MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Selection of Subtractive Manufacturing Technology Versus Additive Manufacturing Technology for Rapid Prototyping of a Polymeric Product

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Abstract: *The Additive Manufacturing (AM) industry has expanded steadily, occupying the market very quickly. New types of 3D printers have appeared and new types of polymeric and composite materials have been developed for these printers. Thus it passed very quickly from the stage in which the parts that were made by rapid prototyping (RP) only to be exposed (demonstration parts) to stage AM the parts are fully functional. Of course, the future of AM is still on the horizon, it is barely visible. The other technologies for forming the geometry of the part, ie subtractive manufacturing technology and formative manufacturing technology are still the basis of industrial production. Each technology has its own advantages and disadvantages and is chosen on a case-by-case basis, depending on the objectives pursued. In this paper, a study is made on the rapid prototyping of a single pump rotor part. The material of the piece is of polymer type, ABS. The piece was made in two variants: by additive manufacturing technology (PolyJet) and by subtractive manufacturing technology (milling). After processing, several parameters were followed, such as the functionality of the part, the surface quality, the mechanical tensile strength, the dimensional accuracy, and last but not least the manufacturing cost and the duration of the manufacturing cycle. The data thus obtained were processed with an artificial intelligence program for decision making.*

Keywords*: plastic part, rapid prototyping, 3D printing, additive manufacturing, artificial intellicence*

1. Introduction

In today's industry, economic issues have become the main problem that business managers have to solve. If there is a question of using Additive Manufacturing (AM) to make any part, two aspects must be considered:

- the strategic aspect;
- the operative aspect of the manufacture of the part.

When the company does not have any technology, and obtains the part through the outsourcing method, these aspects become less relevant, although in this case too the project manager has to make a decision. But this will not be analyzed in this paper. We will only analyze the situation in which the company has several manufacturing technologies, and the project manager must decide which technology to use to make a piece of polymeric material:

- subtractive manufacturing technology;
- formative manufacturing technology;
- additive manufacturing technology.

To make a plastic product, in this paper we will analyze only two types of technology, namely:

- subtractive manufacturing technology, in particular the technology of execution of the part by mechanical milling;

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- additive manufacturing technology, in particular the technology of execution of the part by rapid prototyping – PolyJet.

When choosing AM technology, we can consider that we are in the case of developing a new product. In this situation, there are four more important criteria for the decision to adopt AM technology: prototyping time, prototyping cost, process flexibility and product quality (Figure 1).

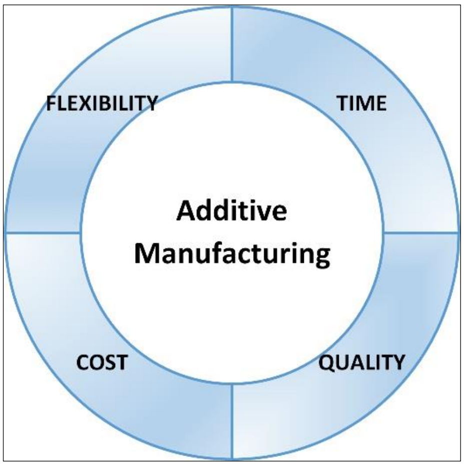

Figure 1. The four criteria taken into account when evaluating AM technology

The use of rapid prototyping versus another traditional manufacturing technology raises various issues, but the main issue remains the economic one. The synthetic structure of the economic aspects that appear in the case of AM technology is presented in Figure 2, according to research [1]. Note that this research uses research results according to Siegwart and Singer's model modified by Steger for additive manufacturing [2]. Depending on the rapid prototyping process used, the scheme shown in Figure 2 may vary. The Figure 2 it should only be considered as a general scheme, in principle.

A fundamental criterion, which many researchers point out, is that through most rapid prototyping processes, parts with a high degree of complexity can be made. This aspect is not to be neglected, but in the industry it does not have a great relevance because the parts must not only be prototyped, but also executed in mass production through a classic technology. Therefore, it is rare the case to design a part with a very complex geometry. Usually, the geometry and configuration of the part (or set of components) are designed according to the requirements of classical technologies, which allow the subsequent realization of the product in large or mass series.

On the other hand, among the strategic success factors (Figure 2), the shortening of the duration of the product to the market and the flexibility of the process – which does not require special tools and mechanical fixtures, is an undeniable advantage.

In addition to the elements presented in Figure 2, there is another element not included in this figure, namely the decision of the project manager: make or buy? This is not the subject of this paper because it is only a management issue, not a technological one. Finally, we want to emphasize that AM technology is superior (or not) to classical technologies and under what conditions – this is the purpose of this paper.

Obviously from a whole range of rapid prototyping technologies and a large number of classic technologies, you can choose the optimal process for a given application, a certain part for example. In our laboratory we did not have all these possibilities available, to make a systematic, comparative, head-to-head study for each technology, rapid prototyping versus classical technology. We believe that such a study is impossible for any institute or research center, no matter how many funding resources it has. We chose for study our equipment, available in the laboratory. In the future we want to complete the research activity with other pairs of equipment, to which we hope to have access.

It should also be considered that in recent times, rapid prototyping technologies have evolved a lot, especially in the last decade. Also, the materials from which the parts are made by rapid prototyping are increasingly diversified. However, currently the market for 3D printers is mainly related to plastic materials. Thus, about 80% of 3D printer sales are for plastics.

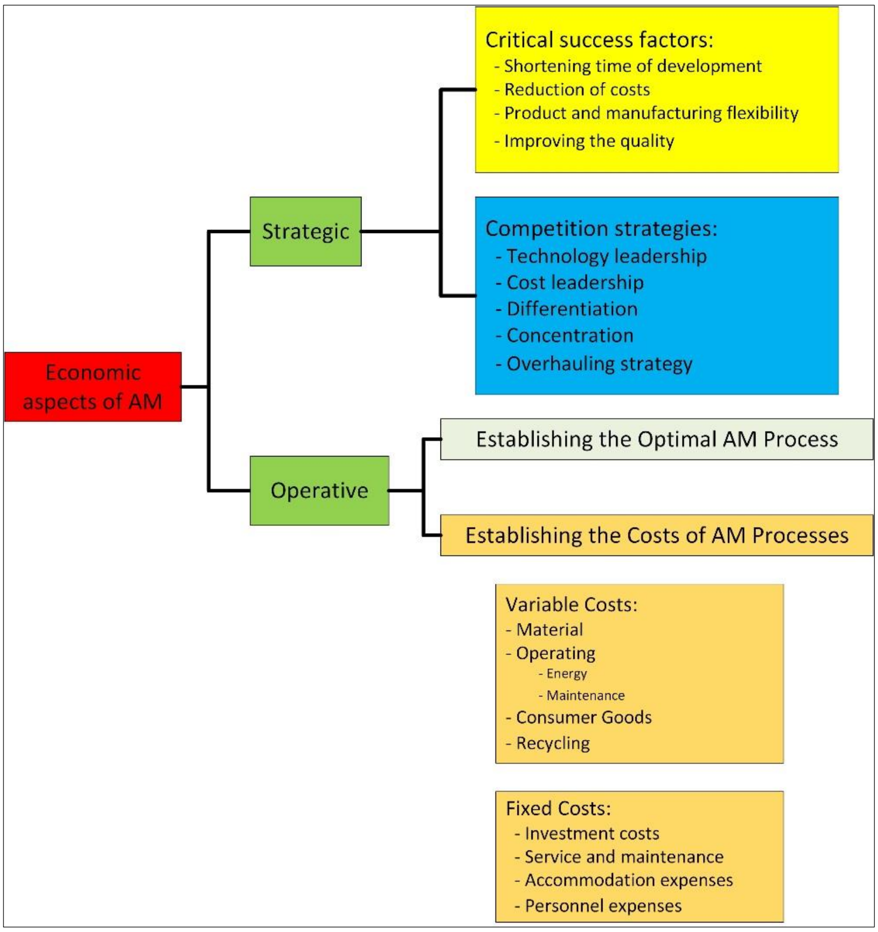

Figure 2. The synthetic structure of the economic aspects that appear in the case of AM technology

Although the scheme in Figure 2 is intended to be a general one, we will consider it in this paper as a scheme that addresses AM technologies for plastics.

2. Materials and methods

2.1. Laboratory experiments

For the laboratory experiments we used the following equipment, available in our laboratory, and on which we could make as many tests:

- Doosan® DNM 650 milling machining center with 4 axes driven simultaneously, and Fanuc® OiD-M CNC equipment;
- Stratasys Objet24™ 3D printer.

The part for performing the test is shown in Figure 3. As can be seen, it is a part with relatively complex geometry – a turbine rotor. The main overall dimensions of this part are shown in Figure 4. The customer appreciated that for tests the part can be made of POM (-H) material (chemically known as Polyoxymethylene [3]) made by milling technology and VeroWhitePlus™ [4] for AM tehchnology.

Figure 3. The part for performing the test (a turbine rotor)

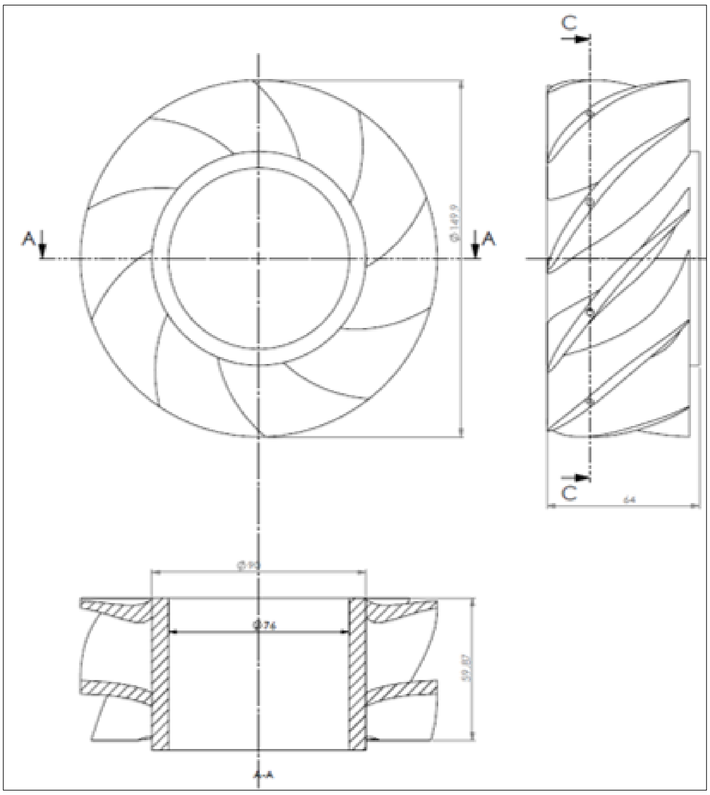

Figure 4. The main overall dimensions of the turbine rotor (material POM-H)

After making the plastic prototype and testing it, the final piece will be made of metallic material (naval bronze). It is important to make the first parts from a material that is easy to process and relatively cheap, but which has operating parameters close to the characteristics of the material from which the final part will be made. This is all the more important as the aim is to change the geometry of the plastic part several times until an optimal geometry is reached.

2.2. The milling operations

The Autodesk PowerMill® Ultimate 2019 CAM system was used to perform the milling operations. Previously, the part was subjected to the roughing turning operation on the Doosan Lynx 220 CNC lathe, Figure 5. The milling operation for the Turbine Rotor was done on Doosan DNM 650, 4 axis, as presented in Figure 6. The presentation of the CAM system is shown in Figure 7. A sequence during the milling process is shown in Figure 8. The entire film of the machining can be watched at YouTube^RO at the address: *https://www.youtube.com/watch?v=LfHpHyAbzcA*.

At the end, the obtained piece looks like in Figure 9. It should be noted that milling machining strategies (in Delcam PowerMill) were required on a 4-axis CNC machine, due to the geometric complexity of the part. In general, the cutting of plastics does not raise particular problems, as they occur in the processing of metallic materials or their alloys. However, cutting plastics also becomes difficult when cutting tools are unsuitable – i.e. worn, or when the geometric shape of the part raises problems, especially in the case of thin or thin-walled parts. Another problem when cutting plastics is the quality of the surface obtained after cutting. For the material from which the piece was made, POM-H, there were no special difficulties.

Figure 5. Doosan Lynx 220L used for the Turbine Rotor prototyping

Figure 6. Doosan DNM 650 used for the Turbine Rotor prototyping

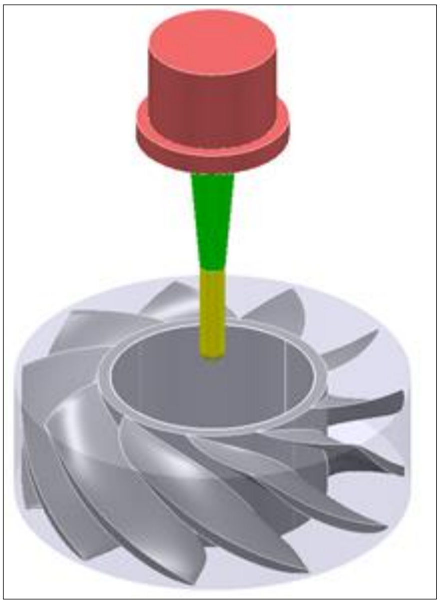

Figure 7. CAM milling system. (Autodesk PowerMill® Ultimate 2019)

Figure 8. The CNC machining on Doosan DNM 650, 4 axis

The following cutting parameters were used for the milling operation of the POM plastic workpiece: - Spindle speed = 20.000 rpm; - Feed = 6.000 mm/min; - Surface speed = 628 m/min; - Feed / tooth = 0.1 mm/th (a sequence of the milling process is presented in Figure 8). The cutting tool was ball nosed, Diameter = 10 mm, number of flutes = 3 (supplier Secotools®).

To make the piece, a single roughing-finishing operation was performed. No two separate operations were chosen (one for roughing and one for finishing) because the customer was not very interested in the quality of the surface, but especially in the functional geometry of the part. As a result, an overall surface roughness of Ra = 3.2 micrometers was obtained, although on some small surfaces the roughness was higher (Ra = 6.3 micrometers).

If an additional finishing operation had been carried out, a general roughness of the part of Ra = 1.6 micrometers could probably have been reached. But, the customer was interested in the short prototyping time, so the piece was accepted with a roughness of Ra = 3.2 micrometers. The quality of the plastic material, however, would have allowed higher performance.

Figure 9. Finished part, POM-H material, obtained by the mechanical milling process on CNC machine tools

2.3. The AM operations (rapid prototyping)

The process of rapid prototyping (AM) is much simpler than that of machining CNC machine tools (turning plus milling). In fact, 3D printers can also be considered a CNC equipment. In this paper we used a printer with 3 axes CNC.

The STL file from a CAD system (SolidWorks® 2020) was prepared for the AM operation. The discretized part looks like in Figure 10. The Objet Studio™ application, characteristic of the Objet24 3D printer, was used for the AM preparation operation. We used the 3D printer from Stratasys Corp., presented in Figure 11. The preparation of the part (ie the location on the tray) looks like in Figure 12. The VeroWhitePlus™ material consumption was 628g, the support material consumption was 681g, and the processing time was 18 h and 23 min.

Figure 10. Preparing the STL file

Figure 11. Objet24® 3D printer, from Stratasys

As you can see, the process of rapid prototyping with PolyJet technology is a long one, especially for complex parts and relatively high heights.

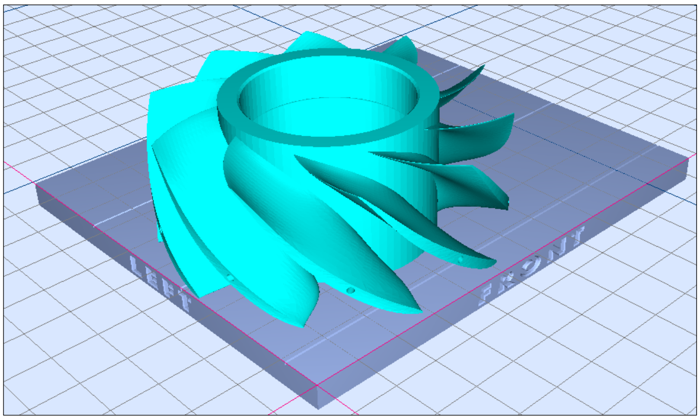

Figure 12. Objet Studio™ application for the AM operation (on Objet24 printer)

The discretization parameters for the STL file are as follows: – Deviation = 0.103 mm; – Angle = 6.33 degree; – Triangles = 6.522 (as it can see in Figure 10). Maximum build size volume of a printed part for Objet24 equipment is: 234 x 192 x 148.6 mm. Build resolution: X-axis: 600 dpi; Y-axis: 600 dpi; Z-axis: 900 dpi. Layer thickness: horizontal build layers down to 28-microns [4].

2.4. The materials, cost, time cycle and quality of plastic parts obtained through the two technologies

Table 1 shows the material characteristics (material data sheet) for the polymeric material used for rapid prototyping (rigid opaque material RDG835), according to the manufacturer.

Table 1. VeroWhitePlus™ RGD835 (primary material)
VeroBlackPlus™ RGD875 (secondary material)

No	Property	Value
1	Tensile strength	50-65 MPa
2	Elongation at break	10-25 %
3	Modulus of elasticity	2000-3000 MPa
4	Flexural strength	75-110 MPa
5	Flexural modulus	2200-3200 MPa
6	HDT, °C @ 0.45MPa	45-50 °C
7	Izod notched impact	20-30 J/m

The cost of the part and the duration of the manufacturing cycle are two very subjective components, which belong to the concrete economic environment and to which the parts are made. On the other hand, the measurement of the quality of the parts obtained by the two different manufacturing processes is a very objective thing, the parts being able to be compared with each other, at any time. Because of this, we separate the analysis of the two situations: the cost and duration of processing aside, and the quality of the parts in another comparison.

In order to keep a somewhat unitary analysis method, we used for the cost analysis of the processed parts the same cost analysis method, integrated in the SolidWorks application, SolidWorks Costing^{TM}. This technique, that of using a unitary method of determining costs, was used to verify the costs obtained experimentally – ie in our laboratory, with the costs recommended by the literature. We emphasize the fact that we determined the costs of the parts and the duration of the manufacturing cycle by both methods: both the experimental one (in the laboratory) and analytically (SolidWorks Costing^{TM}). Both methods led to the same result.

The results are presented in the following tables. The data are presented in a comparative way (subtractive technology and additive technology). Thus, Table 2 presents cost and time per part depending on the manufacturing method, Table 3 presents costs breakdown, Table 4 presents manufacturing cost breakdown for machining operations, and Table 5 presents manufacturing cost breakdown for 3D printing operation.

Table 2. Cost and time per part depending on the manufacturing method

		Machining	**3D Printing**
1	Material:	POM-H	Vero RGD835
2	Stock weight:	2.27 kg	2.22 kg
3	Material cost/weight:	22.05 USD/kg	100 USD/kg
4	Shop Rate:	40 USD	20 USD
5	Total number of parts:	1	1
6	Lot size:	1	1
7	Estimated cost per part:	270 USD	533.64 USD
8	Estimated time per part:	05:29:59	20:35:19

Table 3. Cost Breakdown

	Machining	**3D Printing**
Material:	50.01 USD (19%)	121.86 USD (23%)
Manufacturing:	219.99 USD (81%)	411.78 USD (77%)

Table 4. Manufacturing Cost Breakdown – Machining

Machining		
Name	**Time (hh:mm:ss)**	**Cost**
Setup Operation 1 (Hole)	01:05:00	43.33 USD
Setup Operation 2 (Profile)	01:05:00	43.33 USD
Machining Operation 1 (Hole)	00:16:07	10.75 USD
Machining Operation 2 (Profile)	03:03:51	122.57 USD

Table 5. Manufacturing Cost Breakdown – 3D Printing

3D Printing		
Name	**Time (hh:mm:ss)**	**Cost**
Setup Operation	00:20:00	6.67 USD
Additive Operation	20:15:19	405.11 USD

These synthetic tables did not contain some elements that are difficult to analyze. For example, the duration and value of the CAM technology design were not included. On the other hand, a piece whose geometric configuration could be achieved through both technologies (AM and SM) was intentionally chosen.

3. Results and discussions

The selection of rapid prototyping technology for plastic parts can be a difficult task, influenced by many factors that need to be considered. The decision to choose the optimal technology for the manufacture of a plastic part rests with the engineer (project manager). This decision is a difficult one to take, given the multitude of possibilities available to current industry engineers.

To facilitate a correct decision, in a relatively short time and with a minimum of effort from the project manager we have developed a model based on the analytic hierarchy process (AHP). AHP was developed at the Wharton School of Business by Thomas Saaty [5]. This process allows decision makers to model a complex problem in a hierarchical structure that presents the relationships between goal, objective (criteria), sub-objective and alternatives. The system allows the introduction into the mathematical model of certain uncertainties and factors that influence the decision process. Taking into account those presented in the previous paragraphs, for the selection of the optimal technology for the manufacture of the plastic part we used the software application Expert Choice®, which is based on AHP analysis [6]. The model for analysis is shown in Figure 13.

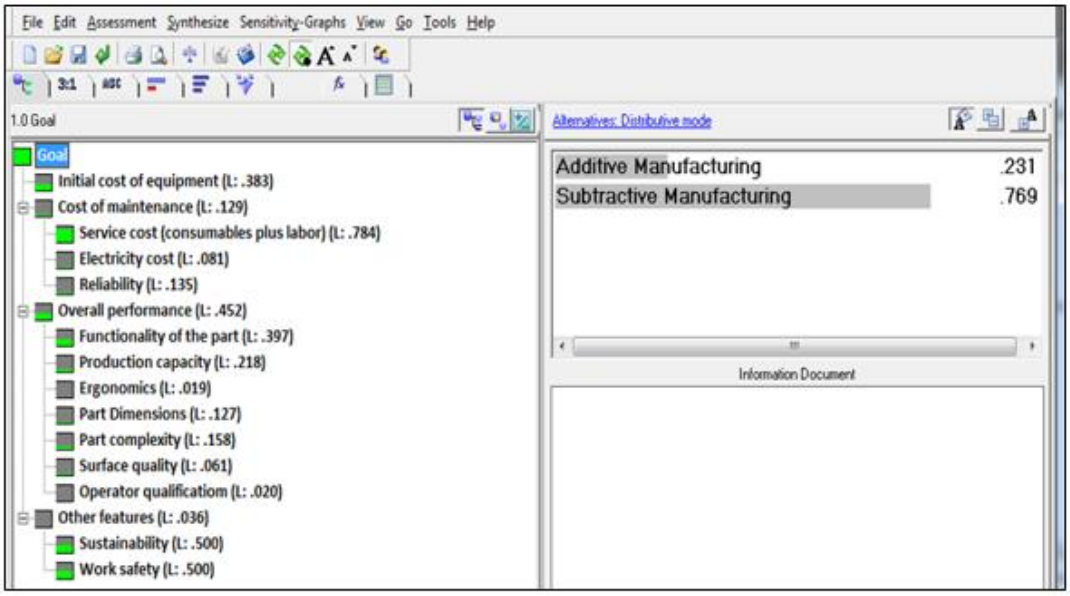

Figure 13. AHP model for the selection of the optimal technological variant

Figure 14 shows the sensitivity analysis for the nodes shown in Figure 13. The nodes are: initial cost of the equipment, the cost of maintenance, overall performance, and other features (sustainability, work safety) [7].

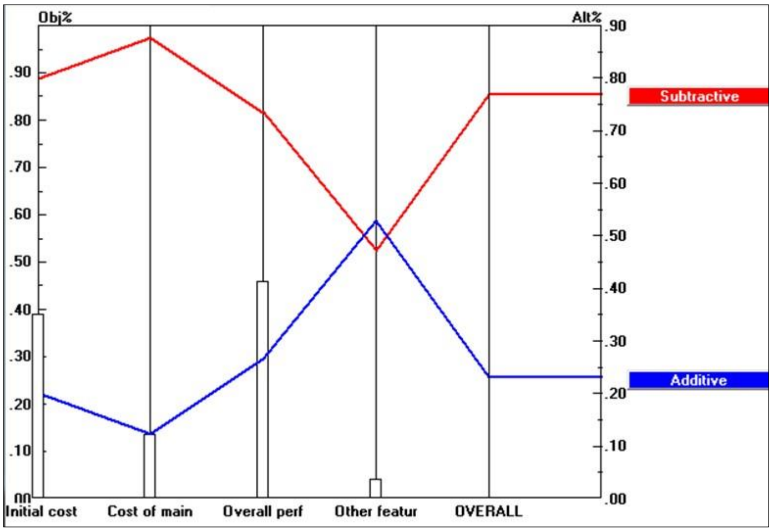

Figure 14. AHP sensitivity analysis with respect to the goal

As can be seen from the sensitivity analysis, Figure 14, for the case of the part taken as an example, the subtractive technology has many more advantages than the additive technology. The software application and the mathematical model developed for analysis and decision can be considered totally reliable. Figure 15 shows that the overall inconsistency in the model was not greater than 0.12.

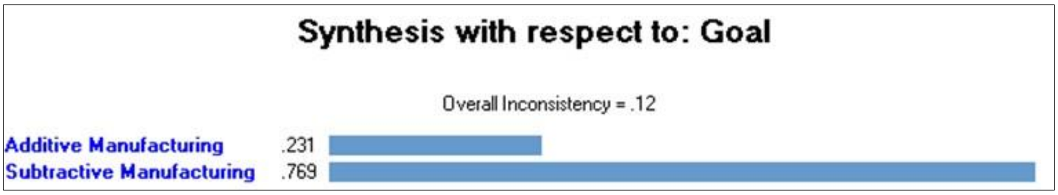

Figure 15. Synthesis of the analysis

For the analyzed case (a specific case) the subtractive technology was superior both in terms of the manufacturing of the part (time and cost) and in terms of the quality of the part obtained.

4. Conclusions

In the present scientific paper, the case of the manufacture of a plastic part was analyzed, through two different technologies. The first technology is classic, traditional, subtractive technology, using common cutting operations (turning and milling). The second technology is a modern one, characteristic of rapid prototyping, additive technology. The study was performed in two directions: an experimental laboratory direction, and an analytical direction by software simulation. The two directions led to the same result: the subtractive technology was superior to all the analyzed parameters.

We can assume that additive technology will become at least equal, if not superior to subtractive technology, with the development of other types of equipment and other materials, much better than those currently existing. We emphasize that this study was conducted for the case of a certain piece of plastic, which was imposed certain conditions of functionality.

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Manuscript received: 04.08.2020