Metal Additive Manufacturing for the Rapid Prototyping of Shaped Parts: A Case Study

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Abstract. Many companies have been evaluating the feasibility and gain of using Additive Manufacturing in their own business. One of the main advantages of this technology is the possibility to produce a shape with complex geometry in a reduced time. Therefore, Additive Manufacturing is often applied in rapid prototyping, which is an essential activity for the evaluation and testing of the design concepts. Even if the advantages and drawbacks of 3D printing are well known in the literature, there is still a lack of tools and methodologies to support a rapid techno-economic analysis for selecting the key manufacturing process between traditional machining tools and 3D printing. A case study on a 3D part of moderate complexity, a gas burner head, fabricated by additive manufacturing, using selective laser melting, has been described in this paper. This test case is focused on the context of rapid prototyping. The 3D part is a gas burner head which has to be printed for testing activity. The analysis focuses on the cost, time, and quality of the built part. An analytical approach has been proposed to calculate the cost of the 3D printing process. The analytical cost is related to the results of the numerical simulations to support the techno-economic analysis. The paper shows a method to compare additive manufacturing and traditional machining processes in rapid prototyping. However, the paper also shows a simulation activity to analyze with more details the 3D printing process in terms of part orientation and deformation of the build.

Keywords: Additive Manufacturing, Metal Printing, Rapid Prototyping, 3D Printing Simulation, Cost Analysis.
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1 INTRODUCTION

Nowadays, 3D printing is more and more used in several fields from the manufacturing industry [21] to medical [8]. This technology could be used to produce spare parts, singular parts, bio-constructs, electronics, and even jewelry [24]. One of the major advantages is the possibility to produce a shape with complex geometry [26]. The applications concern both rapid prototyping [6] and the production of small batches [3]. Many companies have been evaluating the feasibility and gain of this manufacturing process in their own business. Recent technological improvements, such as the increase of the deposition rate, are encouraging the widespread of 3D printing in the manufacturing industry [27].

This technological process, also called Additive Manufacturing (AM), is defined as the process of joining materials to make objects usually layer by layer from a three-dimensional CAD model [15]. This process, which differs from subtractive manufacturing technologies, enhances through computer-aided engineering the advance of digital manufacturing in Industry 4.0 [10]. Recent studies forecast future changes in the global supply chain because of implementing AM technologies in the industry [7]. Additive manufacturing technologies are opening fresh opportunities in terms of production paradigm and manufacturing possibilities [3].

More than one hundred of raw materials are available for 3D printing. These materials are thermoplastics, metal, nylon, acrylic, plaster, ceramic, and also edible materials. Powder Bed Fusion and Directed Energy Deposition are two of the most used AM systems. In the case of the manufacturing of the metallic components, Powder Bed Fusion, also called Selective Laser Melting, is the most used process for melting powdered metallic alloys [20].

The main limits to the widespread of metal Additive Manufacturing are related to four issues: the repeatability of the process, the reproducibility between machines, the quality of the product for a particular use, and the speed of the printing process [27]. All these issues produce an important gap between traditional machining systems and metal additive manufacturing. Firms are discouraged from using 3D printing by uncertainties within the processes and high investment costs [23]. One uncertainty is related to the evaluation of the effective total build time and the relative build accuracy [9]. Therefore, many manufacturing companies implement AM technologies for the rapid prototyping of pre-competitive platforms, used as concepts of demonstrators for commercial releasing [14].

Additive Manufacturing increases the capacity to conceive complex parts if compared with traditional methods [26]. One strength of this manufacturing process is the relationship between the Computer-Aided Design (CAD) tools and the 3D printing. In fact, for the simplification of the manufacturing phases, which mainly regards a 3D printing phase, the building part is directly related to the CAD model, which becomes a necessary input data.

Even if the advantages and drawbacks of AM are well known in the literature, there is still a lack of tools and methodologies to support a rapid techno-economic analysis for selecting the key manufacturing process between traditional machining tools and 3D printing. One limit is surely related to the different design constraints and rules between these two processes. The cost of 3D printing and the estimation of the real process-time are often difficult to be evaluated because related to the printer and part geometry. Finally, without using numerical thermal-structural simulations is not possible to estimate the correct deformation of the part after the 3D printing process. Therefore, the AM process can produce a scrap of built parts with defects that increase the ultimate cost.

This paper aims at proposing an approach for supporting the designer when selecting the manufacturing process for achieving a rapid prototype, suitable in terms of cost, quality, and time. First, the paper describes the state-of-the-art tools and methods for supporting decision making in additive manufacturing. Second, a methodological approach is proposed to support the engineer when evaluating the use of AM for rapid prototyping. The AM process analyzed in this paper is Selective Laser Melting. An analytical approach has been chosen to calculate the cost of the 3D printing process. The analytical cost has been connected with the results of numerical simulations to support the techno-economic evaluation. Third, a test case is proposed to test the rapid prototyping of a gas burner head by analyzing cost and time.

2 RESEARCH BACKGROUND

Prototyping technology plays an important role in the manufacturing industry [30]. Even if virtual prototyping is more and more widespread in the industry, rapid prototyping is still essential for activities such as evaluation and testing of the design concepts. The advantages of using AM in rapid prototyping concerns the reduction of time-to-market by accelerating prototyping, the reduction of the cost involved in product development, the possibilities of increasing the competition and innovation of companies [3]. Different scholars and practitioners have been studying how to reduce the gap between virtual and rapid prototyping using CAD tools and advanced features [30] [31].

The first step of the 3D printing process is the conversion of the 3D CAD model into a facet structure using the STL format which represents the surface with a triangle mesh [17] [30]. The second step concerns the geometry repairing and the model slicing into many layers with a thickness of about 50 μm (between 10 μm and 100 μm). Finally, a G-code file is generated to export data to a 3D printer for building. The virtual prototyping analysis can be introduced into this loop to simulate the thermal-structural behavior related to the build process. The thermal-structural analysis is important because the melting temperature and the cooling conditions affect the deformation of the built part causing a residual stress state [22]. The amount of the generated heat depends on the optical properties of the laser beam and the absorbance of the melt pool and powder particles [1]. In this context, numerical simulations are essential to reduce design iterations and costs related to traditional trial-and-error procedures.

During the last 5-6 years, the metal additive manufacturing has been applied for the production of metal parts in several fields, such as the aerospace [29] and automotive [21], where customization and lightweight are important product features. Several researchers experimented the topological optimization with additive manufacturing to decrease the design efforts of light weighted parts [5].

In 2018, Simons proposed a study to test if additive manufacturing is a feasible solution to produce the basic parts [27]. This study described basic metal parts as parts that can be produced by traditional reductive manufacturing technology. As basic parts, Simons studied components such as aluminum electronic casings, steel axles, and valve blocks in stainless steel. After analyzing these test cases, the author outlined that the cost of additive manufacturing can be reduced while the printing deposition rate is increased, and the cost of printing materials is close to the cost of billet materials used in traditional machining tools. Under these conditions, additive manufacturing can replace traditional machining on a significant scale in the industry. However, this study [27] is based on the analytical calculation of the 3D printing time, without using a simulation activity to evaluate printability and its results in terms of time, deformation, and residual stress. The post-processing phases, such as base removal and post-treatments, are not considered.

The convenience of using 3D printing over traditional manufacturing processes is a current topic in the literature [3]. Oyesola et al. studied a concurrent decision tool to support the techno-economic analysis of production based on additive manufacturing [23]. They provide a decision tree analysis to help engineers rapidly understand the techno-economic impacts of manufacturing decisions when using additive processes. The techno-economic analysis is important in this context because it considers the feasibility of a technological process in terms of cost, performance, and efficiency [28]. This contrasts with the economic feasibility which is limited to evaluate the only economic attractiveness of technology comparing the costs and the benefits for a certain stakeholder. The traditional metrics of economic analysis are the Net Present Value, Internal Rate of Return, and Payback Period. These metrics provide tools to understand the real return on an investment after the adoption of unfamiliar processes.

The rest of the paper describes the key idea with the proposed techno-economic workflow to support the designer when evaluating the application of AM for rapid prototyping. After that, a test case is described with results and conclusions.

3 APPROACH

A design methodology is here proposed to support the techno-economic analysis of using Additive Manufacturing for rapid prototyping (
Figure **1**). The input data comprises the 3D CAD model converted into an STL file and the scheme of Geometric Dimensioning and Tolerances (GD&T) to be observed into the final part. The specifications of GD&T are important for providing information about the quality expected in the final part after the manufacturing process. As an assumption, the research study is based on the analysis and simulation of 3D printing by Selective Laser Melting.

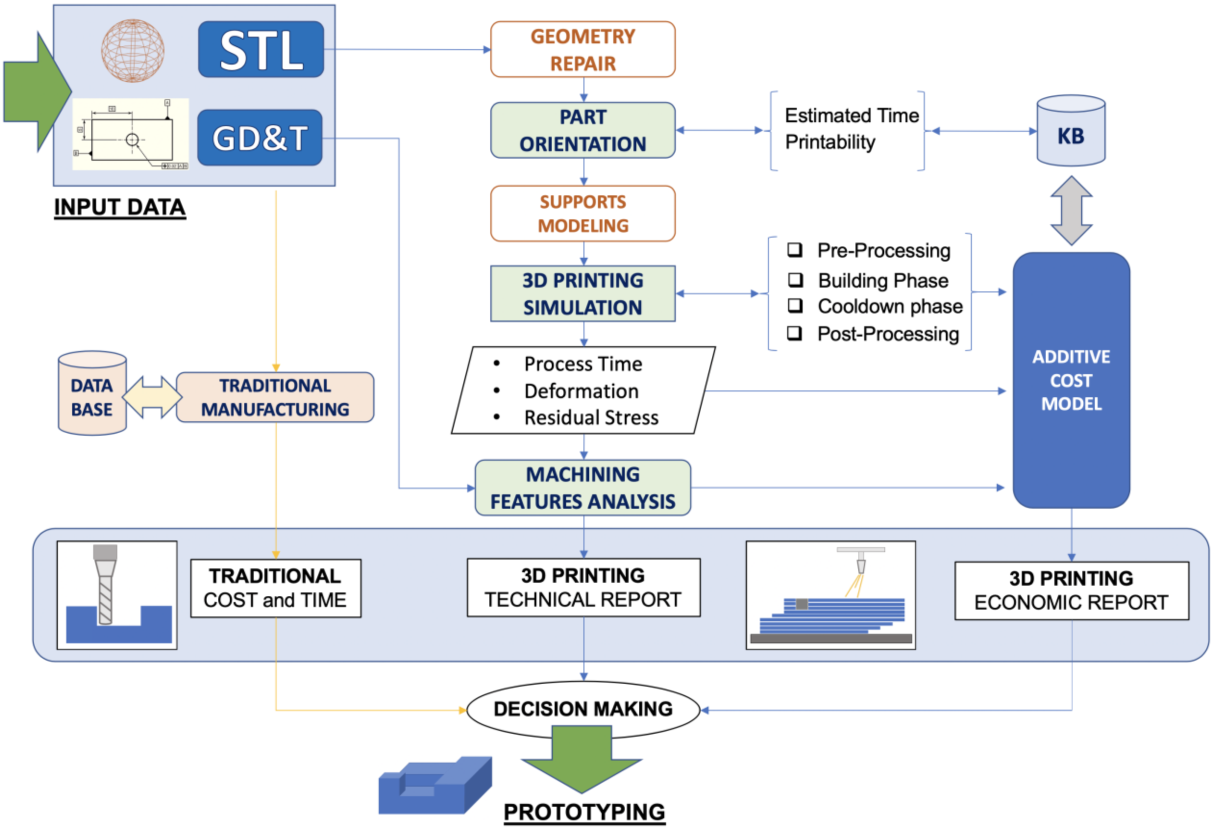


Figure 1: The design platform to evaluate the feasibility of using metal 3D printing instead of traditional manufacturing systems.

The methodological approach integrates the design workflow with numeric simulations and analytical cost analysis. The first step regards the Geometry Repair to avoid errors in simulations and further 3D printing. Afterward, Part Orientation is analyzed to define the optimum solution in terms of building time and printability. This orientation analysis is based on the Knowledge-Base and rules derived from the know-how of practitioners. The Supports Modeling is the phase where the supporting structures are added to the STL model for improving the printability of the build and avoiding structural problems. This issue is for unsupported features with an angle smaller than the minimum self-supporting angle.

The phase called 3D Printing Simulation regards the numerical simulations of the building process. These simulations include 3 phases which are: pre-processing (pre-heating and boundary conditions), building (powder deposition, thermal melting, and cooling), and post-processing (thermal treatments and base removal). These phases are integrated within the Cost Model analysis which uses data from Knowledge-Base and simulation settings for calculating the cost of the 3D printing process. The Cost Model also gains data and information from the results of the numerical simulations (such as the processing time). Information about the necessary machining features is also used by this module. The Machining Features Analysis represents the phase where the simulations result in terms of deformation are analyzed for understanding which machining process is necessary for achieving the required GD&T specifications. The design platform provides the cost report and the simulations result to evaluate whether the 3D printing of a prototype part is a workable solution in terms of technical and economic requirements.

3.1 Cost Model

This section presents the analytic cost model for the economic analysis of the AM process. The analytic cost estimation approach was selected in place of parametric and analogous ones because: (i) it accounts the overall manufacturing process, and (ii) it allows considering a greater number of cost drivers for deeply evaluating the cost items. The analytic cost model here presented, which is largely built on previous cost models already discussed in the literature, permits getting the following cost breakdown [19]: (i) material, (ii) machine, (iii) labor, (iv) equipment, (v) consumables and (vi) energy. Machine and labor cost items were also broke-down according to the typical AM process: (i) pre-processing, (ii) build, and (iii) post-processing.

The material cost (Eq. 1) depends on *Vp* (part volume), *Vs* (supports volume), *Prr* (powder recovery rate), *Pd* (powder density) and *Puc* (powder unitary cost).

$$Material\ cost = (Vs + Vp) \cdot (1 - Prr) \cdot Pd \cdot Puc \tag{1}$$

Part volume is a well-known design parameter. Volume of supports is established using AM software tools such as ANSYS (by Ansys Inc.), MAGICS (by Materialise), and it depends on the part orientation, overhang area and type (solid or shell) and density of supports. Powder recovery rate is a value less than 100 and it mainly depends on the structural and metallography quality to be achieved (the higher the recovery rate the lower the part quality) [2]. Powder unitary cost is defined by the supplier. The machine and labour cost items refer to the overall AM process. Pre-processing activities are:

- *Build preparation*: it consists in preparing the job before running the print (e.g.: part orientation, 3D nesting, supports modelling, slicing). A skilled technician performs this in-office activity. The effort depends by the part complexity (e.g.: complex products may require process simulation before starting the job) and the learnability curve (e.g.: process simulation can be avoided if the technician is familiar with those parts);
- *Powder filling*: the machine operator refills the powder tank with virgin or recycled powder. The times mainly depends on the 3D printer;
- *Build plate loading*: the operator loads a new or a ground plate on the 3D printer. The times mainly depends on the 3D printer;
- *Plate heating*: the 3D printer automatically heats the build plate. The times mainly depends on the 3d printer and the operator is not involved;
- *Gas filling*: the 3D printer automatically fills the build chamber with an inert gas (e.g.: argon, nitrogen). This operation in synchronous and faster than plate heating, hence, it is neglected concerning process cost and time.

The build phase is that moment when the 3D printer selectively melts the powder for creating the part. The cost of this phase depends on the hourly rate of the machine and the build time. Considering that electricity, gas and compressed air consumption belong to energy and consumable cost items, the machine hourly rate accounts for its depreciation, maintenance and production overheads. Since administrative overheads are too much depending on the enterprise configuration, these are not accounted. Depreciation is computed using the cost discounting equation, which considers the 3D printer purchase price, discount rate, lifetime and machine availability (i.e.: working hours per year). The maintenance is commonly managed as an annual service cost provided by the machine vendor. At last, production overhead cost depends on the yearly rent rate and floor area of the facility where the machine is working. A common approach used for computing the hourly rate is proposed in [25].

Two approaches exist for estimating the build time. The first one consists in simulating the build process. For example, ANSYS Workbench®, while simulating the additive manufacturing process, can estimate the build time. The second approach consist in using the average volume rate (commonly provided by the 3D printer and powder vendor). For example, the data sheets of the metals powders provided by EOS® [11] suggest the volume rate (mm^3/s) according to the material and 3D printer used. Since this is an average value, the company disclaims that "*the volume rate is a measure of the building speed during laser exposure. The overall building speed is dependent on the average volume rate, the time required for coating (depends on the number of layers) and other factors, e.g. DMLS settings*". For a first estimation, build time can be assumed as the average of these values. The most important post-processing activities are:

- *Gas removal*: the machine automatically purges the inert gas from the build chamber. This is a quick operation that can be neglected in terms of cost;
- *Powder removal*: the machine operator manually removes the powder from the build chamber to be further recycled. The time mainly depends on the machine (chamber volume);
- *Plate removal*: the machine operator manually removes the build plate from the machine. The time depends on the machine (plate dimensions) and weight built of components;
- *Heat treatment*: a furnace heats the component for removing internal stresses. The total cost for one heating cycle must be split for the components loaded within the furnace muffle;
- *Part cutting from build plate*: a wEDM (wire electro discharge machining) is commonly used for cutting-off the part from the build plate. The time depends on the area of supports. The operator is involved during load and unload operations;
- *Supports removal and finishing*: a CNC machine or an operator firstly remove supports and secondly finish the part. The former is enough for both process steps. Time depends on the supports volume and shape;
- *Plate grinding*: a tangential grinding machine polish the build plate, by removing trace of supports, to restore the original roughness and tolerance. Time depends on plate dimensions.

A 3D printer uses two kinds of consumables: (i) inert gas and (ii) compressed air. The inert gas cost is estimated considering the average gas consumption commonly declared by the machine vendor (liters/minute), the build time and the unitary cost of gas. To be noted that gas is supplied by cylinders (3, 5, 7, 10, 14, 27 and 50 liters) at high pressure (around 200 bar), hence the unit of measure of gas consumption should be adequately converted. Compressed air cost depends on the compressed air average consumption and pression, both declared by the machine vendor. The unitary cost depends on the system used for generating compressed air. A rule of thumb suggests a cost between 0.02 and 0.03 €/Nm^3.

The electricity cost can be estimated according to three different approaches, based on: (i) the average power of the machine (i.e.: kW) [12], (ii) the weight energy density (i.e.: Mj/Kg) [18], and (iii) the volumetric energy density (i.e.: j/mm^3) [18]. For getting the overall amount of energy consumed during the printing process, average power, weight energy density and volumetric energy density are respectively multiplied by the build time, part/supports weight and part/supports volumes. At last, consumed energy is multiplied by the unitary cost of energy (i.e.: €/kWh). The energy cost is the average among these three values. Equipment cost is missing from the cost model because no tooling is required.

4 CASE STUDY

The prototype of a gas burner head is here analyzed. This part is made of aluminum (AlSi10Mg). The geometry of the part has not been optimized for AM. The geometry has not been optimized for AM because this part is fabricated using aluminum die casting in the series production. However, 3D printing could be used for rapid prototyping instead of the traditional machining process. The study analyzes if it is convenient that the same geometry is processed by 3D Printing or by traditional machining processes. Therefore, the effective geometry has been analyzed in terms of cost and then virtually printed using numerical simulations to understand the advantages and disadvantages of this technological process in rapid prototyping of a shaped part.

The 3D Printing simulations were performed by the Print module of Ansys Additive®. This numerical tool was used to compare and reach the optimal part orientation and to evaluate the build quality in terms of strain and stress because of thermal effects.

4.1 The Model

The gas burner head is a component of a gas cooker. The burner with its cap comprises a chamber for mixing air and gas: this mixture produces combustion with flame. This combustion takes place out of the burner when the mixture crosses a pattern of many and small teeth-channels.

The analyzed gas burner head, as described in

Figure **2**, is a three-row model with two circular patterns of teeth channels for the mixture outflow. This piece has a max diameter of about 130 mm and a max axial height of about 27 mm. Data in brief related to this prototype of the gas burner head is described in Table 1.

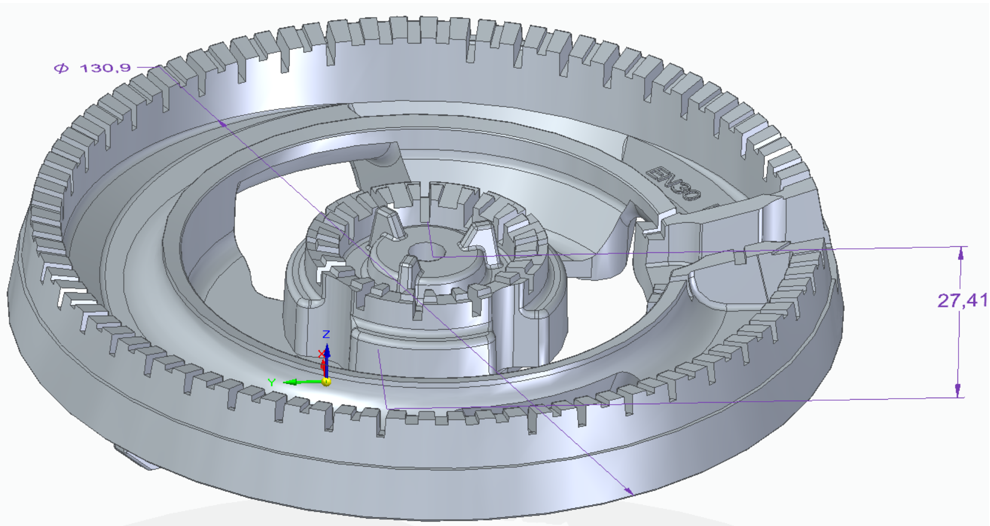


Figure 2: The model of the gas burner head analyzed in this paper.

A tolerance of 0.1 mm is required for the geometry of the small channels. The general tolerances applied for this part are related to the standard ISO 2768 – mK. No specific geometric tolerance is required in the technical drawing of this prototypical part. 3D Printing should guarantee this level of tolerances with a laser focus diameter of about 75μm. The 3D Printing process has been here analyzed using a virtual prototyping approach to avoid and evaluate the residual deformation in the built part.

Property	*Data*
Material	AlSi10Mg
Material density	2760 kg/m^3
Part - weight	0.219 kg
Part – max diameter	130 mm
Part – max height	27 mm
Minimum dimensional tolerance	± 0.1 mm

Table 1: Details in brief of the prototype here analyzed.

4.2 Part Orientation for 3D Printing

3D printing requires a previous analysis of part orientation and supports for improving the quality of the build part. Non-optimized part orientation and an undersized support volume can produce a rupture while printing or an excessive piece deformation. Part orientation impacts on three aspects: the printing time, the process cost, and the process quality in terms of deformation. The height of the build and the number of supports increase the processing time for printing and the cost related to the required metal powders. Therefore, the proposed method considers a part orientation analysis to evaluate the time and result of the build process.

The part orientation has been here analyzed because the early simulation in horizontal condition showed an important deformation with a rupture. In fact, in the analyzed geometry, there is a significant section variation in the bottom part, where there is a thinned section which links two crowns. The built part is a prototype of a gas burner head. The global deformation is important because this part should be tested in laboratory to validate the energy performance. Therefore, the "channels" should have a reduced deformation to not invalidate the burner proof. The deformation is also important in the burner's top where there is the coupling with the cap. Printing the part with an orientation angle could be a solution to reduce the variation of sections' areas per each layer.

A table of virtual experiments was defined to evaluate different part orientation in the range between 0° and 70° with a step of 5° (

Table **2**). Ansys Additive® was used as a tool to simulate each configuration with the automatic generation of supports and using the numerical scheme of *assumed strain* for solving the strain and stress maps. Each CAD model related to a specific orientation angle was imported in Ansys Additive® using the STL format. Focusing on the results highlighted in

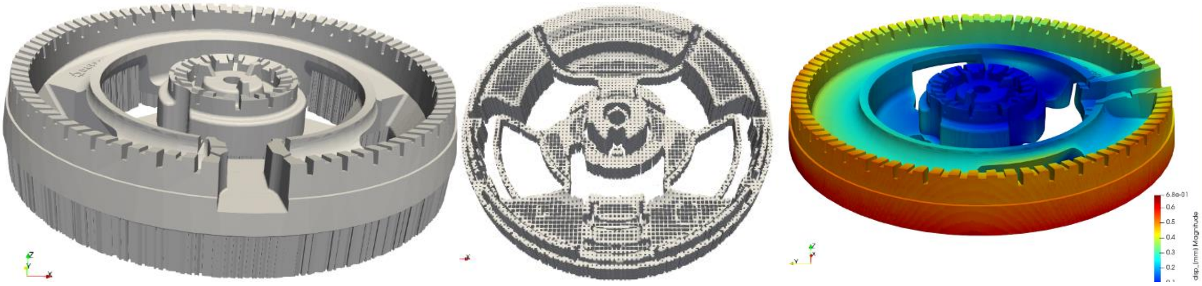
Table **2**, the configuration number 11 was selected as the optimal one in terms of max deformation and printing time. This configuration, with an orientation angle of 50°, minimizes a user-defined function which considers the reduction of cost and deformation.

The user-defined function has been calculated as a sum of two criteria: reduction of the 3D printing cost and the reduction of deformation. A weight factor of 0.6 has been assigned for the cost criterion and 0.4 for the criterion related to the calculated deformation. In this calculation, the 3D printing time is related to the 3D printing time per a generic hourly printing cost. The criterion method used for the computation is "small is better" and the target cost used in the user-defined function was 400 €. Also, in the second criterion, the method "small is better" has been applied and the target deformation value was 0.1 mm. The last column of Table 4 shows the result of the described user-defined function. The value which minimizes this function is the configuration with an orientation angle of 50° which means a max height of 132 mm for the building part and a support weight of 168 g.

ID	Orientation angle	Max height [mm]	Supports weight [g]	Estimated 3D printing time [s]	Max deformation [mm]	User-defined Function
1	0°	47	75	36022	0.68	2.620
2	5°	43	84	39561	0.67	2.633
3	10°	55	93	42457	0.65	2.597
4	15°	66	102	47249	0.64	2.629
5	20°	76	111	51196	0.63	2.648
6	25°	87	120	54274	0.61	2.614
7	30°	97	129	57465	0.60	2.622
8	35°	107	138	59769	0.59	2.617
9	40°	116	147	61191	0.58	2.598
10	45°	124	156	62249	0.57	2.574
11	**50°**	**132**	**168**	**64873**	**0.55**	**2.533**
12	55°	138	180	67580	0.54	2.534
13	60°	145	175	70521	0.53	2.538
14	65°	150	170	76329	0.51	2.545
15	70°	154	165	78656	0.50	2.540

Table 2: Report of the early simulation activity for selecting the part orientation angle.

Figure 3 describes the report related to the first configuration with a horizontal orientation. This figure describes the build part (a), supports (b), and the deformation map evaluated in simulations. The horizontal orientation provides a deformation greater than the 50° angle because of the greater variation in terms of section area between each slice. A slice is the thinner layer of material printed in the additive manufacturing. This variability of mass-area between consecutive slices produces zones with a top level of stress. In particular, the configuration with a horizontal orientation shows an important peak of stress in the area with the smallest thickness.

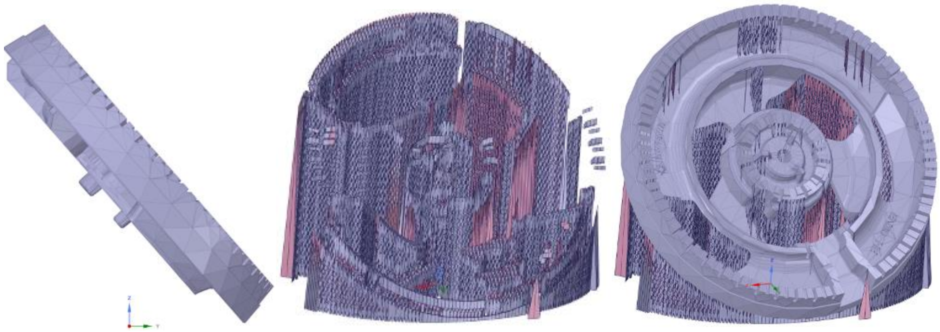


a) b) c)

Figure 3: Build with horizontal orientation (0°) and its supports that have about 20 mm of high from the base plate. In this figure there are: a) The build geometry with supports; b) the scheme of the supports; c) the resultant deformation map after the 3D printing simulation.

Figure 4 reports the configuration with the orientation of 50° between the part and the base plate of the 3D printer. This configuration shows a major volume of supports and an increased high of the build than the horizontal orientation. However, this configuration provides a reduced deformation for a major uniformity in material distribution between each slice. Figure 5 describes the deformation map related to this configuration that achieves a max value of 0.55 mm. The comparison between

0° and 55° degree in terms of stress is described in Figure 6. The first configuration can achieve a rupture when printing for the top level of stress generated after the phases of melting and cooling. The evaluated max stress for the horizontal orientation is about 10 times the value achieved for an orientation angle of 50°. This second configuration shows an important level of stress near to 270 MPa, which is the yield field of the used aluminum alloy.



a) b) c)

Figure 4: Build part and supports with an orientation of 50°. In this figure there are: a) the build geometry; b) the supports; c) the build part with supports.

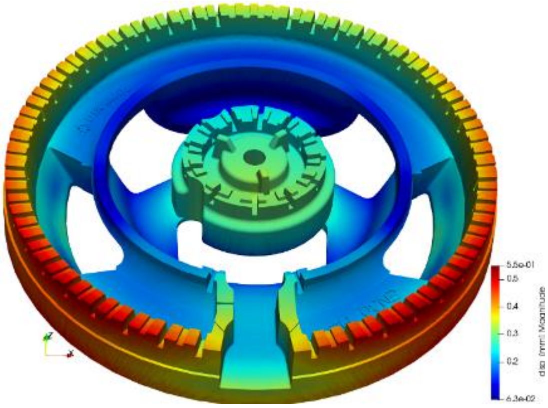
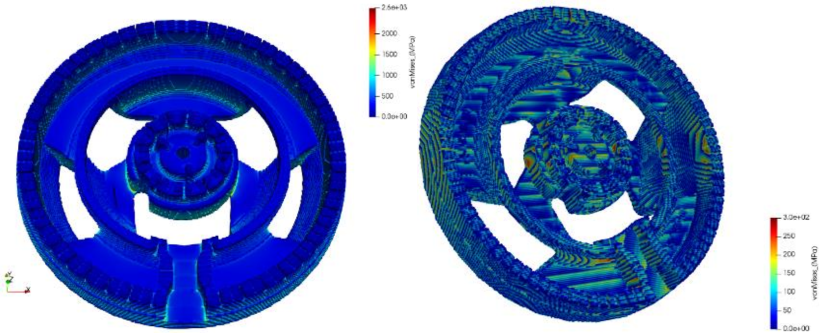


Figure 5: The resultant deformation map after the 3D printing simulation using the numerical scheme of *assumed strain* in Ansys Additive® with a part orientation of 50°.



a) b)

Figure 6: The comparison in terms of stress map between orientation 0° (a) and 55° degree (b).

4.3 3D Simulation

In this section, the 3D Printing process of the build model has been simulated in Ansys Workbench® to reproduce the phases of the Selective Laser Melting process. The build part with its orientation and supports is the model analyzed in the previous design phase (Section 4.2). The material employed is still the aluminum alloy AlSi10Mg. This material has been simulated using the *J2 plasticity* method which is a bilinear method for solving the non-linear behavior.

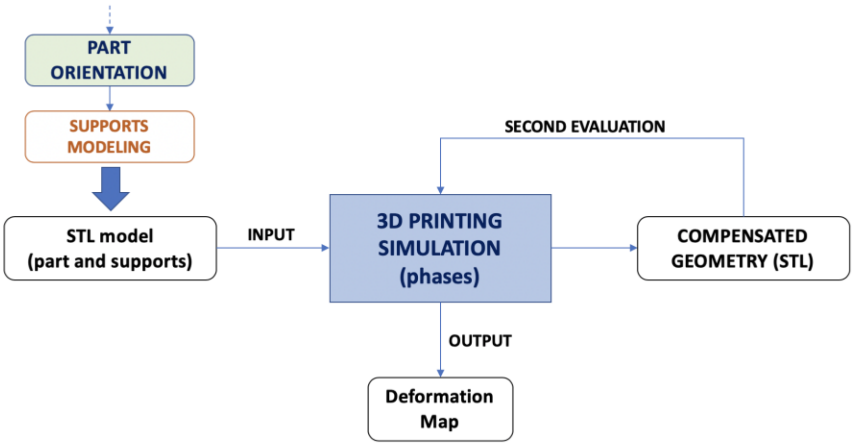


Figure 7: The workflow of the 3D printing simulation.

This second level of virtual prototyping considers all phases of a 3D printing process such as pre-processing, building, cooldown, and post-processing. At this level, the structural simulation used for the stress-strain analysis has been coupled with the thermal simulation to get a more precise result in simulation. The final geometry has been compensated to reduce the final deformation. The compensate model is the way to deform the original geometry to obtain a final build conformed with the required geometry. The compensated model has been calculated in the form of STL and it is related to the correction of the deformation achieved after the building phase. Then, this geometry file has been simulated again to get the last map of stress and deformation. The software tool here used is still an Ansys® solution, but the module involved is related to the Ansys Additive Suite implemented inside Ansys Workbench®. Figure 7 describes the simulation flow related to this second virtual prototyping activity. Table 3 describes the fundamental boundary conditions applied to simulate the phases of the 3D printing process.

Phase	*Boundary conditions*
Pre-processing	Pre-heating temperature: 100°C
Processing	Process type: Powder Bed Fusion; Scan speed: 1400 mm/s Layer thickness: 0.05 mm
Cooldown	Room temperature: 22°C Combinate heat-exchange coefficient: 0.1 W/mK
Post-processing	Thermal treatment: max temperature 400°C First Cutoff: base plate and build part Second Cutoff: build and supports

Table 3: The fundamental boundary conditions related to the simulation of the 3D printing process.

Figure 8 describes the last deformation map evaluated by the simulation of the compensated STL model with supports using the Additive Suite of Ansys Workbench®. In this section, the second level of the analysis shows a 10% reduction of deformation, if compared with the early simulation activity described in Section 4.2. The simulated AM-process time is 790,5 min as reported in
Table 4. These results were achieved after the modeling of the overall simulation process including phases from pre-processing to post-processing and considering the simulation of the compensated analysis.

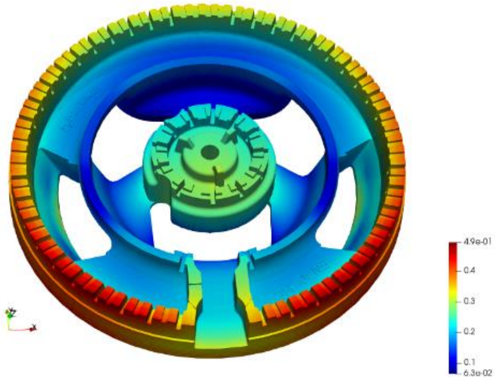


Figure 8: The deformation map (mm) evaluated by the 3D printing simulation. The analyzed model is the STL geometry defined after the compensation analysis.

4.4 Cost Analysis

This section presents the cost analyses of the gas burner realized by employing the selective laser melting and the 5-axis milling machining processes. The manufacturing cost of the first solution, estimated according to the cost model previously described, is summarized in Table 4 and Table 5. Further details are available in Appendix A from Table 7 to Table 15. To be noted that cost results are based on a list of basic information presented in Table 7, Table 8 and Table 9. Part machining is required both for removing supports and finishing the functional surfaces of the gas burner (i.e.: teeth-channels). For respecting the requested tolerances of ±0.1mm, fine machining is required beyond the additive manufacturing. The manufacturing cost of the second solution (5-axis milling) is evaluated by using an analytic cost estimation software tool [16] and the result is reported in Table 6.

The comparison of the production time and cost between the additive and subtractive manufacturing strategies highlights that the latter is the best one. Additive manufacturing is 35% more expensive and 75% longer. The cost estimation for additive manufacturing is optimistic because this is still an innovative technology for that the yield may be much lower than 100% (as considered in this economic analysis). For this case study, additive manufacturing is not convenient also because only one part per build is realized. The requirement was to design and then immediately prototype a gas burner to measure its performances within a specific test lab. In this manner, it is possible to reduce the lead time. According to these results, further adroitness to the additive manufacturing process should be planned as future work.

5 CONCLUSIONS

The research activity is to analyze whether Additive Manufacturing can be applied to replacing traditional rapid prototyping methods in the industry. In particular, the paper aims at providing a method to compare traditional machining technologies and 3D printing focusing on the cost analysis and simulation of the AM process. The AM process analyzed in this paper is the Selective Laser Melting.

	Phase	*Time [min]*	*Source*	*Machine cost [€]*	*Labor engage. [%]*	*Labor cost [€]*
Pre-processing	Build preparation	30.0	Estimation	-	100	25.00
	Powder filling	5.0	Estimation	2.83	100	2.33
	Plate loading	10.0	Estimation	5.67	100	4.67
	Plate heating	40.0	[13]	22.67	0	-
	Gas filling	0.0	Estimation	-	0	-
	Pre-processing	**55.0**	**-**	**31.17**		**32.00**
Build	**Build**	**790.5**	Table 10	**448.04**	**10**	**36.89**
Post-processing	Powder removal	10.0	Estimation	5.67	100	4.67
	Gas removal	0.0	Estimation	-	0	-
	Plate removal	10.0	Estimation	5.67	100	4.67
	Heat treatment	120.0	[4]	5.00	-	-
	Part cutting	15.0	[16]	10.00	30	2.10
	Part machining	100.0	[16]	91.67	5	2.33
	Plate grinding	30.0	[16]	20.00	30	4.20
	Post-processing	**285.0**	**-**	**138.00**	**-**	**17.97**
	Total	**1,130.50**		**617,21**		**86.86**

Table 4 : Additive manufacturing process cost overview.

Cost item	*Cost [€]*	*Share [%]*	*Ref.*
Pre-processing	63.17	7.9	Table 4
Build	484.94	60.3	Table 4
Post-processing	155.97	19.4	Table 4
Material	47.31	5.9	Table 11
Energy	3.88	0.5	Table 12
Gas	41.98	5.2	Table 13
Compressed air	6.17	0.8	Table 14
Total	**803.42**	**100.0**	

Cost item	*Cost [€]*	*Share [%]*
Material	47.31	5.9
Machine	617.21	76.8
Labor	86.86	10.8
Equipment	-	0.0
Consumable	48.14	6.0
Energy	3.88	0.5
Total	**803.42**	**100.0**

Table 5: Additive manufacturing cost overview.

Cost item	*Time [min]*	*Cost [€]*	*Share [%]*
Material	-	5.00	0.8
Machine	600	550.00	92.1
Labor	45	32.00	5.5
Equipment	-	-	0.0
Consumable	-	5.00	0.8
Energy	-	5.00	0.8
Total	**645**	**597.00**	**100.0**

Table 6: 5-axis manufacturing cost review.

The proposed study is not focused on the series production but only on the rapid manufacturing of prototypes to be used in further testing and demonstration tasks. In particular, the paper deals with a case study focused on the rapid prototyping of an aluminum gas burner head. The results achieved in simulations show a maximum deformation of about 0.5 mm after the building process. This state of deformation, tested by simulations, implies that additional machining phases are necessary for achieving the required levels of GD&T. The virtual prototyping process here described for the building simulation considers a first phase for analyzing the part orientation with supports and a second phase for the detailed 3D printing simulation. Results achieved in these simulations show the necessity to simulate all process phase for obtaining a more reliable estimation of the process time and part deformation.

Cost analysis related to additive manufacturing has also evaluated the post-processing activities. The results show an increased manufacturing time of about 75% if the 3D-printing process is used. Considering the described cost assumptions, the AM process is about 35% more expensive than a traditional machining tool process. This process also requires additional machining processes for achieving the desired tolerances. The time for the design of the support structures has not been considered in the cost analysis of the AM-process, and the time of the Computer-Aided Manufacturing (CAM) analysis required in the traditional machining. As future development, the time for the design phases could be evaluated and compared for both technologies.

The paper confirms that Additive Manufacturing can produce parts with complex geometries. However, the metal 3D printing of one part has an important cost to be evaluated. The necessity of additional machining phases contributes to increasing the ultimate cost with AM. Therefore, nowadays, the 3D printing of metal powder can be used for rapid prototyping but with higher costs than traditional technologies. If the cost of additive manufacturing decreases shortly, this technology could be widely applied for rapid prototyping.

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APPENDIX

Cost center	*Value*	*Unit of measure*	*Source*
Labor (machine operator)	28.00	€/h	[16]
Labor (designer)	50.00	€/h	[16]
EDM	40.00	€/h	[16]
5-axes milling machine	55.00	€/h	[16]
Grinder	40.00	€/h	[16]
3D Printer (working)	34.01	€/h	[16]

Table 7: Cost centers database.

Parameter	*Value*	*Unit of measure*	*Source*
Plate width	250	mm	Machine datasheet
Plate length	250	mm	Machine datasheet
Building height	325	mm	Machine datasheet
Maximum power	24	kW	Machine datasheet
Average power	3.2	kW	Machine datasheet
Price	500,000	€	Estimation
Gas consumption	3	liters/minute @1bar	Machine datasheet
Compressed air pressure	6	Bar	Machine datasheet
Compressed air consumption	50	liters/minute	Machine datasheet
Depreciation time	5	years	Estimation
Annual maintenance cost	22,000	€	[25]
Efficiency	57	%	[25]
Building yearly rent rate	130	€/m^2/year	[25]
Building area	60	m^2	Estimation
Discount rate	8	%	Estimation
Depreciation time	5	years	Estimation

Table 8: List of the 3D printer parameters.

Parameter	*Value*	*Unit of measure*	*Source*
Argon unitary cost	17.70	€/Nm^3	Supplier datasheet
Price energy	0.20	€/kWh	Eurostat
Price material	120.00	€/kg	Material datasheet
Compressed air unitary cost	0.025	€/Nm^3	Estimation

Table 9: List of other cost information.

Method 1			*Method 2*		
Parameter	*Value*	*Unit of measure*	*Parameter*	*Value*	*Unit of measure*
			Volume rate	4.8	mm^3/second
Build time	**1085**	**minutes**	**Build time**	**496**	**minutes**

Table 10: Build time estimation. Method 1: ANSYS Workbench®, Method 2: EOS® datasheets [11].

Parameter	*Value*	*Unit of measure*
Part volume	82,074	mm^3
Supports volume	60,878	mm^3
Total volume	142,943	mm^3
Powder recovery rate	94	%
Net powder volume	142,856	mm^3
Powder density	2,760	kg/m^3
Powder weight	0.394	kg
Material	**47.31**	**€**

Table 11: Raw material cost estimation.

Method 1			*Method 2*			*Method 3*		
Parameter	*Value*	*UoM*	*Parameter*	*Value*	*UoM*	*Parameter*	*Value*	*UoM*
			Energy density	437	MJ/Kg	Energy density	37	j/mm^3
Average power	3.2	kW	Energy density	121	kWh/kg	Energy	5.288.897	j
Energy	9.07	kWh	Energy	48	kWh	Energy	1	kWh
Energy cost	**1.81**	**€**	**Energy cost**	**9.55**	**€**	**Energy cost**	**0.29**	**€**

Table 12: Energy cost estimation. Method 1: average machine power [12], Method 2: weight energy density [18], Method 3: volumetric energy density.

Parameter	*Value*	*Unit of measure*
Inert gas cylinder pressure	200	bar
Inert gas cylinder volume	27	liters
Inter gas unitary consumption	0.18	Nm^3/hour
Inert gas consumption cost	3.19	€/hour
Inter gas unitary cost	2.37	Nm^3
Quantity of cylinders	0.44	-
Inert gas cost	**41.98**	**€**

Table 13: Inert gas cost estimation.

Parameter	*Value*	*Unit of measure*
Compressed air unitary consumption	0.30	Nm^3/min
Compressed air consumption	246.69	Nm^3
Compressed air unitary cost	0.45	€/hour
Compressed air cost	**6.17**	**€**

Table 14: Compressed air cost estimation.

Parameter	*Value*	*Unit of measure*
Machine discounted cost	700.000	€
Working time	4993	Hours/year
Depreciation hourly rate	28.04	€/hour
Production overhead hourly rate	1.56	€/hour
Maintenance hourly rate	4.41	€/hour
3d printer hourly rate	**34.01**	**€/hour**

Table 15: 3D printer hourly rate estimation.