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ORIGINAL ARTICLE

Additive manufacturing process selection based on parts' selection criteria

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Abstract Additive manufacturing (AM) has been used to produce complex parts usually in small batch sizes. Recently, AM has been gaining importance with the development of new production technologies encompassing a wider range of materials. These new technologies allow broader AM application in the industry, beyond traditional usage in rapid prototyping. As a result, the number of parts being produced by AM technologies has been increasing. The differences among AM production technologies and the specific capabilities and restrictions of each available manufacturing machine result in complex manufacturing process definition. Moreover, process technology knowledge in the area is still limited to few professionals. In order to support process manufacturing to evaluate which AM technology would be best suited to produce a particular part, this paper presents a method for selecting the AM process based on the technical specifications of a part. The method relies on Analytic Hierarchy Process (AHP) to rank the most appropriate technologies and machines. Relevant parameters of the main machines available in the market were raised. These parameters are considered in the selection of machines able to produce a particular part considering its specifications. Practical applications of the method resulted in adequate responses to support manufacturing process definition.

Keywords Additive manufacturing · 3D printing · Manufacturing process planning · Analytic hierarchy process · Rapid prototyping

1 Introduction

Additive manufacturing (AM) is the process of building solid tridimensional objects by laying down layers, being opposed to subtractive manufacturing [1]. Over the past 20 years, these technologies have been used to make parts for the aerospace [2–4], automotive [5], biomedical [6, 7] industries, and other areas (e.g., design and architecture).

Recently, companies have been growing their interest in adopting AM technology in their product development processes [8]. Adopting such technologies is one way to optimize this process for a shorter development cycle, thus cutting down the time to market [9]. It is noticeable in this scenario that, in spite of this new technology having aroused considerable interest in companies, there is little research on which manufacturing processes are the most suitable to produce a specific item (for an example, see Wang et al. [10]), nor is there a recent market survey to identify the technology options available. In an attempt to contribute to fill this gap in research, this paper focuses on demonstrating a method to select AM process based on a part's requirements.

This article is structured in six sections. Section 2 presents a literature review on AM technologies. Section 3 details the research method and the solution developed. Section 4 focuses on data gathering and analysis for the proposed solution. Section 5 demonstrates the application of the proposed method. Finally, section 6 presents the conclusions and suggestions for further research.

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2 Additive manufacturing technologies

This section presents a review of seven AM technologies considered for the purpose of this research: stereolithography (SLA), 3D printing (3DP), selective laser sintering (SLS), fused deposition modeling (FDM), direct metal laser sintering (DMLS), ColorJet printing (CJP), and MultiJet printing (MJP). These technologies were selected as they are employed by the three major AM machine manufacturer players: 3D Systems, Stratasys, and EOS [11].

2.1 Stereolithography

This process builds 3D models from light-sensitive polymers that solidify upon exposure to UV radiation [12]. When hit by a laser beam, the resin solidifies, one layer at a time, until all layers in the model are shaped, then the solid model is removed, washed, and put in an oven for complete curing. The use of this technology is limited to light-sensitive polymers [13]. In addition to filling in regions not connected to the part, which causes material waste and post-processing to remove these fillings, there is a need for post-cure to improve the parts' finish.

2.2 3D printing

This process builds 3D models by setting powder on a base, this powder being selectively bonded by injecting an agglutinant [14]. The cycle is then repeated, until the entire 3D model has been built. Its advantages are the wider variety of materials [15], the quick production of parts, and the low cost [16]. Disadvantages of this process are the low surface quality and the low strength of the parts made, which significantly limit its possible applications.

2.3 Selective laser sintering

The SLS technique uses a laser beam to melt and solidify, one layer at a time, powder-like materials, like elastomers and metals [17]. In this process, the laser beam scans the powdered material layer to be shaped [8]. SLS widens the array of possible materials for building prototypes, being able to produce metal parts directly, without any later machining being required [18].

2.4 Fused deposition modeling

The FDM process builds objects by extruding polymers like ABS and polyamide in a system having at least one head moving on the *X*-*Y* plane and a platform moving vertically along the *Z*-axis [17]. Low cost of the material and easy to operate machines made led this technology to make quick prototype building by addition [12]. However, these technologies feature low precision and low model-building speed [19].

2.5 Direct metal laser sintering

DMLS is an additive metal fabrication technology. Process begins by applying a layer of the powder material to the building platform. Considering computer-generated data of the part geometry, a laser beam fuses the powder at defined points. This sequence is followed layer by layer in a net-shape process, which produces metal parts with high accuracy and detail resolution, good surface quality, as well as mechanical properties [20, 21].

2.6 ColorJet printing

In the CJP process, material is spread in layers over the build platform with a roller. After each layer is spread, a color binder is jetted—based on part geometry—from heads over each layer, causing the core to solidify [22].

2.7 MultiJet printing

The MJP process technology employs UV bulbs and photopolymer materials. Each layer of fine UV-curable acrylic plastics is cured, including support material, that can be separated from the part by a melting and washing process [23].

3 Methods adopted

This paper is conceptual by nature, aiming to recommend a method for selecting 3D printing machines for AM of parts.

The work was developed in four stages. The first stage is a survey of AM process technologies and machines available in the market, focusing on the machines manufactured by the major players in the AM industry [11]. This survey was done by gathering secondary, public domain information. The second stage comprised developing a rationale for selecting adequate AM machinery for manufacturing a specific part, based on Analytic Hierarchy Process (AHP). The results of this second stage are documented under section 3 herein. The third stage involves building a database with the technical features of the AM machines available in the market. The database was built based on a review of product literature from AM machinery vendors (section 4). Finally, in the fourth stage, the solution developed is applied to specific parts (section 5).

3.1 AHP principles

This section introduces the AHP method and its use in selecting machinery for AM. Using AHP starts by breaking down the problem into a hierarchy of criteria easier to analyze

Table 1 Relative scale of criterion importance

Scale	Numeric assessment	Reciprocal
Extremely preferred	9	1/9
Very, very strong	8	1/8
Very strong	7	1/7
Strong plus	6	1/6
Strongly preferred	5	1/5
Moderate plus	4	¼
Moderately preferred	3	1/3
Weak plus	2	½
Equally preferred	1	1

Adapted from Saaty [24]

and compare than when taking each criterion alone. From the moment this logical hierarchy has been built, decision-makers systematically analyze the options through comparing, two at a time, against each of the criteria [24]. This comparison between criteria is usually done with Saaty's relative scale values [24], as shown in Table 1.

Saaty's [24] relative importance scale (Table 1) is used to determine the importance (weight) of the criteria used. After the weights have been defined, it is necessary to compare criteria, two at a time, and the outcome of this comparison is a scale of criterion importance, used to compare options and rank them in terms of adequacy.

3.2 Solution development

This section introduces the development of the method for AM process selection from parts' selection criteria. Firstly, the rationale behind the solution developed is explained, breaking down the workflow in selecting the production process. Next, the elements of the solution rationale are presented, vis-à-vis the constraining factors and the multiple-criteria selection.

3.2.1 Solution rationale

The solution is AHP based and comprises two steps: constraining factors, which rule out machines unsuitable for this production, and multiple-criteria selection, which sorts machines in growing order, being the first ranked the most suitable for manufacturing a specific part. Figure 1 shows the rationale used in the selection of the AM process via parts' selection criteria.

As shown in Fig. 1, the AM process selection encompasses defining constraining factors for manufacturing and the multiple-criteria selection, based on criterion weights. The part's constraining factors should be compared with existing machines, and only machines that pass this evaluation should move on to the ensuing multiple-criteria selection.

The weights attributed to the parts' selection criteria are used in the multiple-criteria selection to sort the machines following the AHP structure, the best ranked one being the most suitable to produce a specific part.

The specified constraining factors and the criteria considered in the multiple-criteria selection are discussed in the following sections.

3.2.2 Constraining factors

Factors constraining production are those that render model building impossible as requested. For the AM selection method developed, the constraining factors adopted were the maximum production span of each machine, and the material used. This means that for each part being produced, the options

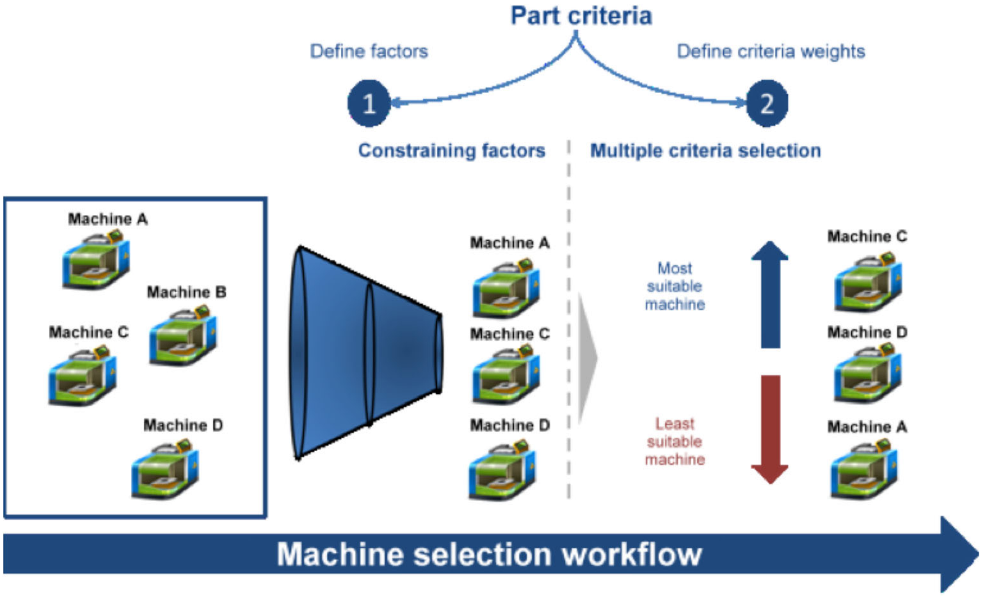


Fig. 1 Rationale used in selecting the additive manufacturing process. Source: developed by the authors

Table 2 Technical characteristics, measurement unit, and description of 3D printing machines

Technical characteristics	Unit	Description
Technology	–	Type of technology used in the machine's additive manufacturing
Printing materials	–	Materials supported by the machine
Printing size	mm×mm×mm	Maximum dimensions of the part
Multicolored parts	Boolean	Prints or not multicolor parts
Resolution	DPI	Maximum printing resolution
Layer thickness	mm	Minimum printing layer thickness
Accuracy	mm	Minimum distance between 1 layer and another
Printing speed	mm/h	Maximum material addition speed
Power specs	V, A, W	Required operating voltage, current, and power
Size	mm×mm×mm	Machine dimensions
Weight	Kg	Machine weight
Price	US$	Machine cost

Developed by the authors

(machines) to be considered in the multiple-criteria selection would be those that could fit in the part dimensions and the requested material.

3.2.3 Multiple-criteria selection

To carry out the multiple-criteria selection, it is necessary to define a list of the criteria to be employed. The criteria considered in the selection method developed are the criteria for the parts to be made. For this purpose, the parts' selection criteria suggested by Raulino [25] were used: material variety, surface quality, post-finishing, precision, resistance to impact, flexural strength, prototype cost, and post cure.

For each criterion, it is necessary to assess how each option (process technology and machine) performs regarding them. This step was conducted during machine database construction (see section 4). Once the machine's comparative performance for each criterion has been established, it is necessary to build a matrix comparing the importance levels of the criteria. The relative importance of each of these criteria varies

Table 3 3D printing machines surveyed

Personal	Professional	Industrial
3DTouch™ 3D printer (1 head)	Zprinter 150	Víper Pro
3DTouch™ 3D printer (2 head)	Zprinter 250	Sinterstation HIQ
3DTouch™ 3D printer (3 head)	Zprinter 350	ProX™ 950
RapMan 3.2 (1 head)	Zprinter 450	sPro™ 230
RapMan 3.2 (2 head)	Zprinter 650	ProX 300
CubePro®	Zprinter 850	Fortus 250mc
ProJet™ 1000	ProJet™ CP 3500	Fortus 360mc (configuration 1)
ProJet™ 1200	ProJet™ CPX 3500	Fortus 360mc (configuration 2)
ProJet™ 1500	ProJet™ CPX 3500 Plus	Fortus 400mc (configuration 1)
Mojo 3D printer	ProJet™ SD 3500	Fortus 400mc (configuration 2)
uPrint SE	ProJet™ HD 3500	Fortus 900mc
uPrint SE Plus	ProJet™ HD Plus 3500	Objet1000
	ProJet™ DP 3500	EOS M 400
	ProJet™ MP 3500	
	ProJet™ 5000	
	ProJet® 860Pro	
	ProJet® 7000	
	Dimension Elite 3D	
	Dimension SST/BST	
	EOSINT P 800	

Developed by the authors

Table 4 Machine assessment factors

	SLA	TDP	SLS	FDM	DMLS	CJP	MJP
Variety of materials	Small	Medium	Large	Medium	Medium	Small	Small
Surface quality	Average	Good	Good	Average	Excellent	Good	Good
Post-finish	Average	Good	Good	Average	Excellent	Good	Good
Accuracy	Excellent	Average	Good	Average	Excellent	Average	Average
Resistance to impact	Average	Low	Good	Good	Excellent	Low	Low
Flexural strength	Low	Low	Excellent	Excellent	Excellent	Low	Low
Prototype cost	High	Medium	High	Low	High	Medium	Medium
Post cure	Yes	No	Yes	No	No	No	No

Developed by the authors

from one specific production case to another, according to the user's needs for the part to be manufactured on that specific situation.

The final evaluation of the priority of each alternative is the sum of the product between the weights of the criteria and the weights of the alternative in the corresponding criteria.

4 Survey of machine data and parts' selection criteria

This section presents the development of the machine database, resulting from the survey of the machines studied in this research, in order to allow selection and ranking among them by means of constraining factors and multiple-criteria evaluation.

4.1 Machine database

The machine database comprises technical features of 45 different AM machines which were surveyed and analyzed. The technical features considered for each machine are listed in Table 2, including their description and the measurement unit.

Machines analyzed were selected from the current portfolio of the three major players in AM industry [11]. Table 3 lists the 45 machines analyzed, segmented by application type in personal, professional, and industrial applications.

4.2 Assessment of manufacturing processes and machines according to established criteria

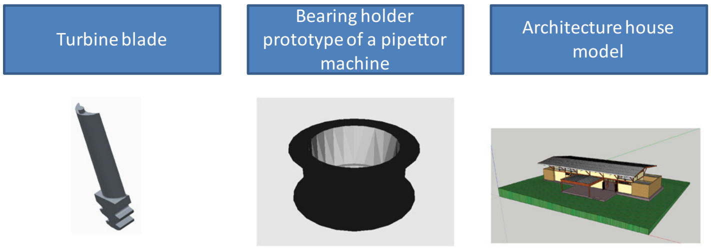
Based on the machine criteria (discussed in 3.2.3), each of the 45 machines in the database was evaluated. The resulting criterion assessment for each process technology is presented in Table 4.

This evaluation made it possible to sort the machines on each of these criteria, so they could be compared one by one relative to the part's requirements, and then be ranked, as prescribed by the AHP method.

5 Method application

This section demonstrates the application of the proposed method in three different applications: a final engineering part, a machine element prototype, and an architectural model. Application scenarios are based on real existing parts (Fig. 2). On each presented application, based on specific part requirements, constraining factors and multiple criteria are used to perform comparisons among machines listed on the machine database. As a result, machines are ranked and the most suitable ones to make the specific part are indicated.

The selection process is performed in two steps. First, for each part, constraining factors (size and material) are analyzed



Constraining factors			
Dimension	135 x 25.63 x 15 mm	Diameter - 32.3mm High - 14.1mm	393.3 x 326.0 x 79.0mm
Materials	High-strength, corrosion-resistant nickel chromium	polymer	polymer, wax or ceramic

Fig. 2 Application scenarios. Source: courtesy of Caue Mançanares (turbine blade), Otto Heringer (bearing holder), and Lucas Corato and Aline Corato (House)

Table 5 Machine grading matrix

	Low	Average	Good	Excellent
Low	1	1/3	1/6	1/9
Average	3	1	1/3	1/6
Good	6	3	1	1/3
Excellent	9	6	3	1

Developed by the authors

and only machines that fit the constraining factors are selected. Second, machines are compared in pairs, by their individual performance—represented by their technology performance and specific machine parameters—in each criterion, according to Table 5.

The weight of the criteria will be analyzed, at each application, according to the relative scale of AHP criterion importance, presented in Table 1.

5.1 Turbine blade

The first application considered is a turbine blade to be employed in real operation to substitute a dandified part of the original equipment. The part works under high pressure and high temperature, which leads to the material as a constraining factor, as detailed bellow:

- *Constraining factors*

– Dimensions: 135×25.63×15 mm
– Material: high-strength, corrosion-resistant nickel chromium material

In order to resist to the erosion caused by the impact of the high pressure and temperature, the major criteria to be considered are the resistance to impact and the surface quality. The expectations on the importance scale defined in this scenario for comparing additive manufacturing machine criterion can be proposed as shown in Table 6.

Applying this scale of importance upon comparing the 45 machines surveyed leads to the result that the most adequate technology to make the proposed engineering part would be DMLS and the prioritized machine was EOS M 400, from EOS.

5.2 Machine element prototype for a pipettor

In the engineering field, the most common application of AM is still for making prototypes. The application scenario considers a bearing holder prototype of a pipettor machine, intended for evaluation of mostly the product's final shape and specially the functionality. Durability tests were not supposed to be performed with this prototype.

- *Constraining factors*

– Dimensions:

Diameter—32.3 mm
Height—14.1 mm
– Material: polymer

As a prototype, there is no need to obey all the mechanical properties of the part. The priority must be given then to an average accuracy and surface quality, what can be found in most of the personal machines. The results of this criterion importance analysis are presented in Table 7.

Comparing the selected printing machines, the best option for this prototyping project is the FDM technology CubePro®.

5.3 Architecture

The most common application of AM in architecture is building scale models. Such pieces should be visually attractive and might not necessarily demand high dimensional precision.

Table 6 Importance scale for a real engineering part

	Multicolored part	Accuracy	Surface quality	Resistance to impact	Flexural strength	Criterion weight
Multicolored part	1	1/9	1/9	1/9	1/9	0.03
Accuracy	9	1	1/6	1/6	3	0.13
Surface quality	9	6	1	1/3	6	0.29
Resistance to impact	9	6	3	1	6	0.46
Flexural strength	9	1/3	1/6	1/6	1	0.09
Sum	37.00	13.44	4.44	1.78	16.11	1.00

Developed by the authors

Table 7 Importance scale for engineering parts

	Multicolored part	Accuracy	Surface quality	Resistance to impact	Flexural strength	Criterion weight
Multicolored part	1	1/9	1/9	1/9	1/9	0.03
Accuracy	9	1	1	3	3	0.33
Surface quality	9	1	1	3	3	0.33
Resistance to impact	9	1/3	1/3	1	3	0.18
Flexural strength	9	1/3	1/3	1/3	1	0.13
Sum	37.00	2.78	2.78	7.44	10.11	1.00

Developed by the authors

- *Constraining factors*

– Dimensions: 393.3×326.0×79.0 mm
– Material: polymer, wax or ceramic

Priority criteria defined were the surface quality and the capacity to make the model applying different colors, such as capacity to create the necessary details (e.g., windows) dependent on support material. Therefore, the expectations on the importance scale used for comparing machines to make this architectural model are shown in Table 8.

Applying the constrain factors and the criterion scale of importance upon comparing the 45 machines surveyed indicates the use of CJP ProJet® 860Pro on this specific application.

6 Conclusions

This paper introduces the development of a method for selecting an AM process from parts' selection criteria and the ranking of the most suitable machines from those surveyed, for three specific applications.

The selection rationale in the method presented has been drawn from AHP, proposing the choice of an option (in the case of AM machine) from the comparison against defined criteria. The criteria are defined in two kinds: technologies available in the market, which determine constraining factors in machine selection, and the parts' selection criteria, which are used to rank the most suitable machine for production. The constraining factors adopted by the method so developed are the part's size and material, which should be compared with the maximum production span and the material for the existing technologies, respectively. The method queries the database comprised 45 machines to allow selecting the most suitable machine for each application, based on part's requirements.

From the method developed, the most suitable machines were identified for making parts intended for three specific application scenarios: turbine blade, bearing holder prototype of a pipettor machine, and architectural model.

It should be noted that the material as a constraining factor plays an overwhelming role in the selection of the AM technology, since the technologies as a whole are related to specific materials.

One limitation of the proposed method is still not being able to circumvent the part size constraining factor by making more than one part for later assembly to compose the final part—whenever this is acceptable for the part. Such improvement should be considered in future works. For the future, it is also suggested that the development of a decision-making support system be based on the rationale and on the machine database developed herein.

Table 8 Importance scale for house model

	Multicolored part	Accuracy	Surface quality	Resistance to impact	Flexural strength	Criterion weight
Multicolored part	1	3	6	6	6	0.46
Accuracy	1/3	1	3	6	9	0.26
Surface quality	1/5	1/3	1	6	9	0.18
Resistance to impact	1/5	1/6	1/6	1	3	0.06
Flexural strength	1/5	1/9	1/9	1/3	1	0.04
Sum	1.93	4.61	10.28	19.33	28.00	1.00

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