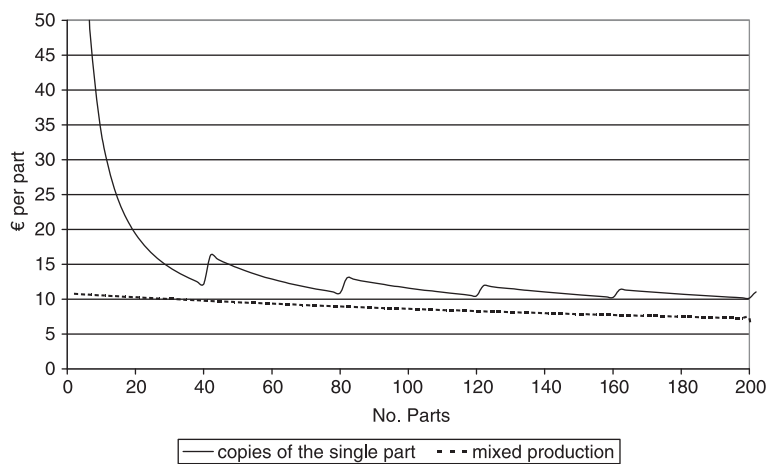


Fig. 6 Comparison between production curves for the spring clip: scenario 1 (only copies of the clip) versus scenario 2 (mixed production of clips with two consoles)

6 CONCLUSIONS

Since 2003, the main method of cost estimation used by both academic and industrial users of LS was based on the Hopkinson–Dickens model [12], which has been shown to be inaccurate for very low production volumes and incapable of determining costs for different parts produced in parallel. The first issue, regarding the low production volumes, was overtaken by the cost estimator presented by Ruffo *et al.* [13] in 2006. The authors demonstrated the deflection for low-volume production and showed innovative sawtooth-shaped graphs, which concept was a logical outcome, but it was not previously shown owing to the lack of automatic computational models. Still, another limitation of previous cost models was evident – the inability to calculate costs for the parallel production of mixed components.

In the paper, a well-known cost modelling method has been extended to the costing of parallel production, which is the simultaneous manufacture of different components on the same machine. Three different

cost assignment methodologies were proposed for mixed parts production. The three methods were tested in a real case study concerning two automotive components, and only one of the three models proved to be an equitable technique for cost assignment.

The results confirmed the intuitive concept of cost saving for mixed components production. Effectively, when different components are efficiently mixed in the building space, the cost of each component decreases. This result has been shown graphically by plotting the production curves from the case study data, illustrating the low deflection obtainable by mixing different parts during low-volume production.

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APPENDIX

Notations

$Cost(_)$	cost of (factor)
m	mass
n	number of parts
V	volume
γ	coefficient used as weight for cost assignment

Subscripts

B	build
beds	beds necessary to complete the build
HC	heat and cool phases
P	part
xy	scanning section in the x and y directions
z	recoating along the z axis

Superscripts

*	imaginative build with only one part
∞	imaginative build with infinite parts

