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

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Introduction:
Nowadays, 3D printing is more and more used in several fields from the manufacturing industry [12] to medical [5]. This technology could be used to produce spare parts, singular parts, bio-constructs, electronics, and even jewelry [15]. One of the main advantages is the possibility to produce a shape with complex geometry [16]. The applications concern both rapid prototyping [3] and the production of small batches [2]. 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 [17].

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 [9]. This process, which is different from subtractive manufacturing technologies, enhances through computer-aided engineering the advance of digital manufacturing in the context of Industry 4.0 [7]. Recent studies forecast future changes in the global supply chain due to the implementation of AM technologies in the industry [4]. Additive manufacturing technologies are opening new opportunities in terms of production paradigm and manufacturing possibilities [2].

Currently, 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, Selective Laser Melting is the most used process for melting powdered metallic alloys [11].

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 [17]. 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 [14]. One of the uncertainties is related to the evaluation of the effective total build time and the relative build accuracy [6]. Therefore, many manufacturing companies implement AM technologies for the rapid prototyping of pre-competitive platforms, used as concepts demonstrators for possible commercial releasing [8].

Additive Manufacturing increases the capacity to conceive complex parts if compared with traditional methods [16]. One of the strengths of this manufacturing process is the relationship between the Computer-Aided Design (CAD) tools and the 3D printing. In fact, due to 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 main manufacturing process between traditional machining tools and 3D printing. One of the limits is surely related to the different design constraints and rules between these two processes. Moreover, 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 final cost.

This paper aims at proposing an approach for supporting the designer when selecting the manufacturing process for achieving a rapid prototype which is suitable in terms of cost, quality, and time. Firstly, the paper describes the state-of-the-art tools and methods for supporting decision making in additive manufacturing. Secondly, a methodological approach is proposed to support the engineer when evaluating the use of AM for rapid prototyping. In particular, 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. Thirdly, a test case is proposed to evaluate the rapid prototyping of a gas burner head by analyzing cost and time.

Research background

Prototyping technology plays an important role in the manufacturing industry [20]. 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 [2]. Different scholars and practitioners have been studying how to reduce the gap between virtual and rapid prototyping employing CAD tools and advanced features [20] [21].

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 [10] [20]. The second step concerns the geometry repairing and the model slicing into many layers with a thickness of about 50 µm (generally 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 [13]. The amount of the generated heat is dependent on the optical properties of the laser beam as well as 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 final metal parts in several fields, such as the aerospace [19] and automotive [12], where customization and lightweight are important product features. In 2018, Simons proposed a study to evaluate if additive manufacturing is a feasible solution for the production of the basic parts [17]. 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 [17] 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. Moreover, 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 [2]. Oyesola et al. studied a concurrent decision tool to support the techno-economic analysis of production based on additive manufacturing [14]. They provide a decision tree analysis to help engineers rapidly understand the techno-economic impacts of manufacturing decisions when employing 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 [18]. This is in contrast to 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 new processes.

The remainder of the paper describes the main 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.

Main Idea:

A design methodology is here proposed to support the techno-economic analysis of using Additive Manufacturing for rapid prototyping (Fig. 1). The input data consists of 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.

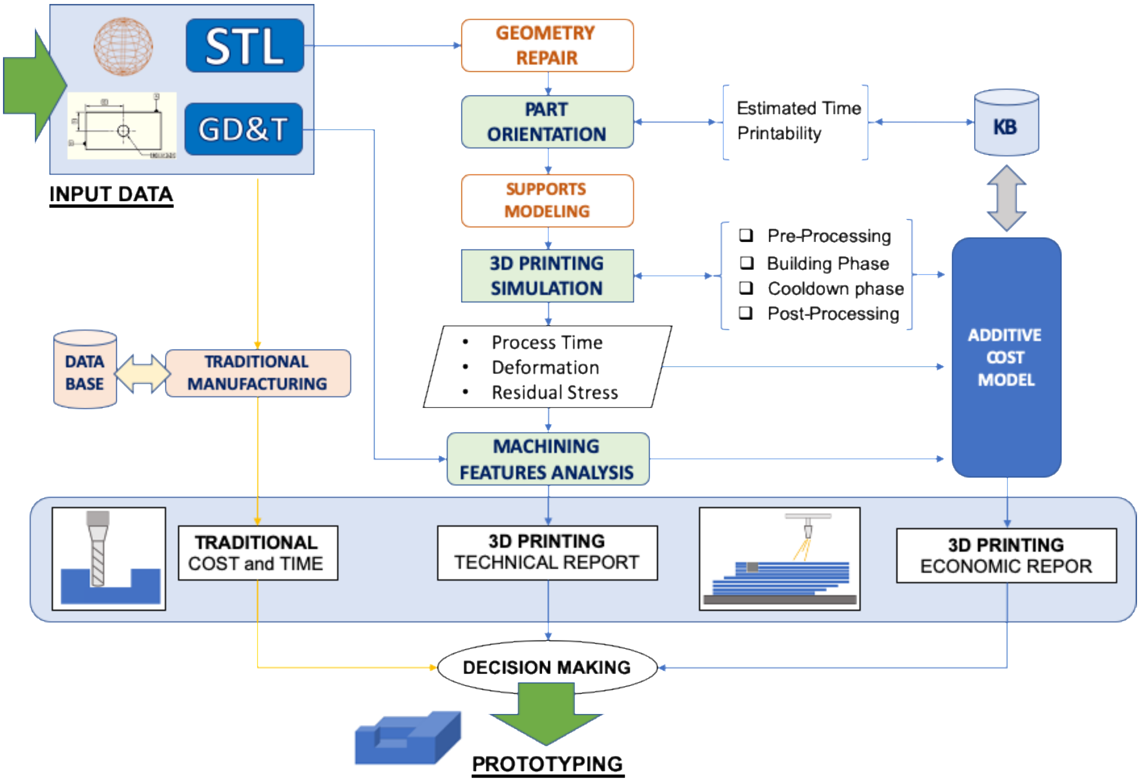

Fig. 1: The design platform to evaluate the feasibility of using metal 3D printing instead of traditional manufacturing systems.

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 due to 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 4 phases which are: *pre-processing* (pre-heating and boundary conditions), *building* (powder deposition, thermal melting, and cooling), *cooldown*, 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 acquires data and information from the results of the numerical simulations (such as the processing time). Moreover, 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 feasible solution in terms of technical and economic requirements.

Case study

The rapid prototyping of a gas burner head has been analyzed in this paper. Following the proposed methodology, the part has been simulated after defining orientation and supports to minimize deformation and residual stress. Firstly, an orientation angle of 45° has been evaluated for the building part. Secondly, the orientation angle has been optimized using Ansys Additive® and Workbench®, which are engineering tools used for the 3D printing simulation. The optimized configuration shows the burner head inclined 50° on the base plate.

Fig. 2 describes the STL model of the geometry with supports (a) and the report of the simulations with the map of total deformation (b) and residual stress (c). The material applied in this test case is AlSi10Mg. In particular, non-linear simulations have been performed using J2 plasticity as stress mode.

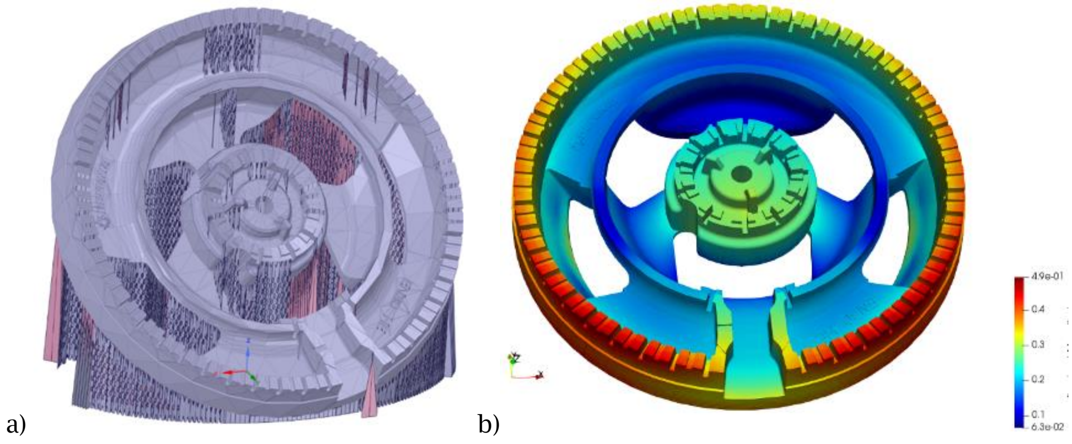

Fig. 2: Additive simulation: a) build and support (STL geometry); b) displacement map (in mm) after the base removal.

The results achieved in simulations show a maximum deformation of about 0.5 mm after the building process. This state of deformation, evaluated by simulations, implies that additional machining phases are necessary for achieving the required levels of GD&T. The virtual prototyping process for the building simulation considers the first phase for analyzing the part orientation with supports and a second phase for the detailed 3D printing simulation.

The cost analysis related to additive manufacturing shows an increased manufacturing time of about 75% if the 3D-printing process is used. Analyzing the proposed test case, the AM process is about 35% more expensive than a traditional machining tool process because this additive process also requires additional machining processes for achieving the desired tolerances.

Conclusions:

The scope of the research activity is to analyze whether Additive Manufacturing can be effectively 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.

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 paper confirms that Additive Manufacturing can be used to produce parts with complex geometries. However, the metal 3D printing of one single part has an important cost to be evaluated in detail. Moreover, the necessity of additional machining phases contributes to increasing the final cost in the case of AM. Therefore, nowadays, the 3D printing of metal powder can be used for rapid prototyping to reduce the development time but with higher costs than traditional technologies. If the cost of additive manufacturing decreases shortly, this technology can be widely applied for rapid prototyping and other application.

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