**FULL RESEARCH ARTICLE**

# A techno-economic approach for decision-making in metal additive manufacturing: metal extrusion versus single and multiple laser powder bed fusion

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## Abstract

This work presents a decision-making methodology that allows the merging of quantitative and qualitative decision variables for selecting the optimal metal Additive Manufacturing (AM) technology. The approach is applied on two competing technologies in the field of metal AM industry, i.e., the metal extrusion AM process (metal FFF) and the Laser Powder Bed Fusion process (LPBF) with single and multiple lasers, which represent the benchmark solution currently on the market. A comprehensive techno-economical comparison is presented where the two processes are analysed in terms of process capabilities (quality, easiness of use, setup time, range of possible materials, etc.) and costs, considering two different production scenarios and different parts' geometries. In the first scenario, the AM system is assumed to be dedicated to one single part production while in this second scenario, the AM system is assumed to be saturated, as devoted to producing a wide mix of part types. For each scenario, two different part types made of 17–4 PH stainless steel are considered as a reference to investigate the effect of shape complexity, part size and production times to select the best technology when metal FFF and LPBF must be considered. The first part type refers to an extrusion die, to represent typical shapes of interest in the tooling industry, while the second part type is an impeller which can be used in many different industrial sectors, ranging from oil and gas to aerospace. In order to include quantitative and qualitative criteria, a decision-making model based on Analytic Hierarchy Process (AHP) is proposed as the enabler tool for decision making. The proposed approach allows to determine the most effective solution depending on the different production configurations and part types and can be used as a guideline and extended to include other technologies in the field of metal AM. On the other side, the critical discussion of the criteria selected, and the results achieved allow to highlight the pros and cons of the competing technologies, thus defining the existing limits to define directions for future research.

**Keywords** Cost model · Decision making · Analytic Hierarchy Process · Metal Additive Manufacturing · Bound Metal Deposition · Metal FFF

## List of symbols

| | |
|---|---|
| $C_{cons}$ | Cost of consumables per part, €/part |
| $C_{en}$ | Cost of energy, €/part |
| $C_{eq}$ | Cost of equipment, €/part |
| $C_{fac}$ | Cost of facility, €/part |
| $C_{mat}$ | Cost of material per part, €/part |
| $C_{lab}$ | Cost of labor, €/part |
| $C_{pp}$ | Cost of post-processing, €/part |
| $C_{sec}$ | Cost of secondary equipment/consumables, €/part |
| $C_{setup}$ | Cost of setup, €/part |
| $c_{cons}$ | Cost of consumable, € |
| $c_{dfl}$ | Cost of debinding fluid per volume, €/l |
| $c_{EDM}$ | Cost of EDM cutting, €/build |
| $c_{en}$ | Cost of energy, €/kWh |
| $c_g$ | Cost of gas per hour, €/h |
| $c_{HT}$ | Cost of heat treatment, €/build |
| $c_m$ | Cost of material, €/kg |
| $c_{mac,eq}$ | Cost of metal AM system, safety equipment, maintenance, and software license, €/y |
| $c_{op}$ | Operator cost, €/h |
| $c_S$ | Cost of facility, €/(y · m$^2$) |
| $c_{start}$ | Cost of starting a new production, €/y |
| $e$ | Power consumption for the considered machine, kW |

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|---|---|
| $f$ | Scrap rate of the process |
| $M$ | Mass of material used for the part production, kg/part |
| $m_w$ | Wasted mass, kg/build |
| $N$ | Production volume, – |
| $N_b$ | Number of builds with a single consumable, – |
| $n_b$ | Number of parts in a build, – |
| $n_{cons}$ | Number of consumables to evaluate, – |
| $n_{op}$ | Number of operators, – |
| $S$ | Space occupied by the production systems, $m^2$ |
| $t_b$ | Time spent by the part to perform the considered operation on the machine, h/build |
| $t_{b,eq}$ | Cycle time of the part, h/part |
| $t_{b,prep}$ | Time to prepare the build, h/build |
| $t_{post}$ | Time to perform the considered operation on the part, h/part |
| $t_{start}$ | Time to start the production, h/y |
| $y$ | Depreciation time, y |
| $u$ | Yearly machine uptime, h/y |
| $w_{dfl}$ | Volume of debinding fluid per build, l/build |

# 1 Introduction

Since the past few years, there has been a rapid increase in industry interest in Additive Manufacturing (AM) technologies and these technologies has been turned into reliable and accurate solutions that can manufacture functional metallic parts at an industrial scale [1].

This growth was supported by the reduction in part lead times and costs, expansion of the supply chain, rapid design-fail-fix cycles, faster time to market, reduced scrap material waste, and higher flexibility in the production of complex shapes and highly customized parts [2]. Powder Bed Fusion technologies, such as Laser Powder Bed Fusion (LPBF) or Electron-Beam Powder Bed Fusion (EBPBF), are the two most consolidated technologies. The high quality at lower costs, and the less complicated machine equipment make the LPBF the preferred solution across different industries and many consolidated fields. The latest generation multi-laser LPBF systems provides an even stronger increase in the deposition rates of metals while maintaining the same level of achievable quality and reliability of single laser systems.

Most recently however, industrial-ready binder-based metal AM technologies such as metal AM Extrusion (also called metal Fused Filament Fabrication—metal FFF or Metal Fused Deposition Modelling—metal FDM) [3] and metal Binder Jetting (BJ) [4] started to tackle the market. These binder-based metal AM processes are claimed to deliver a competitive cost per part and therefore it is interesting to understand their real potential from both technical and economical perspectives.

In particular, since metal FFF is a newcomer with respect to the leading LPBF processes the metal AM market, limited information is available in the scientific literature about the sustainability of this production process, intended both from a technical and economical point of view. On one side, thanks to the smaller equipment investments and other factors coupled with the easiness of use of the system, the metal FFF process is claimed to have the potential to compete with the LPBF in the low production batches and smaller production scenarios. But providing a comparative analysis between these two processes, which is currently missing in literature, requires the adoption of a tool for merging both quantitative and qualitative decision variables.

For these reasons, this work aims to present a techno-economical comparison of the metal FFF process with the more consolidated LPBF process, considering both single- and multi-laser systems (presented in Sect. 2). The study proposes an innovative application of the Analytic Hierarchy Process (AHP) for the development of an integrated decision-making model in AM (presented in Sect. 4).

Considering that the two AM technologies have different characteristics and relatively different market targets, two case studies considering metal components made of stainless steel 17–4 PH with relatively small geometry are considered as reference, to represent the overlapping region of interest for the two AM technologies. The two components are an extrusion die, representative of the tool and machinery industrial sector, and an impeller, useful in many applications of AM in different fields (automotive, aerospace, oil and gas).

Eventually, two productive scenarios (system dedicated to the production of one single part type or shared in producing a wide part mix) and two production volumes are further considered to enrich the critical discussion.

The two selected test cases and productive scenarios were chosen to have a common base for the comparison and to highlight the strengths and weaknesses of the two AM technologies, driving the identification of future research directions and development in this context. Despite that this work focuses on the above-mentioned technologies, the authors propose a methodology that can be easily applied and extended to other metal AM systems/technologies and to a specific industrial sector.

# 2 Technological comparison

In the binder-based AM scenario, metal FFF is declared to be one of the more affordable technologies from both the economical and the user-friendliness viewpoint. Essentially, the metal FFF follows the same steps as the consolidated Metal Injection Moulding (MIM) process but entailing the typical, greater, AM design freedom.
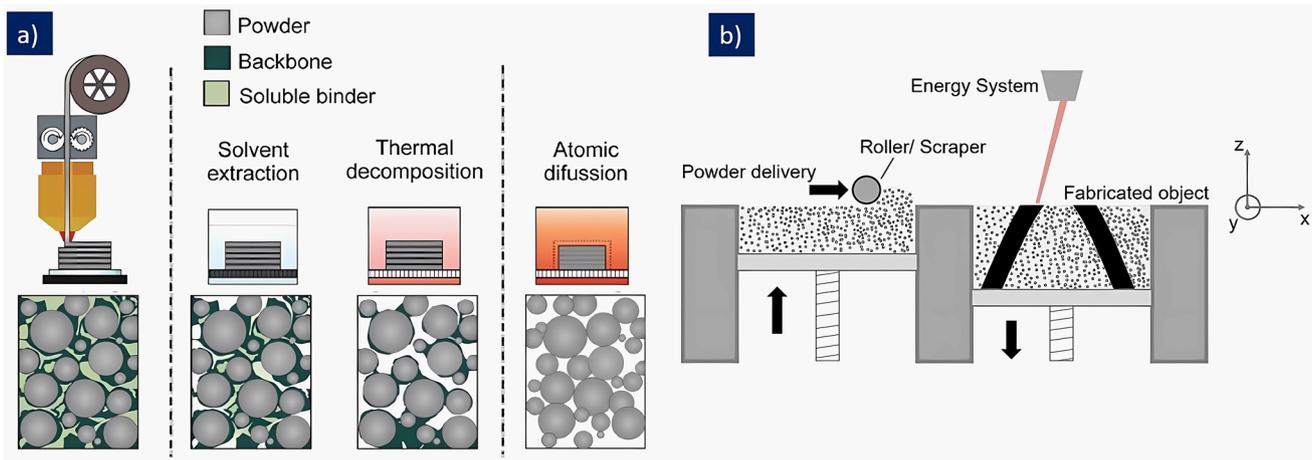
**Fig. 1** **a** Metal FFF processes (taken from [13]) and **b** LPBF processes (taken from [14]) schemes

The process phases can be summarized in (1) printing, (2) debinding, and (3) sintering. The printing phase is basically an FFF, like that of polymers, but a composite mixture of multi-component thermoplastic polymeric binder and build atomized material powder, i.e., feedstock, is used. Both process families are schematized in Fig. 1.

With respect to power-beam AM, metal FFF and all the binder-based metal AM technologies can easily work with materials that suffer thermal stresses (as brittle ones like ceramic) or that show poor absorption capacity of the irradiated beam power (as copper with laser beams) [5]. The production paradigm of these binder-based technologies is based on decoupling the shaping phase (printing) and the densification phase (sintering). As a result, parts do not require post-sintering heat treatments to release thermal stresses or homogenize microstructures since no energy beams are adopted for sintering, but instead slower thermal cycles are conducted in a controlled way during the furnace sintering step. Since this production routine does not involve specific material properties such as electrical conductivity (as required by the EBPBF process) or laser absorption (governing the LPBF process), it opens the possibility to produce both standards steels (such as 17–4 PH, AISI 430, 316L [6]), and titanium alloys [7], but also difficult-to-AM materials (such as tungsten alloys [8], pure copper [9], silicone steel [10] and ceramics [11]).

One important aspect regarding the metal FFF consists of being a powder-less process, in the sense that the powder is contained in the polymeric matrix. This releases the safety issue related to the presence of free powder as entailed by powder-bed AM processes, like LPBF. Safety management is claimed to be easier but also the production of complex internal channels can be improved since no

powder removal step is necessary after the sintering process.

The difference between the two processes in terms of labour work required is another point that is worth discussing. All the AM powder-bed technologies of metals require specific labour knowledge to deal with free powder, that is potentially hazardous for human health, and the associated risk of ignitions in the atmosphere. Powder loadings, machine cleaning, and parts depowdering are among the most critical steps in the LPBF process chain that require the adoption of specific powder management devices (along with personal protection equipment and powder-compliant facilities in the workshops). The presence of free powder brings additional complexity that limits the material change in the LPBF machines. Since the change of building powder, together with the steps required to avoid contamination issues between the materials, usually requires hours of labour work, in most of the cases in the industry the LPBF machines are dedicated to specific materials, thus reducing the production flexibility.

The powder bed in the LPBF introduces another limit to the material usage flexibility. In fact, they require a relatively large amount of powder to start printing a job, therefore preventing the opportunity to print when low powder volumes are available. Finally, in LPBF the support removal operations usually require skilled labour work and specific cutting machines (such as sawing or Electrical Discharge Machining EDM devices).

The majority of the LPBF systems require the use of supports in the printing thus requiring support removal operations which are time-consuming. Despite some LPBF manufacturers have recently developed commercial solutions that reduce, and in some cases remove, the need for support structures in the printings, most of the LPBF still prescribe the use of supports. On the opposite, the

production of metals with metal FFF can be considered more approachable for new players given the absence of free powder. Powder confinement guaranteed by the binder components in the feedstock, and the absence of energy beams make the metal FFF equipment less complicated and less expensive, asking for lower-skill labour work to be operated. This turns into commercial costs for the systems that are sensibly lower than LPBF machines, by also considering the post-processing equipment (such as debinding unit and sintering furnace). In the majority of the turnkey metal FFF systems currently available on the market, support removal is simplified by the adoption on specific interface layers which allows easy and manual support removal, requiring a reduced labour work with respect to LPBF. It is typical to find commercial industrial solutions of the metal FFF that ask for more than 70 k€ for the printers, but there are instances of metal FFF printers for metals that are by far more affordable. In metal FFF the material switching is a quick operation that can be conducted in less than half an hour. However, to reduce the risk of contaminations and reduce the cleaning time, each new material requires a specific and dedicated set of printing devices (such as extruder head and printing devices as cleaning brushes, printing sheets, and other machine parts), thus increasing the investment costs in case of production with multiple materials. Debinding and sintering furnaces can also require specific adjustments during material switching but in most of the cases these adjustments are not relevant or impact costs.

In terms of productivity, metal FFF is far behind LPBF, Table 1. An increase in the metal FFF productivity is possible by adding one or more process stations, printers, debinders, and furnaces, to better manage the system saturation and decrease the cycle time.

However, despite that there are other binder-based technologies, such as the BJ, which are claimed to become in the near future direct competitors of LPBF in terms of volumes, productivity, and costs, currently the shares in the market of these new technologies for metal AM are still not comparable with LPBF [12]. Moreover, in some sectors, such as the biomedical or med-tech sectors, binder-based technologies still suffer from some limitations caused by the presence of binder contaminations in the final sintered material.

The binder-based technology considered in this study is the commercial version of the metal FFF process provided by *Desktop Metal* (*DM*), called Bound Metal Deposition (*BMD*) implemented in the *Studio System +* [15]. In this system, the feedstock material is proprietary, and it is available in form of cartridges containing $\Phi 6$ mm feedstock bars. The bars are extruded through an extrusion head (containing a heated nozzle at a temperature ranging from 160 to 180 °C). An additional extrusion head deposits a ceramic interface that simplifies the release of the parts from the supports on the sintered components. A big difference between the two families of processes, metal FFF and LPBF, consists in the presence of much larger part shrinkage affecting the metal FFF printed parts. An oversizing factor of 16–18% is used to compensate for the shrinkage that affects the parts during the sintering, and in the case of the *BMD* system, each material type is provided with pre-defined shrinkage compensation factors so that users are relieved of choice [16]. However, sintering shrinkage, together with the possible related deformations that can happen to the parts in case this shrinkage is not perfectly homogeneous, are some of the factors that determine the relatively small accuracy of the metal FFF with respect to the LPBF process, Table 1. In metal FFF, under a good high repeatability of input feedstock material and furnace behaviours, the dimensional accuracy of metal FFF can be improved by a fine tuning of oversize factors in all three directions. This approach however is not resolutive when the parts result distorted and with limited geometrical accuracy after the sintering process, as typically happens when there are long overhangs or disharmonious wall thicknesses within the part.

It is well known that also LPBF parts, especially where wall thicknesses vary relevantly within one single part, suffer of distortions. This is mainly due to the fast and local

**Table 1** Comparison between the main characteristics of metal FFF and LPBF in printing metals. Dimensions are reported in millimetres

| | Metal FFF [15] | LPBF |
|---|---|---|
| Build chamber dimensions [mm] | 255×170×170 | 400×400×500 [20] |
| Layer thickness [μm] | 50–220 | 20–60 [20] |
| Min wall thickness [mm] | 0.5 | 0.15 [20] |
| Max fully dense wall thickness [mm] | 10 | – |
| Printing build rate [cm³/h] | 1–10 | 12–75 [20] |
| Surface roughness ($R_a$) [μm] | 13–22 | 5–10 [21, 22] |
| Achievable density [%] | 94–98 | > 99.5 [22] |
| Tolerance [mm] | ± 0.5 (for features with L < 64 mm) ± 0.008 L (for features with L > 64 mm) | ± 0.02–0.05 [23] |

thermal history that influences the part features, making the thermal management one of the most important aspects of process control. Thermal management is also a concern during the sintering process in metal FFF but the slower heating and cooling rates adopted help avoiding the generation of internal stresses on the parts. In any case, the presence of supports on both metal LPBF and metal FFF parts typically exacerbates parts' distortions. This is due to the presence of ceramic interlayers and different thermal behaviour of the supports (and the fact that parts are removed from support after the printing), respectively,, for the two processes. In metal FFF it is found that parts handling requires specific care given the low hardness/resistance of the material in the green and brown states. The primary binder component in the metal FFF parts is removed in the solvent bath and this step determines the suggested maximum wall thickness of around 10 mm for the parts, Table 1. The maximum wall thickness represents a factor to take under control also in LPBF because of its effects on heat management during printability, and residual stress generation [17]. However, in case of LPBF this limit has strong coupling with other parameters like part geometry, printing orientation and material characteristics (such as thermal elongation etc.), and, therefore, its definition becomes more complex and less predictable. For this reason, the maximum thickness limit is considered existing for metal FFF only, since it is mainly coupled with a single aspect, namely the debinding properties.

The secondary binder component in the metal FFF is removed thermally in the furnace during the first phases of the sintering treatments and final part density is achieved after sintering the parts. Typically, steel metal FFF parts can achieve up to 94–98% final porosity, Table 1, and this factor is mainly determined by the air voids generated during the printing process and the gas/vapours that cannot escape the part during densification.

In fact, in the metal extrusion AM printing phase, the round beads of material are extruded line by line in the horizontal plane and then layer by layer in the vertical plane. This strategy generates voids, commonly named toolpath-based microporosity or simply air-voids, which are inherent to the FFF technology and can be exacerbated during the sintering phase. Moreover, as in the MIM process, during the sintering phase micro-porosity is generated (15–25 μm), scattered randomly throughout the printed material. These micro-pores are indicative of the quality of the sintering phase and typically constitute 2–6% of the volume of the solid areas of the final parts obtained via metal FFF (consistent with 94–98% density). To support the achievement of fully 17–4 PH dense parts with correct chemical composition and purity, the sintering in *BMD* is supported using Argon (97%) – Hydrogen (3%) gas mixture, and its duration is governed depending on the size of the components

(it can last for about 40 h, door-to-door opening time). On the opposite, the parts manufactured by LPBF are affected either by micro-porosity or by lack of fusion [18]. Their origin can depend on the set of process parameters chosen, an out-of-control condition in the process chamber, or it can be related to the quality of the powder material employed [19]. In some cases, tight control of the porosity levels is possible with LPBF with porosity levels that can be lower than 0.5%, guaranteeing the best mechanical performance, Table 1. Moreover, for both LBPF and metal FFF parts, further densification processes like hipping can be applied to reduce internal porosity. While the efficacy of hipping process on metal FFF is still uncovered in scientific literature, the good hipping efficacy on LPBF parts is known along with some of the limiting factors (for example the presence of unmelted powder in the internal pores).

Another element of comparison of BMD with respect to a generic LPBF is related to the range of materials available. LPBF systems are usually open material-wise, even if some producers certify the use of their machines for certain powder types only. Examples of a wide range of LPBF processable materials are found in not onlu in the industry including alloys based on Steel, Aluminium, Titanium, Nickel, but also including precious metals and other non-ferrous alloys such as Magnesium. Similarly, most of the metal FFF suppliers provide a wide range of materials, but metal FFF in its BMD implementation, the available ones are currently five different types of steel (three stainless steel type and two tool steel types), Titanium alloy Ti6Al4V, Inconel 625, and pure Copper.

The LPBF typical building chamber size is around $250 \times 250 \times 400$ mm, but currently, the manufacturers offer solutions with a wider volume, Table 1. In terms of the layer thickness, there are differences between the two processes, going from the typical 20–60 μm for the LPBF to the wider range of 50–220 μm for metal FFF, which consequently affects both the surface quality of the manufactured parts and the printing build rate.

The minimum layer thickness inevitably affects the achievable resolution on the parts which is better in the case of the LPBF processes, allowing geometrical features smaller than 0.5 mm to be easily processable. On the opposite, the metal FFF typically gives the smallest achievable features and wall thicknesses in the order of 0.8/1 mm [16]. One difference that makes the metal FFF in some cases preferable is the fact that small internal closed cavities can be produced since it is a powderless process that does not require depowdering.

Metal FFF proposes the following two different print-heads: the standard resolution print-head (0.4 mm diameters) achieves a layer thickness of 100–220 μm (depending on the planned strategy), while the high-resolution one (0.25 mm diameters) can achieve a maximum resolution of 50 μm layer

but causing a relevant decrease of the printing build rate. The metal FFF achieves on average lower productivity compared to the LPBF process, while minimum thin walls and part size are limited by the physics involved in the sintering process. The production of thin walls and structures in metal FFF is far from standard values set by LPBF, due to the nozzle size effect and because of densification and gravity loading in sintering that can cause the failure of these structures (like cracking or collapse under their weight). In terms of maximum size and weights, it is not common to see metal FFF parts that weight more than 1 kg and have size bigger than 200 mm, whilst LPBF processes allow easy processability of bigger and heavier metal parts.

The as-built surface roughness in all the metal AM processes strongly depends on the building direction. Commonly, the worst finishing is generated on the surfaces developed along the build direction and in the overhang surfaces, including those that rely on supports. The removal procedure always generates a footprint on the parts that decreases the finishing quality. In this last case, the ceramic interlayer exploited in the metal FFF process has the potential to mitigate the footprint effect due to the support removal if compared to the LPBF processes. As indicated in Table 1, the best surface roughness achievable with LPBF can be as low as 5 mm, while metal FFF can hardly obtain values that are less than 15 mm in terms of average surface roughness. In addition, the surface texture obtained with these two processes is different where the staircase effect on surfaces perpendicular to printing direction is typically more visible on parts produced with the metal FFF technology. At the same time, the material laser processing in LPBF techniques can guarantee more homogeneous surfaces parallel to printing direction promoting an easy post-process polishability of components.

This can reduce in some cases the need to post-process the surfaces for matching the surface finishing requirements. Clearly, the residual porosity and the external roughness are process limitations that affect the mechanical properties of the part. In [24], the authors reported that metal FFF and LPBF technologies exceed the required tensile properties defined for conventional and metal injection moulded 316L according to ASTM A276 and ISO 22068, respectively. At the same time, for the 17–4 PH hardened and the H1025 condition, the strength of both technologies complies with the conventional and MIM material, while the elongation values provided exceed the standard for MIM material by far. Literature shows a specific lack of detailed studies on the mechanical properties achievable by the metal FFF process of metals. Masurtschak et al. [25] explored different recent processes in terms of their manufacturing possibility, in particular, *BMD* and *ADAM* [26] (another commercial version of the metal FFF process) in the family of metal FFF processes by investigating the material properties of the 17–4 PH. The results obtained were then compared to the traditional LPBF and MIM processes. The authors found that while tensile strength is in the range of traditional processes, the direction of fabrication appears to have a significant influence on the microstructure.

As in all the other sinter-based manufacturing processes, the microstructures of the metal FFF products appear to be fairly homogeneous with equiaxial grains and reduced variation in material properties, such as hardness or grain size, between internal and external portions, as well as along the main axial part coordinates. On the contrary, due to the above mentioned thermal management problem, LPBF parts tend to be characterised by larger material properties anisotropy which not rarely require further thermal post-processes for stress relief or microstructure homogenization.

Data from the tensile tests are depicted in Fig. 2. The reference MIM sample exhibited the standard MIM values for 17–4 PH with a UTS of around 1100–1200 MPa, while LPBF values between 900–1000 Mpa and metal FFF only 800–900 MPa.

Multiple studies have investigated the fatigue life of LPBF manufactured parts, while there is a lack in the literature for binder-based or sinter-based metal AM technologies as the metal FFF. Jiang et al. [27] studied the fatigue behaviour of 316L stainless steel fabricated by a cost-effective metal FFF technology. The existence of process-induced pores showed a significant worsening effect on tensile fatigue. Large pore-induced voids were observed near the surface of the sample, contributing to the fast failure of the tensile fatigue specimen. Within the part, interlayer pores were observed, and a crack growth direction perpendicular to the loading direction inhibited the enlargement of voids, thus prolonging the fatigue life. The authors suggested that the most effective way to improve fatigue life could be to reduce the number of surface pores by different surface finishing technologies.
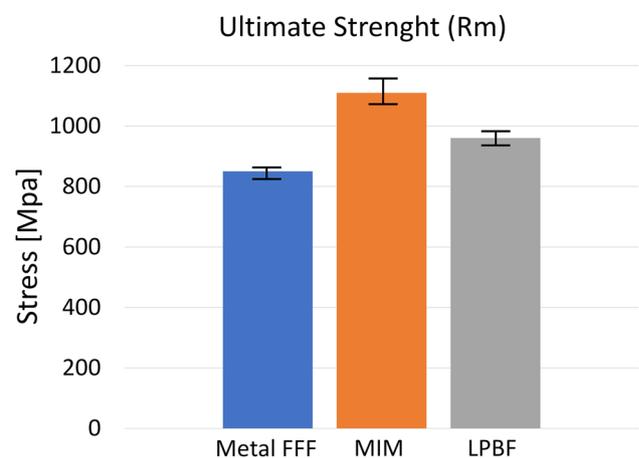


**Fig. 2** Ultimate Strength (Rm) of the different technologies, adjusted from Masurtschak et al. [25]

For what concern the tolerances, both technologies require post-processing of surfaces acting as functional interfaces with other parts in an assembly, while metal FFF showed lower accuracy. However, metal FFF allows the possibility to treat green parts to reduce the need for post-processing [28], assuming that shrinkage of the machined parts can be predicted.

As known, in most of industrial cases, the selection of the most suitable manufacturing technologies is not only based on technical aspects regarding the involved machinery and processes, but also on production costs and additional qualitative criteria that can have a huge impact on the final optimal choice. It is therefore needed to analyse the state of the art in cost and decision-making approaches, as done in the following section.

## 3 Cost and decision-making models in AM

The economic aspect is relevant for a decision-maker in all the contexts, including the manufacturing one. Considering the global markets, along with the consequent competitiveness on product prices, and the novel opportunities opened by the AM technologies, with their expensive equipment and materials, the economic aspects are particularly relevant drivers in the AM field. Innovative design and production paradigms enabled by AM can open new market opportunities, but profitable market outcomes can only be achieved if the cost sustainability of AM production is guaranteed. Therefore, cost models for evaluating AM opportunities are needed to support decision-making in the industry [29].

Typically, the AM cost models proposed in the scientific literature are mostly focused on a process-oriented approach, where the production cycle is divided into distinct phases i.e., pre-processing, production, and post-processing, and are aimed at obtaining the unit cost of the desired product. In this perspective, the cost estimators are highly dependent on the specific process analysed and on the production time estimation, by influencing most of the indirect costs (i.e., labour, overheads, etc.). Hopkinson and Dickens [30] introduced one of the first cost models for AM, aimed at comparing rapid prototyping technologies (such as Vat Photopolymerization, FFF and Selective Laser Sintering—SLS) to traditional manufacturing processes, such as injection moulding and machining. The cost model in their study is resource-based and it expresses the total cost per part as the sum of machine cost, labour cost, and material costs. One of the main assumptions of the model refers to the production mix. The model analyses a scenario where the same component is produced throughout the year on the same machine. The unit cost per part is then calculated by assuming that the machine operates in saturation conditions. Post-processing, a critical stage in AM, is not considered however

in the model. All the assumptions led to a cost per part that is constant with respect to the number of units produced. The peculiarities of each AM technology from the point of view of the required post-processing and in relation to the complexity of the produced parts, can impact on optimal selection of the processing technology to adopt. In [31], the case of spare metal parts production via both additive and subtractive methodology is studied by proposing a method to identify the most economically profitable option among these two processing techniques. The leading parts feature for the cost determination was identified as the AM part's physical properties, which were assessed via functional testing of the AM components and quantified as the Mean Time To Failure (MTTF).

Ruffo et al. [32] conducted a further investigation on the production costs analysis through an Activity-Based Costing (ABC) method. The authors classified the costs into direct and indirect ones, with reference to a case study. The research is based only on the analysis of the SLS process, as the activity-based model developed cannot be applied to different additive processes.

One of the first cost models which considered the contribution of the energy consumption in the cost per part is the one developed by Baumers et al. [33], maintaining the ABC structure employed in [32]. All the considered costs are classified into direct (energy, material) and indirect (time-based) costs. The study showed that the average production cost is highly dependent on the saturation rate. Lindemann et al. [34] in the same year introduced in the model the post-processing costs, which consider the costs of quality control, surface treatments on the parts, and support removal operations. Also, these authors applied an ABC formulation to describe properly the model. Rickenbacher et al. [35], used a parametric linear regression approach to confer to the model the capability to analyse multiple parts designs. Unlike previous studies, this approach calculates the time fraction related to a part for every build job, thus introducing the production mix in the cost model. In this work, pre- and post-processing operations were included in the cost model, while energy costs and administrative overheads were neglected.

Schroder et al. [36] developed a more general cost model, based on a time-driven ABC, that calculates the production-related costs of FFF, SLS, LPBF, and EBPBF, while Hart [37] integrated previous works by proposing a methodology with the addition of a new factor i.e., the value. This allowed them to take into account also the non-economic benefits provided by metal AM technology, the LPBF process in his study. Colosimo et al. [38] presented a cost model to evaluate the economic impact of defects and process instability in metal AM by considering the contribution of scrap fractions and in-situ monitoring performances on the process and material costs, including pre- and

post-processing operations. Their work helped to determine whether and when the use of an in-situ monitoring solution is effective to prevent defectiveness for different value-added product categories. In general, for low-value-added products, if the monitoring tool is poorly reliable (high false alarm rate), it may be not economically convenient, because the detrimental effect of false alarms counterbalances the potential benefits of in-line defect detection. In the case of high-value-added products, the availability of an in-situ monitoring tool is convenient even in the presence of non-optimal fault detection performances, because high manufacturing and material costs to produce one part make the production of scraps quite critical.

In [39] a new AM cost model was proposed to incorporate the risk of an outright process failure and part rejection. The proposed modelling supports better management of the expected cost of process failures by allowing to incorporate of both a $U$-shaped average cost function and an L-shape cost function. This is done by including in the failure cost model a damage factor that describes what share of the build is lost in case of a failure event. The work was applied to material jetting technology adopted for a pharmaceutical AM manufacturing test case, but a wide generality to other AM processes is claimed. The work demonstrates that the magnitude of the cost effect of failure depends on the AM technology adopted.

In [40], research on the costs associated with different production scenarios for internally-produced LPBF parts (make) and for externally purchased LPBF parts (buy) is proposed. Based on the extended quotation study of a considered benchmark, it is found that there exists a relevant scale effect for the external supply costs and an external supply cost difference larger than five times.

In [41] the economic but also the environmental performance of AM systems are compared, by taking into considerations LPBF and BJ, as well standard MIM, methods. The process design and life cycle assessment (LCA) methods are applied to quantify both the costs and environmental impacts. The coupling between cost analysis and LCA allowed to point out that traditional MIM technique can overcome the higher AM production costs but for low production volumes its environmental impact tends to be bigger due to the usage of consumables.

As previously mentioned, production costs are not the only decision variables that are taken into consideration for selecting the best AM process for metal part fabrication. Besides quantitative criteria, also qualitative criteria must be considered in decision-making by industrial players. Therefore, the use of structured technologies that can support analysing complex decisions is surely helpful. One of these tools is the AHP, which is proposed in this paper for this aim. Khan et al. [42] proposed a literature review of publications that have incorporated the AHP and Analytic

Network Process (ANP) methods in various scientific areas from the years 2000 to 2019. In their work, they pointed out that those engineering/technology/applied sciences had the highest number of publications when compared to the other categories. This analysis proves that researchers highly trust this technique and that it can be applied in different fields and to new problems and technologies.

In the manufacturing field, Calderaro et al. [43] presented a decision support model based on the characteristics of additive technologies and competitive criteria. The AHP techniques and conjoint analysis were used together to indicate the recommended technology for the specific problem of interest. Three distinct points of view were considered in this study, the one of a vendor, of a user, and of an expert in the field. Liu et al. [44] applied a decision-making methodology that can be integrated into the product design stages. The proposed decision-making model consists of four elements namely initial screening, technical evaluation and selection of feasible AM processes, and re-evaluation of the feasible solutions. In their study, the AHP was used in the initial screening phase to reduce the number of alternatives, while a cost model was applied in the last step of machine selection. Ransikarbum et al. [45] used the integrative multi-criteria decision analysis technique (MCDA) to evaluate a polymer AM selection problem for healthcare applications. The Fuzzy-AHP (FAHP) was integrated with the TOPSIS approach (Technique for Order of Preference by Similarity to Ideal Solution) to investigate criteria weights related to the 3D printer selection, as well as to investigate the best AM printer. The fuzzy logic was incorporated to tackle the uncertainty from two groups of decision-makers preferences. Eventually, Armillotta [46] described a computer-based tool for the selection of technologies used in the manufacturing of prototypes and limited production runs of industrial products. The AHP approach is enhanced with a procedure that adapts the parameters of the decision model to the prototype specifications. The author pointed out a reduction in the ambiguity on the values of weighting factors that allows an easier interpretation of the rationale behind the selection process.

It is clear from this analysis that a systematic approach for the technical and economical comparison of the emerging metal FFF and the consolidated LPBF process is not present in the literature, up to the authors' knowledge.

In the present study, a new comparison study is therefore proposed to compare the techno-economic benefits of metal FFF against the more traditional solution based on LPBF by taking into account both quantitative and qualitative aspects. The technological comparison presented in the previous section is followed by a proposed cost model and an AHP applied to a real case study. The approach selected for the cost model will be a resource-based one, following the

model framework already presented in the literature [30] and given its suitability to compare different technologies. On the other side, AHP is adopted to merge the production cost estimation with other qualitative criteria, thus supporting the development of a decision-making model to aid the selection of the best metal AM technology for the case study at hand.

Three different alternative technologies are here specifically selected in the analysis, namely the metal FFF, LPBF single laser (LPBF-SL), and quad laser (LPBF-QL).

# 4 Decision-making model definition

The proposed decision-making model relies on an AHP that integrates a cost comparison. Two different cost models are developed to address two distinct production scenarios.

The first scenario assumes that the AM system is fully devoted to the production of a single family of products on a yearly base. This scenario is named Dedicated Machine. The second scenario assumes that the system is devoted to the fabrication of a large number of products and thus the cost comparison assumes that when the process is not producing the specific part types of interest, its production time is absorbed by other parts in the mix. This scenario is named General Purpose Machine.

Both the cost models follow the cost-breakdown structure shown in Fig. 3, where each cost voice is in €/part. The results produced by the cost models are used as an input for the AHP and compared with other qualitative criteria. By merging these latter criteria with an estimation of the production costs, the AHP can confirm if a purely economic decision based on the output of the cost model is the most suitable for the studied cases or not.

## 4.1 Cost model—Dedicated Machine

In this first scenario, the main assumption consists of considering a manufacturing system fully dedicated to a single family of products. In other words, the AM system, which could be either based on metal FFF or LPBF technologies, is bought to fabricate a single product or a family of products, fabricated with the same material.

The other specific assumptions considered in this scenario are listed below as folows:

(a) Each build contains a fixed number of parts, and it is filled to saturation, depending on the part volume and build area constraints.
(b) The yearly machine uptime $u$ is 5400 h/y.
(c) The baseline comparison in terms of maximum production volume is considered the saturation condition of the LPBF-SL system.

(d) The metal FFF system is configured in a way that it can achieve the production volume of LPBF-SL. This means that the system bottleneck is identified among the three subsystems of metal FFF (i.e., the printer, the debinder or the furnace) and one single unit of them is added accordingly, until the required productivity is reached.
(e) The scrap rate $f$ identifies the percentage of the out-of-spec parts produced. In LPBF $f$ refers to the single printing step, while in metal FFF $f$ refers to failures and scraps that originated in one of the three production steps.

The first element of the cost model is given by the **equipment cost** $C_{eq}$ (€/part), which is defined as Eq. 1.

$$C_{eq} = \frac{c_{mac,eq}}{N \cdot (1-f)} \tag{1}$$

where $c_{mac,eq}$ (€/y) includes the yearly investment for a new AM system, which includes the yearly depreciation cost of the machine and the accessory equipment (adopting a linear depreciation model), plus the yearly maintenance and software costs; $N$ (parts/y) represents the maximum yearly production volume and $f$ the scrap fraction for the specific process under study. Only for the metal FFF system, the cost of the system includes the yearly investment for all the different units to be adopted (printers, debinders, and furnaces). Information about the equipment cost is reported in Table 13 in Appendix A.

The **material cost** $C_{mat}$ (€/part) is given by Eq. 2, (see also Table 14 in Appendix A).

$$C_{mat} = \left( M + \frac{m_w}{n_b} \right) \cdot \frac{c_m}{1-f} \tag{2}$$

where $c_m$ is the cost of the material (€/kg), $m$ is the final part mass (kg/part), which includes the material used for the part and all the supports, while $m_w$ (kg/build) represents the mass of material wasted divided by the number of parts fabricated in one single build $n_b$ (part/build). The material waste consists of non-recyclable powder for the LPBF process and wasted metal-binder mixture for the metal FFF (e.g., the material lost for purging and cleaning the extrusion nozzle).

The **energy cost** $C_{en}$ (€/part) for each part is expressed in Eq. 3, Table 15 in Appendix A, where $c_{en}$ (€/kWh) is the unit cost of the energy, $e$ is the machine power consumption (kW), $t_b$ is the time of machine-related activities in a building job (h/build) and $n_b$ represents the number of parts fabricated in one build job. The percentage of energy lost to process defective parts is included via the scrap rate $f$.

**Fig. 3** Cost-breakdown structure

$$C_{en} = c_{en} \frac{e \cdot t_b}{n_b \cdot (1-f)} \tag{3}$$

In the **secondary costs** $C_{sec}$ (€/part), two components are considered: one is related to the working gas consumption (valid for both the LPBF and the metal FFF) whilst the other is related to the debinding solvent consumption (valid for the metal FFF process only). In Eq. 4 the items $c_g$ (€/h) and $c_{dfl}$ (€/l) are the costs of gas and solvent, respectively, and $w_{dfl}$ (l/build) is the volume of solvent fluid consumed per each debinding cycle (only for the metal FFF process), Table 16 in Appendix A.

$$C_{sec} = \frac{t_b}{n_b \cdot (1-f)} \cdot c_g + \frac{w_{dfl}}{n_b \cdot (1-f)} \cdot c_{dfl} \tag{4}$$

The **consumable cost** $C_{cons}$ (€/part) considers lifecycle costs of consumables, consisting of metal and ceramic print heads for the metal FFF process (as all the other consumables are negligible) and the recoater, building plate and powder filter for the LPBF, Eq. 5, Table 17 in Appendix A.

$$C_{cons} = \sum_{i=1}^{n_{cons}} \frac{c_{cons,i}}{N_{b,i} \cdot n_b \cdot (1-f)} \tag{5}$$

where $c_{cons,i}$ (€) represents the cost of the $i$th consumable ($i = 1,..,n_{cons}$) for the specific technology, whilst $N_{b,i}$ represents the number of builds that can be produced with that consumable.

The **cost for post-processing** $C_{pp}$(€/part), Eq. 6 and Table 18 in Appendix A., is considered for the LPBF process only and includes the heat treatment costs for stress relief $c_{HT}$ (€/build), and the wire-EDM cutting operations $c_{EDM}$ (€/part), to remove parts and supports from the build plate. In case of the metal FFF system, the post-processing cost is neglected since this technology does produce stress-free components (thanks to the sintering cycle in the furnace) and an easy manual support removal operation (thanks to the presence of an interface ceramic layer).

$$C_{pp} = \frac{c_{HT} + c_{EDM}}{n_b \cdot (1-f)}. \tag{6}$$

Any cost for additional post-processing to be performed after the metal FFF or the LPBF processes is neglected in our work.

The **labour cost** $C_{lab}$ (€/part) considers the time $t_{post}$ (h/part) needed to perform the support removal operation (for both the metal FFF and LPBF) and depowdering on each part (for LPBF only), Eq. 7, Table 19 in Appendix A.

$$C_{lab} = \frac{c_{op} \cdot t_{post}}{(1-f)} \tag{7}$$

where $c_{op}$(€/h) represents the operator costs.

The **facility costs** $C_{fac}$ (€/part) consider the amount of space $S$ (m²) occupied by the production systems, where $c_S$ (€/(y • m²)) is the cost per square meter in the facility, Eq. 8, Table 20 in Appendix A.

$$C_{fac} = \frac{c_S \cdot S}{N \cdot (1-f)} \tag{8}$$

Finally, the **setup cost** $C_{setup}$ (€/part), Eq. 9, Table 21, is obtained as the sum of two different contributions: the first is related to the fixed yearly investment costs $c_{start}$ (€/y) and the variable costs due to operators' activities ($c_{op} • n_{op} • t_{start}$) when a new production has to start; the second term ($c_{op} • t_{b,prep}$) is related to the operator costs devoted to a new build-job preparation.

$$C_{setup} = \frac{c_{start} + c_{op} \cdot n_{op} \cdot t_{start}}{N \cdot (1-f)} + \frac{c_{op} \cdot t_{b,prep}}{n_b} \tag{9}$$

### 4.2 Cost model—General Purpose Machine

In the second scenario, the manufacturing systems are considered always saturated on a yearly base. When not devoted to the specific part considered in the cost analysis, the system is assumed to be saturated with other products. In this

way, the equipment and facility costs have a different impact on the produced parts costs. In particular, the Eqs. 2–8, that define the cost model for the first scenario, are still valid while the equipment and facility costs can be computed considering the Eqs. 10–11.

$$C_{\text{eq}} = c_{\text{mac,eq}} \cdot \frac{t_{b,\text{eq}}}{u \cdot (1-f)} \tag{10}$$

$$C_{\text{fac}} = c_S \cdot S \cdot \frac{t_{b,\text{eq}}}{u \cdot (1-f)} \tag{11}$$

where $t_{b,\text{eq}}$ (h/part) is the time to manufacture the part and $u$ (h/y) is the yearly machine uptime.

For what concerns the rest of the cost model, this second scenario follows similar structure and assumptions valid for the Dedicated Machine.

### 4.3 Decision-making model—Analytic Hierarchy Process

In order to compare the different alternatives considered in this study, namely metal FFF, LPBF-SL and LPBF-QL, different criteria are considered relevant for the decision maker, basing on the discussion presented in the Introduction section.

The considered criteria are listed below:

- Cost per part: the first criterion considers the cost per part derived through the cost model described in the previous sections.
- Safety: metal FFF and LPBF manufacturing systems have different safety requirements. The substantial differences in terms of safety (for the environment as well as for the operators) during the ordinary use and maintenance of the production system can be then considered.
- Easiness of use: this criterion refers to the different level of skills required to machine operators as well as part designers, to guarantee good quality of parts printed with the selected technology.
- System adaptability: the metal FFF and LPBF have different characteristics of available material range, material suppliers, and setup time. The availability of materials and suppliers refers to the processable materials currently available on the market. The technological maturity of powder bed technologies as well as the considerable number of systems producers result in a wider material spectrum that involves many commercial powder suppliers. The metal FFF system instead presents a closer approach to material supply, since the *BMD* system can operate only with build materials provided by *DM*. Another relevant aspect for system adaptability is the capability to switch from one material to another,

including all the cleaning procedures required to reach the change. Eventually, system adaptability is also concerned with the possibility of tuning the system layout, which is possible for the metal FFF systems by adding a number of stations (e.g., printers, debinder, or furnace) based on the production volume requirements.

- Design Freedom: this criterion includes aspects like the 3D complexity and the maximum build size. The 3D complexity refers to the capability of the process to manufacture complex geometries, for example, lattice structures, or parts with internal features and thin walls.
- Part quality: The achievable surface quality and dimensional/geometrical tolerances are relevant points of comparison between the two technologies. It has a direct impact on the outcome, and it indeed affects the number of post-processes (as machining) required to finish the parts.

The hierarchy structure is selected among the ones proposed by Saaty [47]. The adopted choice considers the costs item divided by the benefits item, as shown in Fig. 4. The cost item includes the cost per part, the safety, and the easiness of use. Here, safety is considered as a cost since it includes the need of having special spaces, equipment, and training as well as more usage responsibility. Also, the easiness of use can be considered as a cost criterion, indeed, a complex technology requires high skilled operators and part designers, which must be trained. All the remaining criteria are included in the benefits hierarchy.

Once the hierarchy is defined, the relative importance of the different criteria must be expressed. For this purpose, a survey was submitted to ten industrial interviewees, selected among different end user companies, and having either a leading or a technical role. The selection of the interviewees preliminary covers a wide industrial field, to represent a situation as general as possible, that includes most of the current AM users. Each specific industrial sector is led by different requirements and objectives, and they are approached with different perspectives. Consequently, the collected answers could not be representative for each of them specifically. For example, medical or aerospace users would prioritize criteria such as part quality and design freedom while tooling industry would likely give more attention to cost per part. Therefore, if a specific sector wants to be addressed, a new set of answers should be collected, given their impact on the final AHP priorities.

The survey was aimed at collecting their preference (of one element over another through a number from 1 to 9). Starting from these judgments, a pairwise comparison matrix was built, and the priority vectors estimated using the *Analytic Hierarchy Process Software* from SpiceLogic. A consistency test was performed at this stage to detect departures from reasonable transitivity of judgments [47],

calculating and verifying the consistency ratio (CR) for each interviewee. When CR < 0.1 the hierarchy matrix is considered consistent (namely, no controversial judgments are given by the interviewees). When CR > 0.1 the hierarchy matrix is adjusted with the method proposed by Saaty [47] and after that, the scores of the ten interviewees were averaged using the geometric mean, Table 22.

Once the priorities were known, the three alternatives were also evaluated by building a pairwise comparison matrix for each criterion. The cost per part comparison matrices were built according to the output of the cost model. On the opposite, the qualitative criteria were evaluated by a panel of three academic experts, with considerable experience in the metal FFF and L-PBF manufacturing technologies.

All the pairwise comparison matrices are reported in Appendix A, Tables 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35. For further details on the AHP procedure, the reader can refer to [47].

## 5 Application of the model to a real case study and metal AM systems

The proposed decision-making model was evaluated in two case studies, considering 17–4 PH stainless steel as reference material. for both the metal FFF and LPBF technologies. The case studies are the same for both technologies to compare them on a common base, and they are selected to be manufacturable with both LPBF and metal FFF without any re-design step. The first case study consists of an extrusion die part, Fig. 5. This represents a typical example of the application of AM technology to the tooling and mould-making sector, one of the most resource-intensive manufacturing processes. Producing moulds by using conventional processes is typically expensive, time-consuming, and technically challenging. Moreover, the selected geometry presents four overhanging surfaces in the central region, which are typically difficult to print. Metal AM can tackle the challenges of the tool-making industry, improving the moulds performances, for example by manufacturing inner cooling pipes, as well as the degree of customization, gaining an advantage over other processes such as the MIM. Furthermore, the production cycle time can be reduced with respect to conventional manufacturing, drastically reducing the lead time, and thus meeting the requirements of low batch volume [48] by decreasing the costs.

The second case study is the impeller component shown in Fig. 5, a typical component of pumps and compressors employed in different engineering fields, from aerospace to biomedical and automotive one. The impeller represents another typical case study where AM couples cost-saving with an increase in performance over conventional technologies. The curved and thin-walled blade profiles of the geometry selected represent remarkable geometrical complexities requiring soft cutting operations to obtain the required surface finish but preserving at the same time the blade structural integrity. In subtractive manufacturing, these geometries are produced by time-expensive and material-wasteful milling operations starting from the bulk.

From a performance perspective, the design freedom of AM can be exploited to create flow-optimized surfaces and thus increase the overall performance. The main characteristics are summarized in Table 2, and the case studies present a similar footprint (i.e., the extension in X and Y direction once considered the printing orientation), with a radius of 58 mm and 63 mm for the extrusion die and impeller respectively, but with the first case study being double in height. The choice to study these two components was also made to investigate the influence of build height and number of layers.

Three metal AM systems were selected to quantify the manufacturing costs, the metal FFF *DM Studio System +*, the LPBF *Renishaw AM 250* (LPBF-SL), and the LPBF *Renishaw RenAM500Q* (LPBF-QL), for the metal FFF process and LPBF, respectively. For what concerns the metal FFF, the manufacturing time is assessed through the proprietary *DM Fabricate software*. In this regard, the "Standard +" printing profile was adopted, whose main process parameters are reported in Table 10 of Appendix A. For the *AM 250 system*, the printing time was estimated by considering the process parameters shown in Table 9 of Appendix A, while the printing times for the *RenAM 500Q* are courtesy of *Renishaw* [20]. The manufacturing times for both the case studies on the three machines are reported in Tables 11 and 12 of Appendix A.

### 5.1 Case studies and production scenarios

In order to facilitate the analysis and comparison of the results among different case studies and scenarios, the results are presented according to the summary in Table 3. For each case study, the two cost model scenarios are applied, and two production volume targets are set (low/high) and further discussed by applying the AHP, for a total of eight combinations. In particular, the "high" production volume is set equal to the production volume of the LPBF-SL in saturation conditions for both case studies, whilst the "low" production volume is set to 100 parts/y.

The cost per part obtained for each combination indicated in Table 3 is then used as input for the AHP modelling (Sect. 6.2). Since the AHP requires the use of scores also for the cost items (quantitative values), an arbitrary conversion is adopted, Table 4. When the difference in cost per part

**Fig. 4** Hierarchy structure for the decision-making model
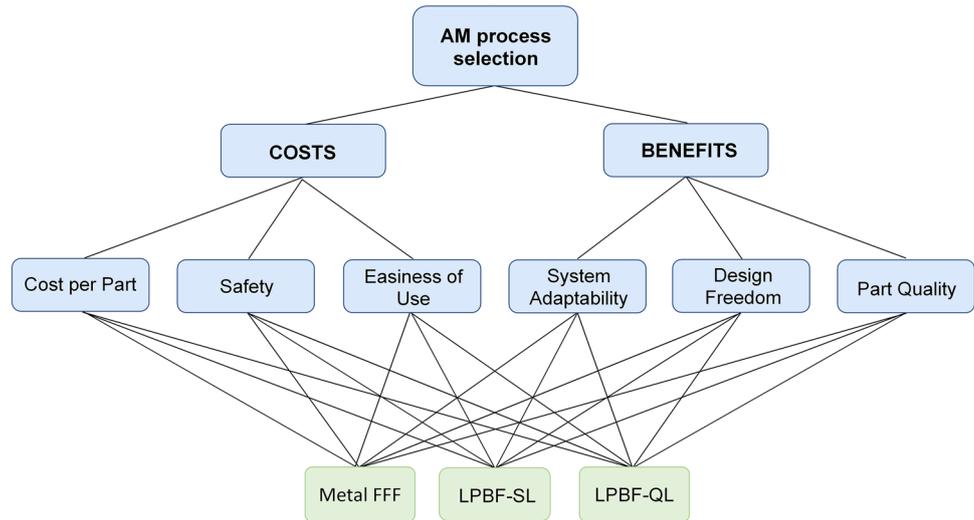


given by the two technologies in each case (e.g., in the Dedicated Machine scenario with low production volume of Extrusion die) is negligible, namely less than 10%, a score equal to 1 is used in the AHP. Since in the high production volumes, the same cost per part difference between the compared technologies produces a big absolute cost bias, a different conversion scale is adopted (see the second row "high" in Table 4). In this case, the conversion score equals to 1 corresponds to a cost per part difference of less than 2%.

## 5.2 Process characteristics and constraints

### 5.2.1 LPBF systems

To calculate the production volume in a year with an LPBF-SL system, a build platform of size $350 \times 250 \times 250$ mm, in agreement with the considered LPBF *Renishaw AM 250* was considered. The maximum number of parts printed per build was derived from the build processor of the software *Materialise Magics* [49]. The software also provides the mass of the part and its supports, as well as the build height, necessary to calculate the amount of wasted material and powder. The cost of the 17–4 PH powder was provided by *Sandvik Osprey* [50], while all the other costs, as inert gas consumption and consumables were provided

by internal sources from the authors' affiliation laboratory [51, 52], Table 8 in Appendix A. The data for the LPBF-QL were instead directly provided by the machine manufacturer.

### 5.2.2 Metal FFF

The costs of the metal and ceramic materials, the print heads, and the debinding solvent were extracted from market available cost information. Moreover, *DM Fabricate* software provides the user with information about the total amount of metal and ceramic material used per part. The values of the energetic consumption of the three machines were extracted by the *Studio System +* datasheet, and the price of the gas $(Ar + 3\% \ H_2)$ for the sintering cycle was given by an external provider. For the debinding and sintering phases, the following guidelines were considered for the nesting and the calculation of the number of parts per cycle:

- Debinding:

  o The components must be placed at a minimum distance of 10 mm from each other in every direction.
  o Whenever the part is higher than 60 mm, only one layer can be placed in the debinder to perform the run, otherwise, three layers can be stacked.

**Table 2** Main characteristics of the two case studies

|  | Extrusion die | Impeller |
|---|---|---|
| Build material | 17–4 PH | 17–4 PH |
| Dimensions [mm] | $58 \times 58 \times 44$ | $63 \times 63 \times 20$ |
| Market sector | Tooling | Mechanical components |
| Mass [kg] | 0.5 | 0.2 |

**Table 3** Summary of case studies and scenario investigated

|  | Dedicated machine | General purpose machine |
|---|---|---|
| Extrusion die | Low/high | Low/high |
| Impeller | Low/high | Low/high |

**Fig. 5** 3D models of the
selected case studies
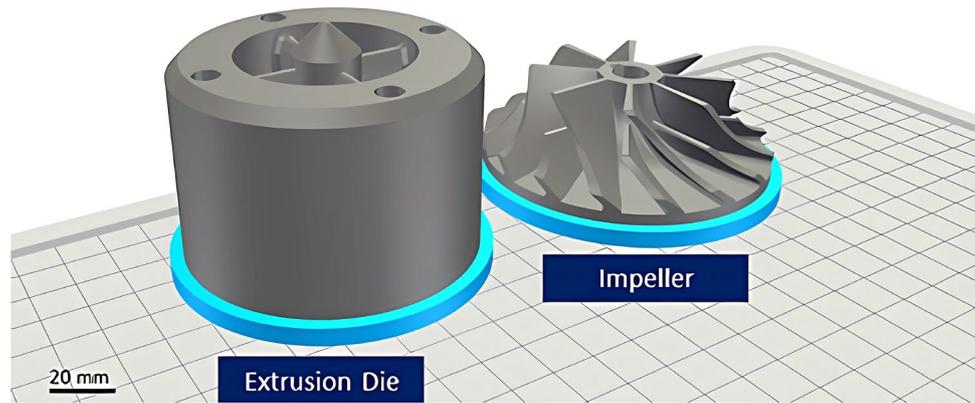


o A maximum of 3.6 kg can be placed in the debinding per run.

- Sintering:

  o The sintering furnace has a stack structure, with a maximum of five stacks. If the parts are smaller than 60 mm in height, then five stacks can be used, otherwise, the number of stacks needs to be reduced.
  o A maximum of 3 kg can be placed in the furnace per run.

The metal FFF system can be purchased in different configurations. The base configuration of this system includes one printer unit, one debinder unit, and one furnace unit, which can be synthesized into the layout 1–1–1. In this configuration, the typical bottleneck of the process is represented by the printer, due to its low build rate. Therefore, the maximum number of parts that can be manufactured in one year is computed starting from the printing time. When changing the layout, for example adding one or more printers, it is necessary to first verify which station of the system is the bottleneck, to calculate the maximum number of parts.

## 6 Results and discussion

The presented techno-economic analysis is performed on two AM technologies with different characteristics and relatively different market targets. The two processes are in fact not perfectly overlapped in terms of processable materials, part complexity, and dimensions, and therefore comparing the two technologies required the definition of a common base that can be addressed by both.

The two case studies utilized consist of mechanical components made of stainless steel 17–4 PH with relatively small geometry, that well represents general AM application cases and is compliant with the process limits of both technologies. This provides a good validity to the presented numerical results that can then be considered industrially representative. Clearly, due to the extreme vastness of the AM application fields, it is still possible to find specific applications where the choice between the two AM families is somehow forced, hindering the opportunity to adopt any other process alternatives. In these cases, the comparison between technologies loses sense but the proposed methodology, based on the use of AHP to merge qualitative/quantitative criteria for the decision making, can still be applied to compare, within the same AM process family, the optimal choice.

The two selected test cases were selected to have similar complexity and footprint, but different heights. The height difference can in fact be used as a degree of freedom for the determination of the printing time between the two processes. Due to the lower vertical resolution of the metal FFF process, taller parts determine a reduction of the productivity gap between the two technologies (since a smaller number of layers are deposited in the metal FFF for the same part height), with possible shifting between the cost voice balance. In this study, the two case studies are used for the costs estimation in their original geometry. No design for additive step was carried out.

**Table 4** Scale to convert the cost per part ratio into a 1–9 score

| Score | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Low | [1; 1.1] | [1.1; 1.2] | [1.2; 1.4] | [1.4; 1.6] | [1.6; 1.8] | [1.8; 2] | [2; 2.3] | [2.3; 2.6] | > 2.6 |
| High | [1; 1.02] | [1.02; 1.04] | [1.04; 1.07] | [1.07; 1.1] | [1.1; 1.15] | [1.15; 1.2] | [1.2; 1.3] | [1.3; 1.4] | > 1.4 |

## 6.1 Cost model

The results of the cost model are summarized in Fig. 6, where the cost per part is expressed as a function of the production volume. Four panels are presented, one per each combination of case studies and scenarios, where the three alternatives (metal FFF, LPBF-SL, LPBF-QL) are compared.

With reference to the first part type, i.e., the extrusion die, Fig. 6a, b reports results for the Dedicated and General Purpose Machine scenarios, respectively.

In this context, the maximum production volume achievable with one LPBF-SL system is 460 part/y (this value is set as the upper limit of the investigation) while the LPBF-QL system presents higher potential productivity, reaching up to 1800 parts/y. On the contrary, the metal FFF system in a 1–1–1 configuration can guarantee only 250 part/y Therefore, in order to reach the target production volume of 460 part/y, a different layout including two printers, i.e., a 2–1–1 layout, must be considered.

Considering the Dedicated Machine scenario, the metal FFF system represents always the cheapest solution compared to the other ones. On the other side, the LPBF-QL system is the more expensive technology, despite of the yearly production volumes considered in the range. This is mainly due to the higher equipment cost of LPBF systems, as clearly shown in Fig. 7a.

It is worth mentioning that in this scenario, the LPBF-QL system is not saturated for the selected production volume of $N = 460$ part/y, and therefore the equipment costs are so relevant in determining the most profitable solution.

Moving to the General Purpose Machine scenario for the extrusion die parts, where all the alternatives are working in saturation conditions, the metal FFF solution results the most convenient one until a production volume of around 90 part/y is reached. On the opposite, the LPBF-SL is the less convenient solution in all the cases.

For $N = 260$, there is a step decrease in the metal FFF cost per part, which is justified by two effects: the increase of $c_{mac,eq}$ (Eq. 11) given by the addition of one printer when the maximum capacity of the 1–1–1-layout is reached and the consequent decreases of the cycle time $t_{b,eq}$ (that reduces by half of its value) leading to an overall decrease of costs. The same behaviour can be seen in Fig. 6d for the impeller case study. Here, the decrease in the total cost, given by the addition of new printers, occurs until the 3–1–1 configuration. On the contrary, the costs slightly increase when one printer and one furnace are introduced (passing to a 4–1–2 layout) as identified by the onset of the last staircase in the blue curve of Fig. 6d (starting at around 1250 parts). The adoption of a new furnace is mandatory in the metal FFF to reach the target production volume of 1600 part/y.

The second case study shows a trend that mimics the first case study of the Dedicated Machine, where the metal FFF is always winning over the other alternatives. On the opposite, considering a General Purpose Machine for the impeller, the metal FFF is the most economical solution only for a low production volume, Fig. 6d, (until 170 parts/y which represents the break-even point between metal FFF and LPBF-QL). The cost per part of metal FFF is comparable to the LPBF-QL system for a medium production volume, even if, interestingly, there is a window between 200 and 400 parts where LPBF-QL overtakes metal FFF. At the same time, the LPBF-QL results in the most economical alternative for a production higher than 1250 parts/y.

A clear description of the cost contributes is given in the histograms of Fig. 7b–d that refer to the General Purpose Machine scenario, where all the systems are saturated by working at 5400 h/y.

The equipment cost is the most important contribution for all the three AM systems, while metal FFF presents a material cost higher than the LPBF cases. This can be related to the specific market approach of the studied commercial metal FFF solution (i.e., the *BMD* from *DM*), which forces the use of its own building materials. There are other metal FFF system alternatives for metals that allow the use of open materials, such as the low-cost MIM pellets material, and that could result in cost savings from the material viewpoint.

On the opposite, the powder-based AM supply chains, modelled by the open approach to materials supply, show constant reductions in material costs year after year, especially when common materials, such as the 17–4 PH, are considered. By analysing the other cost items, the LPBF solution presents an important contribution from the post-processing (stress relieving and EDM cutting) viewpoint. It can be reminded that these activities are not considered for the metal FFF process, due to the presence of a standalone sintering step and of the ceramic interface strategy for quick supports removal. Another different element between the two technologies is represented by consumable costs, which are higher for the LPBF processes because of the replacement of some machine elements, such as the recoater or the powder filter etc., which is required frequently (at every build or after a few builds). The contribution of the secondary cost is particularly high in the LPBF-SL system, due to a higher gas consumption (a factor of five on the hourly gas usage between the two analysed LPBF technologies). This is mainly because LPBF-SL has lower productivity with respect to LPBF-QL, thus leading to longer processing times and consequent larger use of gas quantities.
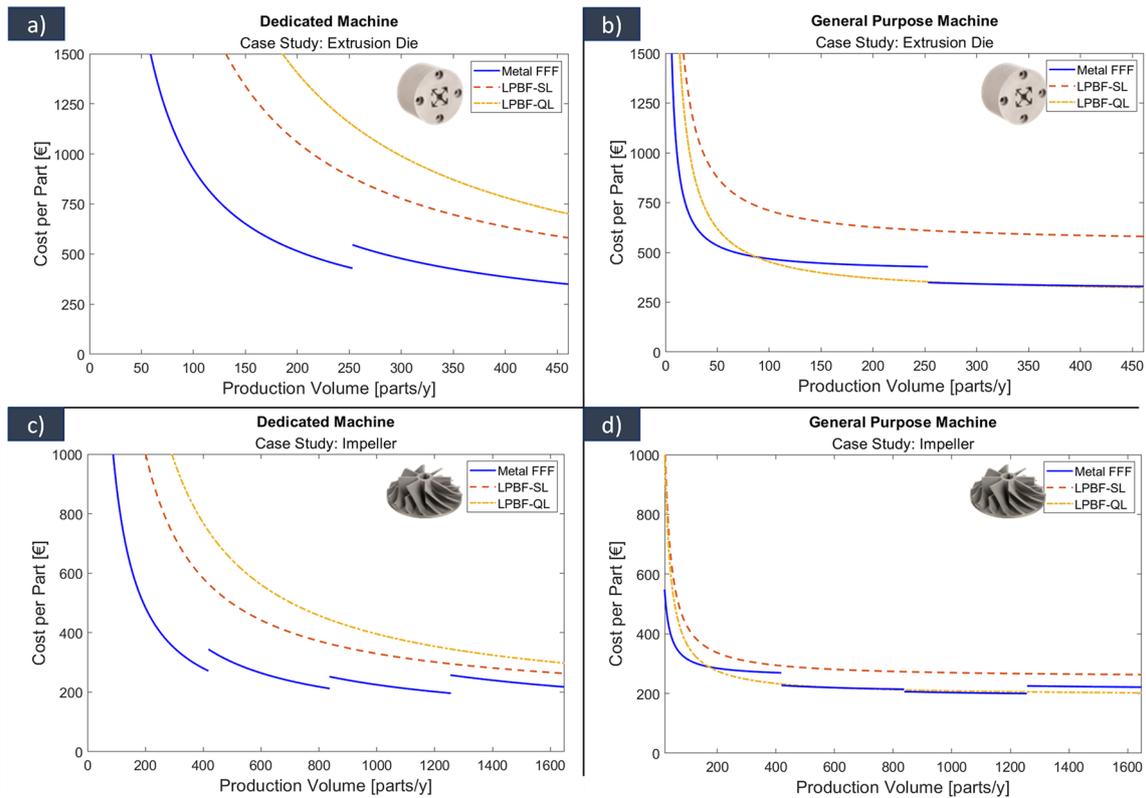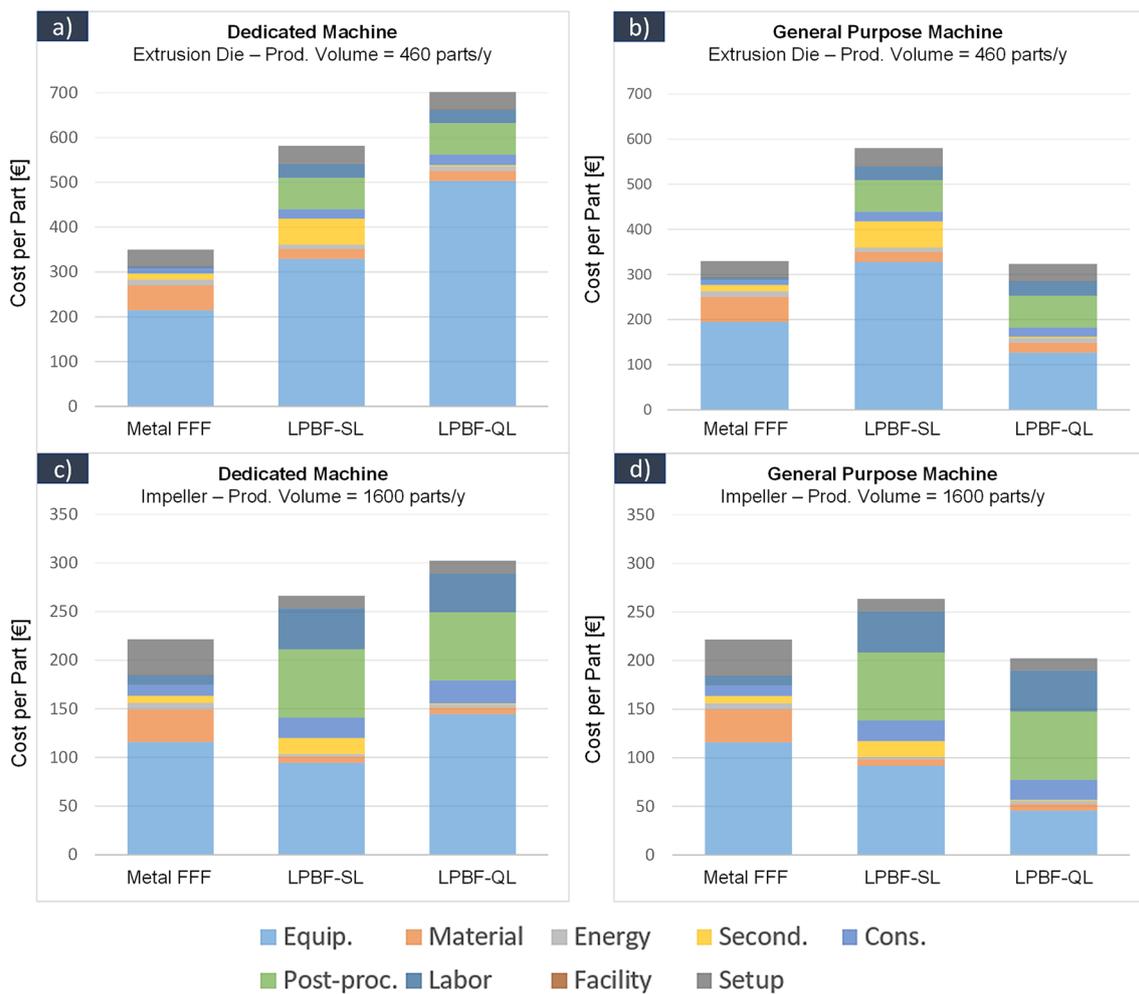
**Fig. 6** Cost per part vs production volume: **a** Extrusion die with Dedicated Machine; **b** Extrusion die with General Purpose Machine; **c** Impeller with Dedicated Machine; **d** Impeller with General Purpose Machine

It is worth mentioning that all results assume a yearly machine uptime $u$ equal to 5400 h/y. On one side, the LPBF data can be considered extremely reliable, given the large experience gained by the producers in several years of use. On the other hand, data for the metal FFF reliability can be considered more uncertain as metal FFF, and in general binder-based technologies, are relatively new processes with a smaller number of industrial installations currently on the market. Obviously, given the strong effect of the system performances on the techno-economic comparison, any shift between the nominal and the real system behaviours should be carefully evaluated and considered prior to take any decisions. Clearly, these cannot disregard the matching with the requirements in terms of AM material performance and AM parts functionally (e.g., mechanical performance, chemical resistance, bio/food compatibility etc.).

In the economic evaluation, one of the drivers is surely represented by the building material costs. On one side, the LPBF-SL and LPBF-QL systems typically give the opportunity to print with different material suppliers and different powders, by opening opportunities for cost savings. However, this can be hindered by the fact that LPBF system providers typically ask for additional costs to adjust and re-qualify the printing parameters to be adopted. Therefore,

cheaper powders of a certain material typically lead to cost savings only when they can be processed with the same printing parameters or when large production justifies the fixed cost required for process optimization. On the other hand, margins of cost-saving for closed/turnkey metal FFF systems, as the one considered in this study, are much less possible. A different situation is represented when considering open metal FFF systems, capable of processing low-cost MIM feedstock (generally available in pellet shapes for the injection moulding).

This open approach for metal FFF production can also be exploited to evaluate alternatives in the process chain. For instance, the opportunities of performing the sintering operations externally (for example, exploiting the MIM-based sintering solution) by a third-party sintering service provider can be evaluated as a potential additional degree of freedom for cost savings. Sintering is a step that absorbs relevant time and that could become the production bottleneck, especially when a batch of a small number of parts can be processed simultaneously. Cycle time in sintering is constrained by metallurgical aspects and is mostly determined by the furnace technology adopted. Potential time reduction can only be obtained using industrial continuous belt furnaces or with high-vacuum

**Fig. 7** Cost breakdown: **a** Extrusion die with Dedicated Machine; **b** Extrusion die with General Purpose Machine; **c** Impeller with Dedicated Machine; **d** Impeller with General Purpose Machine

furnaces, but the applicability of these technologies is not guaranteed a priori. In a closed commercial integrated system like the *BMD*, there are no opportunities from this point of view and therefore this step cannot be relaxed.

Moreover, metal FFF suffers from less productivity and the bottleneck is generally represented by the printing step due to the inherent limits of the feedstock extrusion process. In any case, in both processes metal FFF and LPBF, the optimal processing window for the printing parameters are quite narrow thus limiting the opportunities to increase the productivity for a given material and system configuration. The use of a more productive set of printing parameters can be obtained in both processes by accepting a lower quality of produced parts, which is usually not possible in AM markets.

Another aspect that must be tackled is the initial investment in the system. metal FFF surely presents lower costs with respect to LPBF-QL. When comparing metal FFF to LPBF-SL and considering the wide range of LPBF-SL

systems in commerce, the investment cost gap reduces, and in some cases can be even zeroed. In the initial investment, the facilities required to run a metal AM system, and the availability of specialized personnel to train, are two other important aspects that should not be forgotten. The present analysis has partially included these aspects in the qualitative judgments driven by the AHP, but in some cases, they can require more attention.

**Table 5** Hierarchy pairwise comparison matrix for costs criteria

| Costs (0.5) | Cost per part | Safety | Easiness of use | Priorities (weight) |
|---|---|---|---|---|
| Cost per part | 1 | 5 | 3 | 0.65 |
| Safety | 0.2 | 1 | 1 | 0.16 |
| Easiness of use | 0.3 | 1 | 1 | 0.19 |

**Table 6** Hierarchy pairwise comparison matrix for Benefits criteria

| Benefits (0.5) | System adaptability | Design freedom | Part quality | Priorities (weight) |
|---|---|---|---|---|
| System adaptability | 1 | 1 | 3 | 0.44 |
| Design freedom | 1 | 1 | 2 | 0.39 |
| Part quality | 0.3 | 0.5 | 1 | 0.17 |

## 6.2 Analytic Hierarchy Process

The hierarchy matrices calculated following the methodology discussed in Sect. 4.2 are reported in Tables 5 and 6, together with the priority vectors. At the same time, the interview data are reported in Table 22 of the Appendix A. In the hierarchy pairwise comparison matrix for Costs criteria the highest priority is given to the cost per part criterion since it receives a weight of 0.65, Table 5. The easiness of use and safety criteria follow. In the benefits matrix, Table 6, the criterion system adaptability received the highest priority (weight), followed by the design freedom. A lower weight was assigned to the part quality.

All the alternatives were evaluated, and the results were obtained (see Appendix, section A). Tables 23, 24, 25, 26, 27, 28, 29, 30 refer to the cost per part criterium and contain the scores associated with the conversion of cost per part ratio (see Sect. 5.1). The eight combinations analysed for the cost per part criterion in the AHP, are summarized in Table 7. At the same time, Tables 31, 32, 33, 34, 35 refer to the scores regarding all other qualitative criteria discussed in this study.

In terms of results, the metal FFF received higher weight with respect to the LPBF systems in the following criteria: safety, easiness of use, and system adaptability (weights equal to 0.72, 0.66, and 0.66 respectively, Tables 31, 32, 33). The LPBF is preferred for design freedom and part quality (weights equal to 0.43, and 0.43, respectively, for both single and quad laser, Tables 34, 35).

In the Dedicated Machine, the metal FFF always shows an advantage with respect to the other two alternatives. Instead, in the General Purpose Machine both metal FFF and

LPBF-QL are economic solutions, but for high production volumes, the LPBF-QL system gains an advantage over the other alternatives. The results are summarized in Fig. 8. For the first case study, the Extrusion die in the Dedicated Machine scenario, the winning alternative is by far the metal FFF process with around 55% of priority, for both the low and high production volumes. This result is mainly given by two factors, namely the lower cost per part, resulting in a higher priority in the same criterion, and a higher score in the System adaptability, which is a property assigned to the technology that is not part related. The outcome is the same for the General Purpose Machine, but with a noticeable difference. Indeed, for both the low and high production volumes, the LPBF-QL system provided a lower Cost per part (453€ and 323€, Table 7), which is translated into a higher score, depicted in Fig. 8 but the higher score of the metal FFF system in the criteria system adaptability and easiness of use changed the outcome of the cost-based choice.

For what concerns the second case study, the Impeller, considering the Dedicated Machine, the metal FFF system is always prioritized by the AHP, because of the significant difference in the cost per part with respect to the LPBF processes. For the General Purpose Machine scenario with high production volume, the outcome of the cost model is not changed, but the two alternative solutions metal FFF and LPBF-QL get close to each other (metal FFF 221 €, LPBF-QL 202 €), indicating a high sensitivity of the results to small changes in the hierarchy matrices.

## 7 Conclusions

This paper proposes a methodology that joins together quantitative cost data and qualitative considerations to support the decision-making for metal AM technology selection. As a matter of fact, AM operators and AM decision-makers in the industry typically struggle to perform an optimal choice for process selection and this is possibly slowing down the adoption of metal AM technologies. The present paper contributed to define an easy-to-apply process selection model to aid decision-makers to adopt the appropriate AM technology.

**Table 7** Summary of the eight scenario combinations analysed for the cost per part criterion in the AHP

| Case study | Prod. volume | Dedicated machine | | | General purpose machine | | |
|---|---|---|---|---|---|---|---|
| | | Metal FFF | LPBF-SL | LPBF-QL | Metal FFF | LPBF-SL | LPBF-QL |
| | | Cost per part $C_{tot}$ | | | | | |
| Extrusion die | Low (100 parts/y) | **924** € | 1900 € | 2600 € | 468 € | 710 € | **453** € |
| | High (460 parts/y) | **350** € | 581 € | 701 € | 330 € | 580 € | **323** € |
| Impeller | Low (100 parts/y) | **895** € | 1850 € | 2600 € | **313** € | 420 € | 358 € |
| | High (1600 parts/y) | **221** € | 266 € | 302 € | 221 € | 263 € | **202** € |

A techno-economical comparison was here proposed to compare traditional single and multi-LPBF solutions with metal FFF (i.e., 3D extrusion of polymer-metal feedstock, followed by debinding and sintering steps). This was possible by adopting cost modelling that is flexible enough to represent both the metal FFF and the LPBF technologies.

When the AM system can work in saturated conditions, as typically happens when the same machine can be used for many different part types ("General Purpose scenario"), the cost differences between the different technologies are less relevant for a wide range of production volumes and the LPBF-QL represents the most cost-effective solution. Only when the production volume is particularly low, the metal FFF production starts becoming a competitive solution, thanks to its lower investment cost. On the other side, when a machine is specifically devoted to one single part type ("Dedicated Machine scenario"), the metal FFF technology can be preferred, even when other qualitative aspects are combined with the economic evaluation of costs.

The proposed use of the AHP provides a quite general framework to include many elements to aid process selection in different production scenarios, thanks to

a proper assessment of benefits and risks associated to each technology. As shown in the paper, the integration of qualitative elements in the AHP analysis can sometimes invert the optimal choice based on the solely economic evaluation. In the studied cases, when the cost per part difference among different technologies is limited, other relevant factors than the costlike the system adaptability and the easiness of use demonstrated to favour the metal FFF technology.

The specific discussion on different production scenarios and different part types can be easily applied to other industrial contexts and cost vs performance comparison of AM technologies. Moreover, following the presented approach, the AHP matrix could be rebuilt by collecting answers from experts in a specific sector (aerospace, biomedical, or others), considering different requirements and objectives.

Future developments will extend the comparison to also include, not only other systems of the considered technologies, but also other metal AM technologies, such as metal Binder Jetting, EB-PBF, and others that are growing in the market.

**Fig. 8** Summary of AHP on the case studies and for both cost models scenarios
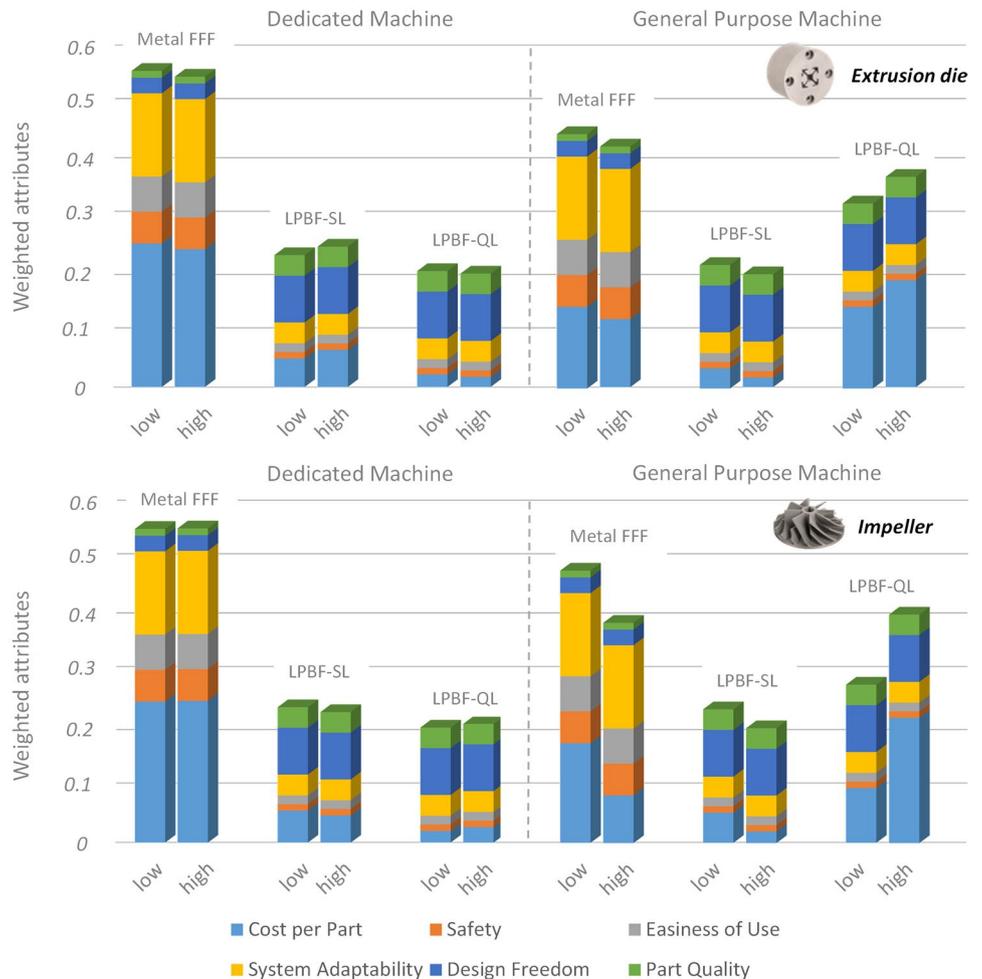
## Appendix A: Input data

### Cost model—Input data

See Tables 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21.

**Table 8** Input data for cost model calculation

| Parameter | Value | Unit | Source |
|---|---|---|---|
| Depreciation period ($y$) | 5 | years | Internal [51] |
| Max yearly machine uptime ($u$) | 5400 | h/y | v [51] |
| Scrap rate ($f$) | 0.05 | – | Internal [51] |
| Cost of energy ($c_{en}$) | 0.26 | €/kWh | Internal [51] |
| Operator cost ($c_{op}$) | 20 | €/h | Internal [51] |

**Table 9** Process parameters used to estimate the printing time values for the LPBF process

| Parameter | Value | Unit |
|---|---|---|
| Point distance ($d_p$) | 0.050 | mm |
| Hatch distance ($d_h$) | 0.090 | mm |
| Layer thickness ($z$) | 0.040 | mm |
| Exposure time ($t_{on}$) | 90 | μs |
| Recoating time ($t_{recoat}$) | 10 | s |

**Table 10** Most relevant process parameters of the Standard + profile of Fabricate used to estimate the printing time values for the metal FFF process

| Parameter | Value | Unit |
|---|---|---|
| Layer height | 0.2 | mm |
| Line width | 0.5 | mm |
| Print speed | 15 | mm/s |
| Printing temperature | 165 | °C |

**Table 11** Extrusion die dimensions and processing time

| Drivers | Extrusion die | | | | |
|---|---|---|---|---|---|
| Part size [mm] | $57 \times 74 \times 65$ | | | | |
| Market sector | Tooling | | | | |

| | $t_b$ [h] | | $t_{post.}$ [h/part] | $n_b$ |
|---|---|---|---|---|
| | $t_{b\_mac}$ [h] | $t_{b\_prep.}$ [h/build] | | |
| **Metal FFF** | | | | |
| Printing (for single printer) | 20 | 0.25 | 0.25 | 1 |
| Debinding (for single debinder) | 28 | 0.25 | | 7 |
| Sintering (for single furnace) | 40 | 0.5 | | 5 |
| LPBF-SL | 11 | 1 | 1.5 | 9 |
| LPBF-QL | 2.70 | 1 | 1.5 | 9 |

**Table 12** Impeller dimensions and processing time

| Drivers | Impeller | | | | |
|---|---|---|---|---|---|
| Part size [mm] | $58 \times 58 \times 44$ | | | | |
| Market sector | Mechanical component | | | | |

| | $t_b$ [h] | | $t_{post.}$ [h/part] | $n_b$ |
|---|---|---|---|---|
| | $t_{b\_mac}$ [h] | $t_{b\_prep.}$ [h/build] | | |
| **Metal FFF** | | | | |
| Printing (for single debinder) | 12 | 0.25 | 0.25 | 1 |
| Debinding (for single debinder) | 20 | 0.25 | | 12 |
| Sintering (for single debinder) | 40 | 0.5 | | 10 |
| LPBF–SL | 3 | 1 | 2 | 9 |
| LPBF–QL | 0.9 | 1 | 2 | 9 |

**Table 13** Equipment cost considered in the study

| Equipment cost | | | | | |
|---|---|---|---|---|---|
| System | Metal FFF | | | LPBF-SL | LPBF-QL |
| | Printer | Debinder | Furnace | Printer | Printer |
| Machine [€] | 80,000 | 20,000 | 128,000 | 600,000 | 950,000 |
| ATEX structure [€] | 30,000 | | | 38,000 | 38,000 |
| Maintenance [€] | 24,000 | | | 20,000 | 30,000 |
| Maintenance [%] | 11 | | | 3.5 | 3 |
| Software License [€] | 500 | | | 3800 | 3800 |

January 2021, market price in Italy

**Table 14** Material cost considered in the study

| Material cost | | | |
|---|---|---|---|
| System | Metal FFF | LPBF-SL | LPBF-QL |
| $M$ [g] | 530 | 565 | 565 |
| $c_m$ [€/Kg] | 94 | 32 | 32 |
| $c_m$ (interface) [€/Kg] | 1000 | – | – |
| $\%m_{\text{(non-recyclable)}}$ | 2 | 7 | 7 |

**Table 15** Energy cost considered in the study

| Energy cost | | | | | |
|---|---|---|---|---|---|
| System | Metal FFF | | | LPBF-SL | LPBF-QL |
| | Printer | Debinder | Furnace | Printer | Printer |
| $e_{\text{time}}$ [kWh] | 1 | 0.2 | 3 | 3 | 13 |
| $t_{\text{op}}$ [h] | 20 | 28 | 40 | 11 | 2.70 |
| $N_b$ | 1 | 7 | 5 | 9 | 9 |
| $c_{\text{en}}$ [€/kWh] | 0.26 | | | | |

**Table 16** Secondary cost considered in the study

| Secondary cost | | | | | |
|---|---|---|---|---|---|
| System | Metal FFF | | | LPBF-SL | LPBF-QL |
| | Printer | Debinder | Furnace | Printer | Printer |
| $c_{\text{gas}}$ [€/h] | – | – | 0.8 | 5 | 1 |
| $c_{\text{dfl}}$ [€/l] | – | 90 | – | – | – |
| $m_{\text{dfl}}$ [l/build] | – | 0.5 | – | – | – |
| $n_{\text{build}}$ | 1 | 7 | 5 | 9 | 9 |

## AHP—Input data

### Hierarchy construction

### Alternatives evaluation

**Table 17** Consumable cost considered in the study

| Consumable cost | | | | | |
|---|---|---|---|---|---|
| System | Metal FFF | | | LPBF-SL | LPBF-QL |
| | Printer | Debinder | Furnace | Printer | Printer |
| Recoater | | | | | |
| $c_{\text{cons}}$ [€] | – | – | – | 2.5 | 2.5 |
| $N_{\text{build}}$ | – | – | – | 3 | 3 |
| $n_{\text{build}}$ | – | – | – | 9 | 9 |
| $C_{\text{cons}}$ [€] | – | – | – | 0.1 | 0.1 |
| Build plate | | | | | |
| $c_{\text{cons}}$ [€] | – | – | – | 240 | 240 |
| $N_{\text{build}}$ | – | – | – | 12 | 12 |
| $n_{\text{build}}$ | – | – | – | 9 | 9 |
| $C_{\text{cons}}$ [€] | – | – | – | 2.2 | 2.2 |
| Filter | | | | | |
| $c_{\text{cons}}$ [€] | – | – | – | 27 | 40 |
| $N_{\text{build}}$ | – | – | – | 1 | 6 |
| $n_{\text{build}}$ | – | – | – | 9 | 9 |
| $C_{\text{cons}}$ [€] | – | – | – | 3 | 0.74 |
| EDM | | | | | |
| $c_{\text{cons}}$ [€] | – | – | – | 150 | 150 |
| $N_{\text{build}}$ | – | – | – | 1 | 1 |
| $n_{\text{build}}$ | – | – | – | 9 | 9 |
| $C_{\text{cons}}$ [€] | – | – | – | 16.7 | 16.7 |
| Print head metal | | | | | |
| $c_{\text{cons}}$ [€] | 2000 | – | – | – | – |
| $N_{\text{build}}$ | 202 | – | – | – | – |
| $n_{\text{build}}$ | 1 | – | – | – | – |
| $C_{\text{cons}}$ [€] | 9.39 | – | – | – | – |
| Print head ceramic | | | | | |
| $c_{\text{cons}}$ [€] | 2000 | – | – | – | – |
| $N_{\text{build}}$ | 2226 | – | – | – | – |
| $n_{\text{build}}$ | 1 | – | – | – | – |
| $C_{\text{cons}}$ [€] | 0.89 | | – | – | – |

## Appendix B: Sensitivity analysis printing time vs cost per part

A sensitivity analysis on the impact of printing time on cost per parts is reported, Table 36. This is important since in the cost analysis, the nominal printing time is used for estimating the cost per part but most of the AM machines tend to generate printing time estimation errors. In particular, the considered variation on the printing time consists in $\pm 20\%$, basing on the direct authors' experience on printing with the investigated machines. The results are reported for both case studies (Impeller and Extrusion die) and both cost model scenarios (Dedicated and General Purpose Machine ones) in the high production

**Table 18** Post-processing cost considered in the study

| Post-processing cost | | | |
|---|---|---|---|
| System | Metal FFF | LPBF-SL | LPBF-QL |
| $c_{HT}$ [€/plate] | – | 600 | |

**Table 19** Labour cost considered in the study

| Labour cost | | | |
|---|---|---|---|
| System | Metal FFF | LPBF-SL | LPBF-QL |
| $t_{operator}$ [€/h] | 0.25 | 1.5 | 1.5 |
| $c_{operator}$ [€/h] | 20 | | |

**Table 20** Footprint of the systems and facility cost considered in the study

| Facility cost | | | | | |
|---|---|---|---|---|---|
| System | Metal FFF | | | LPBF-SL | LPBF-QL |
| | Printer | Debinder | Furnace | System | system |
| $S$ [m$^2$] | 2 | 1 | 3 | 10 | 10 |
| $C_S$ [€/m$^2$] | 60 | | | | |

**Table 21** Setup cost considered in the study

| Setup cost | | | |
|---|---|---|---|
| System | Metal FFF (single printer, single debinder, single furnace) | LPBF-SL | LPBF-QL |
| $c_{start}$ [€] | 5000 | 15,000 | 15,000 |
| $c_{op}$ [€/h] | 20 | 20 | 20 |
| $n_{op}$ [–] | 2 | 2 | 2 |
| $t_{start}$ [h] | 40 | 40 | 40 |
| $t_{build\_prep.}$ [h/part] | 0.4 | 1 | 1 |

volume condition. The reference values indicated in the Table 36 are taken from Table 7 (that reports the cost values for all the cases). The ± 20% variation in printing time corresponds to a − 16%/16% variation in the total cost per part. There is one case (namely, Extrusion die, General Purpose Machine, high production volume),

**Table 22** Interviewee summary after CR correction

| ID | Cost per part vs safety | Cost per part vs easiness of use | Safety vs easiness of use | CR | System flexibility vs design freedom | System flexibility vs parts' quality | Design freedom vs parts' quality | CR |
|---|---|---|---|---|---|---|---|---|
| 1 | 7 | 8.1 | 3 | 0.09 | 2.2 | 3.4 | 3 | 0.05 |
| 2 | 3 | 1 | 7 | – | 3.3 | 0.8 | 0.5 | 0.07 |
| 3 | 5 | 5 | 2.1 | 0.06 | 7 | 5 | 5 | – |
| 4 | 7 | 5 | 0.3 | 0 | 1 | 7 | 7 | 0.05 |
| 5 | 8 | 7 | 2 | 0.07 | 2.5 | 3 | 3.1 | 0.09 |
| 6 | 1.5 | 0.6 | 0.8 | 0.06 | 0.3 | 1.5 | 2.2 | 0.05 |
| 7 | 4.3 | 0.33 | 0.2 | 0.10 | 0.25 | 5 | 0.33 | – |
| 8 | 5 | 7 | 3 | 0.05 | 5 | 7 | 1 | 0.01 |
| 9 | 6 | 5 | 1.9 | 0.08 | 0.8 | 5 | 3 | 0.05 |
| 10 | 5 | 5 | 1 | 0 | 0.33 | 2.5 | 3 | 0.09 |
| Geometric mean on judgements | 4.98 | 3.32 | 1.15 | 0.02 | 1.3 | 3 | 2.2 | 0.01 |

The scores in grey colour are excluded from the geometric mean since they resulted inconsistent even after CR correction (see Sect. 4.2)

where there is a switch in the "winner" technology in terms of cost per part (as highlighted in bold in Table 36). In this situation, when both the three technologies are more productive than the reference (namely, printing time −20%), the minimum cost per part is given by the

**Table 23** Pairwise comparison matrix (cost per part) for the extrusion die: dedicated machine (low production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 7 | 9 | 0.78 |
| LPBF-SL | 1/7 | 1 | 3 | 0.15 |
| LPBF-QL | 1/9 | 1/3 | 1 | 0.07 |

**Table 24** Pairwise comparison matrix (Cost per Part) for the Extrusion die: Dedicated Machine (high production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 9 | 9 | 0.74 |
| LPBF-SL | 1/9 | 1 | 7 | 0.20 |
| LPBF-QL | 1/9 | 1/7 | 1 | 0.06 |

**Table 25** Pairwise comparison matrix (Cost per Part) for the Extrusion die: General Purpose Machine (low production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 4 | 1 | 0.44 |
| LPBF-SL | 1/4 | 1 | 1/4 | 0.12 |
| LPBF-QL | 1 | 4 | 1 | 0.44 |

**Table 26** Pairwise comparison matrix (cost per part) for the Extrusion die: general purpose machine (high production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 9 | 1/2 | 0.37 |
| LPBF-SL | 1/9 | 1 | 1/9 | 0.05 |
| LPBF-QL | 2 | 9 | 1 | 0.58 |

**Table 27** Pairwise comparison matrix (cost per part) for the Impeller: dedicated machine (low production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 7 | 9 | 0.76 |
| LPBF-SL | 1/7 | 1 | 4 | 0.18 |
| LPBF-QL | 1/9 | 1/4 | 1 | 0.06 |

**Table 28** Pairwise comparison matrix (cost per part) for the Impeller: dedicated machine (high production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 6 | 8 | 0.77 |
| LPBF-SL | 1/6 | 1 | 2 | 0.15 |
| LPBF-QL | 1/8 | 1/2 | 1 | 0.08 |

**Table 29** Pairwise comparison matrix (cost per part) for the Impeller: general purpose machine (low production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 3 | 2 | 0.76 |
| LPBF-SL | 1/3 | 1 | 1/2 | 0.17 |
| LPBF-QL | 1/2 | 2 | 1 | 0.07 |

**Table 30** Pairwise comparison matrix (cost per part) for the Impeller: general purpose machine (high production volume)

| Costs | | | | |
|---|---|---|---|---|
| Cost per part | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 6 | 1/4 | 0.26 |
| LPBF-SL | 1/6 | 1 | 1/8 | 0.06 |
| LPBF-QL | 4 | 8 | 1 | 0.68 |

**Table 31** Pairwise comparison matrix (safety)

| Costs | | | | |
|---|---|---|---|---|
| Safety | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 5 | 5 | 0.72 |
| LPBF-SL | 1/5 | 1 | 1 | 0.14 |
| LPBF-QL | 1/5 | 1 | 1 | 0.14 |

**Table 32** Pairwise comparison matrix (easiness of use)

| Costs | | | | |
|---|---|---|---|---|
| Easiness of use | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 4 | 4 | 0.66 |
| LPBF-SL | 1/4 | 1 | 1 | 0.17 |
| LPBF-QL | 1/4 | 1 | 1 | 0.17 |

Metal FFF instead of the LPBF-QL. For the reference printing time, the LPBF-QL generates a 323€ unit cost with respect to the metal FFF which gives 330€. With

**Table 33** Pairwise comparison matrix (system adaptability)

| Benefits | | | | |
|---|---|---|---|---|
| System adaptability | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 4 | 4 | 0.66 |
| LPBF-SL | 1/4 | 1 | 1 | 0.17 |
| LPBF-QL | 1/4 | 1 | 1 | 0.17 |

**Table 34** Pairwise comparison matrix (design freedom)

| Design freedom | Metal FFF | LPBF-SL | LPBF-QL | Weights |
|---|---|---|---|---|
| Metal FFF | 1 | 1/3 | 1/3 | 0.14 |
| LPBF-SL | 3 | 1 | 1 | 0.43 |
| LPBF-QL | 3 | 1 | 1 | 0.43 |

**Table 35** Pairwise comparison matrix (Parts Quality)

| Benefits | | | | |
|---|---|---|---|---|
| Parts quality | Metal FFF | LPBF-SL | LPBF-QL | Weights |
| Metal FFF | 1 | 1/3 | 1/3 | 0.14 |
| LPBF-SL | 3 | 1 | 1 | 0.43 |
| LPBF-QL | 3 | 1 | 1 | 0.43 |

the decreased printing time of 20% the two cost per parts become 289€ and 285€ for the LPBF-QL and metal FFF, respectively. Despite, the suggested modification of the printing times generates a switch in the cost per part winning technology, the cost difference remains very little thus making no changes in the conducted AHP results.

## Declarations

**Conflict of interest** The authors report no declarations of interest.

**Table 36** Change in the cost per part as a result of a change in the printing time of the components

| Case study | Printing time variation | Dedicated machine | | | General purpose machine | | |
|---|---|---|---|---|---|---|---|
| | | Metal FFF | LPBF-SL | LPBF-QL | Metal FFF | LPBF-SL | LPBF-QL |
| | | Cost per part $C_{tot}$ | | | | | |
| Extrusion die (460 parts/y) | −20% | 301 € (−14%) | 494 € (−15%) | 592 € (−16%) | **285 € (−14%)** | **495 € (−15%)** | **289 € (−11%)** |
| | 0% (Ref.) | 350 € | 581 € | 701 € | 330 € | 580 € | 323 € |
| | 20% | 398 € (14%) | 669 € (15%) | 811 € (16%) | 374 € (13%) | 666 € (15%) | 357 € (11%) |
| Impeller (1600 parts/y) | −20% | 193 € (−13%) | 240 € (−10%) | 268 € (−11%) | 195 € (−12%) | 240 € (−9%) | 191 € (−5%) |
| | 0% (Ref.) | 221 € | 266 € | 302 € | 221 € | 263 € | 202 € |
| | 20% | 243 € (10%) | 286 € (8%) | 328 € (9%) | 247 € (12%) | 286 € (9%) | 213 € (5%) |

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