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REVIEW

Preliminary manufacturability evaluation of complex geometrical parts based on layer thickness in the metal powder bed fusion process

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Abstract

Powder bed fusion of metals using a laser beam (PBF-LB/M) is a widely adopted additive manufacturing (AM) technique, particularly effective for producing complex geometries and thin-walled structures. While thin powder layers enable high precision and fine surface finishes, they also reduce manufacturing speed, creating a trade-off between quality and productivity. This study explores the relationship between geometrical complexity and manufacturability in PBF-LB/M by developing a specialized numerical framework. A comprehensive review of existing manufacturability evaluation methods, which focusses on feature-based and knowledge-based approaches is presented, with applications across the aerospace, biomedical, and automotive industries. The study highlights the importance of layer thickness as a key process parameter and conducts a preliminary evaluation of its impact on building time and manufacturability. The proposed framework provides step-by-step guidance to support early-stage design decisions, allowing optimization of part geometry for reduced cycle time and cost. Initial validation is performed using industrial case studies and build-time simulations using Aconity and Netfabb software. Although the current focus is on layer thickness, the framework sets the groundwork for future studies that incorporate broader process parameters, contributing to improved manufacturability evaluation and decision-making in AM.

Keywords Additive manufacturing · PBF-LB/M manufacturability · Layer thickness · Complex geometries

1 Introduction

Additive manufacturing (AM) processes have opened new opportunities and expanded the scope of manufacturing by reducing the number of operations required to produce complex geometrical parts [1–3]. In this age of manufacturing, companies are facing continuous challenges due to increasing competition and rapidly changing market dynamics. The increasing demand for higher product quality, shorter lead times, and lower costs continues to exert additional pressure on manufacturers. As a result, the ability to forecast the results of the process and identify potential product quality failures has become essential for designers in the early stages of development [4–6]. In general terms, the manufacturability of the design of parts is defined as the ability or ease with which it can be manufactured [7, 8]. This ease can be evaluated in terms of quality, time, and cost involved [9]. In the context of AM technologies, it is important to consider the degree of utilization and inherent advantages of AM, particularly its ability to produce geometrically complex parts [9–11]. Therefore, in this study, the ease of manufacturing is defined in terms of the total time required to build complex part designs by considering the layer thickness process parameter of the PBF-LB/M process. In contrast, the geometrical complexity, in this context, can be defined as the difficulty of manufacturing a part due to its intricate and often non-standard shapes and features such as sphere or cube; hence, it is often quantified as the ratio of the part's volume to the volume of its bounding box, typically represented by a simple geometry such as a cube or sphere [12, 13]. Furthermore, complexity significantly influences various aspects of project management, including part design, quality control measurements, and technical production methods, all of which directly impact time [14, 15]. Therefore, it must be evaluated before proceeding with the design of the part to the production stage to avoid

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insignificant fabrication and time loss after returning it for design modification [4, 7].

Metal powder fusion (PBF-LB/M) is one of the most useful AM processes for producing complex geometrical components by applying a laser beam to a very thin layer of metal powder [11]. Here, the layer thickness can be defined as the specific height or thickness of each layer of powder material that is spread on the building platform and then fused by the laser beam [16]. This process is also known as laser powder bed fusion (LPBF) and selective laser melting (SLM) [17]. It offers high design freedom to produce complex geometric parts with unique geometries and complex internal structures, i.e., thin-wall structures [15, 18, 19]. However, the PBF-LBM process is known for its ability to produce complex geometries, but these geometries can present challenges in terms of process stability, material behavior, and post-processing [20]. Furthermore, due to the geometrical complexity of parts, the geometric accuracy of the surfaces produced is limited and often insufficient for highly accurate parts in industries such as mold making, biomedical, and aerospace [14].

1.1 Importance of layer thickness in manufacturability evaluation

Manufacturing time and geometrical accuracy are critical factors in evaluating the manufacturability of geometrically complex parts, as they directly influence overall production cost, product quality, and the ability to meet stringent design and performance requirements [21]. In the PBF-LB/M process, parts are fabricated layer-by-layer, which inherently introduces a “stair-step effect” on inclined and curved surfaces. This effect, which becomes particularly prominent at lower build orientation angles, can lead to volumetric inaccuracies due to the mismatch between the idealized CAD model and the actual manufactured geometry, as shown in Fig. 1a [22].

Increasing the layer thickness can reduce manufacturing and cycle time but exacerbate volumetric error by intensifying the effect of stepping on the stairs. In addition, at the meso-level scale, it is observed that surface roughness can become uneven due to non-uniform powder fusion near sharp edges and corners, further impacting part quality due to the thermal effects and interaction with metal powder, as shown in Fig. 1b. A mesoscale is a length scale, which lies between the microscale and the macroscale. On this scale, the structure and properties of the material are influenced by the way the laser melts and solidifies the powder layers. This scale is significant in this study to analyze the unique characteristics of PBF-LB/M, such as apparent solidification patterns, and can be customized to control and final properties of the microstructure and part [23, 24]. The build rate is seen to be a key process parameter for efficient part production, showing a linear relationship with the layer thickness [9]. The build rate (B_i) is the product of the scanning speed (v), the height of the feature or complete part (h), and the layer thickness (t), as shown in Eq. 1.

$$B_i = v \cdot h \cdot t. \tag{1}$$

Equation 1 describes the volumetric rate at which material is added during the PBF-LB/M process, essentially how fast the process is to build a part. It quantifies the productivity of the PBF process by linking machine parameters directly with manufacturing time. It helps to compare the efficiency between different sets of units or parts designs. The result is a volumetric build rate, typically in mm^3/s or mm^3/h. The higher build rate shows faster builds, implying lower production time and cost. However, lower build-rate values show to be more time consuming, suggesting greater manufacturing difficulty. The build rate is used as a key indicator of manufacturability, where higher build rates are preferred in the design of additive manufacturing (DfAM). In the narrative of a preliminary manufacturability evaluation framework, this equation plays a central role by linking design parameters with process performance, providing a quantitative foundation for comparing part complexities, and supporting the goal of rapid and cost-effective production,

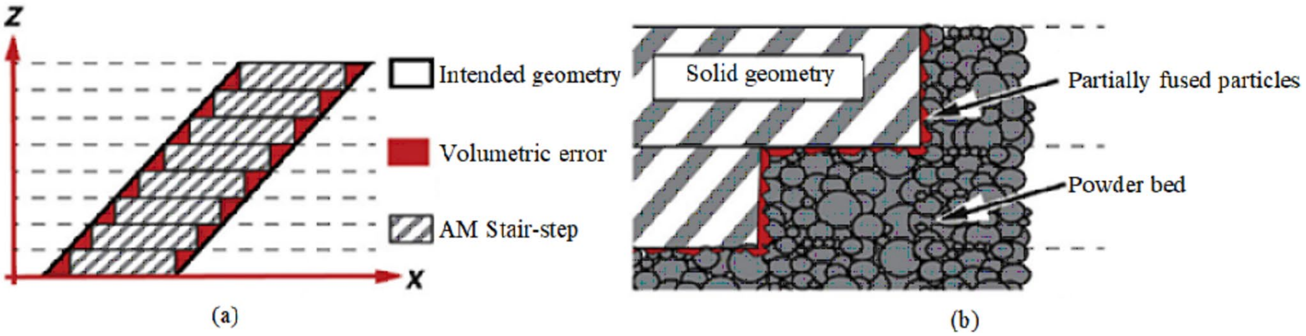


Fig. 1 **a** Effect of the staircase step on geometry. **b** Surface roughness due to non-uniform diffusion at sharp edges and corners [22]

which is a core theme in modern manufacturing research. In addition, an evaluation of the build rate can help to understand why certain parts are "easy' or 'difficult' to manufacture, beyond just visual complexity.

The study showed that reducing the layer thickness improves the density of the part, in addition; the layer thickness enhances part density, additionally; layer plays a crucial role in meeting the requirements for high precision and productivity [25]. Consequently, it is considered one of the most important parameters for controlling the resolution of the AM machine [26]. To summarize all controllable process parameters, it is found that to achieve stability in the PBF-LB/M process, the thickness of the layer is the most important parameter to control the geometry of the part [27]. Hence, it is an important process parameter to consider while preliminary evaluating the manufacturability of complex geometrical parts by controlling geometrical accuracy and build rate to control overall production time at the same time, although other process parameters are also correlated [28].

1.2 Research hypothesis

The preliminary manufacturability of geometrically complex parts produced via PBF-LB/M can be quantitatively predicted and optimized through the feature of the part geometry and the process parameter, such as the layer thickness. This framework will improve preliminary decision-making by reducing cycle time, improving dimensional precision, and lowering production costs, thus addressing the inherent trade-off between quality and productivity in additive manufacturing. The application of the numerical framework for design optimization leads to measurable improvements in production metrics, such as reduced build time and material waste, without compromising part integrity. The proposed framework is generalizable and adaptable to multiple industries (aerospace, biomedical, automotive) with domain-specific tuning of input parameters and geometry evaluation strategies.

2 State-of-the-art manufacturability evaluation

2.1 Evaluation of part complexity

The complexity of parts allows manufacturers and designers to balance functionality and manufacturability, ensuring efficient, cost-effective, and high-quality production. Evaluation of linear complexity index ($C(d_X)$) is important when a part building follows linear paths, such as cube-shaped components. A linear complexity index can be calculated as the ratio of the length of one side (LX_0) to the maximum length (LX_{max}) of the same side of a feature in a component, as shown in Eq. 2 [13].

$$C(d_X) = \frac{LX_0}{LX_{max}} \tag{2}$$

This equation provides a normalized measure of part size in a specific direction (for example, the X, Y, or Z axis) relative to the maximum build volume of the machine. It is a dimensionless ratio between 0 and 1. Here, the values close to 0 represent a very small feature of the component in that direction or a low linear complexity. On the other hand, values close to 1 show that the feature uses most of the machine capacity on that axis or has a high linear complexity. Therefore, this is essentially a spatial occupancy index that indicates how much machine space is being used in a specific direction. This equation is typically useful in DfAM to evaluate the suitability of the AM part. This equation can be used for build orientation studies, where part dimensions affect build time, and multipart layout planning within the build chamber. For example, if a part has a large height and thin layers, then the number of layers required is high, leading to a longer build time. Thus, $C(d_X)$, especially in the building direction, becomes critical in estimating how the building time scales with the height of the part and the resolution of the process. In another way, this equation can help designers avoid exceeding machine limits, especially when parts are tall or elongated in a specific direction. It can be concluded as a design-space occupancy metric that indicates how efficiently a part uses the available build volume. For this study, it anchors the dimension of spatial complexity, how much of the machine capacity is challenged, and helps contextualize why some parts, although seemingly simple, can be complex to build due to their size or orientation. As a result, it gives the user an intuitive way to visualize and compare part designs in relation to building constraints.

Evaluation of the radial complexity index (C(r)) is important, when parts are in cylindrical shape. The radial complexity index can be calculated by the ratio of length (*L*) to diameter (*D*), as shown in Eq. 3 [13].

$$C(r) = \frac{L}{D}. \tag{3}$$

The radial complexity index is particularly useful for designers to control the diameter with respect to the length in parts. The higher values of C(r). are indicating more complex geometries.

Overall volumetric complexity index ($C_{i(global)}$) can be calculad as the ratio of the sum of complexity indexes of local areas over the volume of that specific area, as shown in Eq. 4 [13].

$$\mathrm{C}_{\mathrm{i(global)}}=\frac{\sum_{\mathrm{j}}\left(C(i_{\mathrm{local}})_j\cdot \mathrm{V}_{\mathrm{j}}\right)}{\sum_{\mathrm{j}}\mathrm{V}_{\mathrm{j}}},\tag{4}$$

where $C_{i(local)j}$ is the complexity index of j_{th} area according to Eqs. 2 and 3; V_j is the volume of j_{th} area. These areas can be different, and more than one in part, which needs to be evaluated for complexity, as shown in Fig. 2 [12].

$\mathrm{C}_{\mathrm{i(global)}}$ represents a weighted average of local complexity values across a part, with each region's contribution scaled by its volume. In essence, it represents the average geometric complexity of a part, accounting for the amount of space which each complex region occupies. High-complexity regions that occupy more volume have a greater influence on the global score. Equation 4 summarizes the overall manufacturing complexity from a volumetric standpoint. This global complexity index is widely used in DfAM to evaluate how complex a part is to manufacture, in general. It is useful for evaluating geometry-based manufacturability frameworks where local complexity features (like overhangs, internal cavities, thin walls, etc.) are first evaluated individually, and topology optimization or lattice structure design, where complexity varies throughout the volume. The output values will be between 0 and 1, where 0 shows mostly simple geometry or is easily manufacturable, and close to 1 represents highly complex geometry, difficult to manufacture, or requires support structures. In this study, it can be useful to demonstrate how the complexity of parts is distributed and weighted, providing a general idea other than simple linear or surface indices, and the geometry of the bridge design and the efficiency of the process, giving the methodology credibility and practical relevance.

The spherical complexity of the part can be determined in terms of the sphere area ratio (C_{AR}). It is the difference from 1 to the ratio of the surface area of the sphere (A_{s}), in which it can fit, and the surface area of the part (A_{p}), as shown in Eq. 5. According to another approach, it can be evaluated by the difference from 1 to part volume ratio

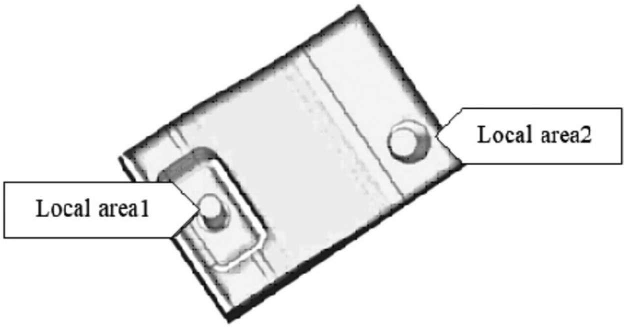


Fig. 2 Local areas for evaluating volumetric complexity index [12]

(C_{PR}). It is the ratio of part volume (V_{p}) and part bounding box volume (V_{b}), in which it can fit, as shown in Eq. 6 [12].

$$\mathrm{C}_{\mathrm{AR}}=1-\frac{\mathrm{A}_{\mathrm{s}}}{\mathrm{A}_{\mathrm{p}}},\tag{5}$$

$$\mathrm{C}_{\mathrm{PR}}=1-\frac{\mathrm{V}_{\mathrm{p}}}{\mathrm{V}_{\mathrm{b}}}.\tag{6}$$

These metrics are used for AM to quantify the geometric complexity of parts, especially those designed for optimized performance or bioinspired functionalities. shows how the surface complexity of the part deviates from a perfect sphere; a simple, minimal surface form. Equation 6 reflects the efficiency with which the part occupies space relative to its bounding box. Both indices yield values between 0 and 1, where values closer to 1 indicate higher geometric or spatial complexity, which means more intricate surfaces or more irregular nonsolid filling of volume. These metrics are particularly useful when designing parts with topology optimization, lattice structures, which are commonly used in AM to reduce weight while maintaining strength.

The thickness ratio (C_{TR}) and depth ratio (C_{DR}) of parts help to evaluate the complexity of parts with long ribs and flanges. The thickness ratio can be evaluated with the difference of 1 from the minimum and maximum thickness ratios in part. The depth ratio can be calculated as the difference of 1 to half of the ratio of the minimum value of length, width, height and the maximum distance of the tooling or the maximum depth. It can be assessed as shown in Eqs. 7 and 8, respectively [12].

$$\mathrm{C}_{\mathrm{TR}}=1-\frac{\mathrm{T}_{\mathrm{min}}}{\mathrm{T}_{\mathrm{max}}},\tag{7}$$

$$\mathrm{C}_{\mathrm{DR}}=1-\frac{0.5(\min(\mathrm{L,W,H}))}{\mathrm{D}_{\mathrm{d}}},\tag{8}$$

where $\mathrm{T}_{\mathrm{min}}$ is the minimum thickness of the part or required feature; $\mathrm{T}_{\mathrm{max}}$ is the maximum thickness of the part or required feature; L, W and H are the length, width and height of the part or required feature, respectively, and D_{d} is the maximum depth. Thickness and depth ratio are important considerations when the depth of the parameters is the main challenge in the process.C_{TR} describes the variation in wall thickness. A value of 0 means uniform thickness, while values closer to 1 indicate high variation.C_{DR} represents how deep an internal feature is relative to the size of the part. A higher value means a deeper, potentially harder-to-manufacture feature. These ratios are commonly used in manufacturability analysis, especially to identify parts that are difficult to manufacture due to geometry.

2.2 Manufacturability evaluation

The complexity of parts is one of the most important factors in evaluating manufacturability. Therefore, a detailed worksheet was initially created to design parts, providing specific guidelines based on the complexity of the part [29]. Applicability of the AM process or selection of an alternate process is mentioned in this worksheet, based on the complexity and functionality of the part. In addition to this, a cloud-based manufacturability evaluation method has been created [26]. The major contribution of this method is to use cloud data instead of the written database in the program. The main advantage of this method is to create a more flexible and adaptable database to obtain more extendable and safe data to support the manufacturability decision. This research mainly focused on the minimum wall thickness and hole size. It is based on three major steps, as shown in Fig. 3a: slicing the 3D model, calculating the area of slices, and calculating the aspect ratio and area of maximum and minimum features.

Using this method, the user needs to analyze the mesh from the 3D CAD model. The program allows evaluating manufacturability by highlighting features with red color, as shown in Fig. 3b. Another study has evaluated the manufacturability with the help of software applications to analyze the build time using the voxel-based analyzer [30]. This method analyzes the 3D CAD model by converting it into voxels. These voxels are the three-dimensional building blocks of a 3D CAD model, which will become solid during the building process. After detecting all faces and geometries from the 3D CAD model, it can evaluate the minimum feature size, then select support material and estimate total build time considering the spot size diameter of laser beam [30].

Another study demonstrated the importance of evaluating manufacturability by investigating the correlation of process parameters. In this study, the manufacturability has been evaluated in terms of the percentage of porosity achieved by manually measuring the pore diameter of the microstructure, as shown in Fig. 4 [31].

Figure 4 shows the image of a porous structure, which can be divided into small square-shaped lattice cells that cover the pores evenly. In the next step, the pore diameters must be calculated by manually measuring them in the microstructure, as shown in Fig. 4.

The percentage of porosity in the lattice (p) can be calculated by Eq. 9 [31].

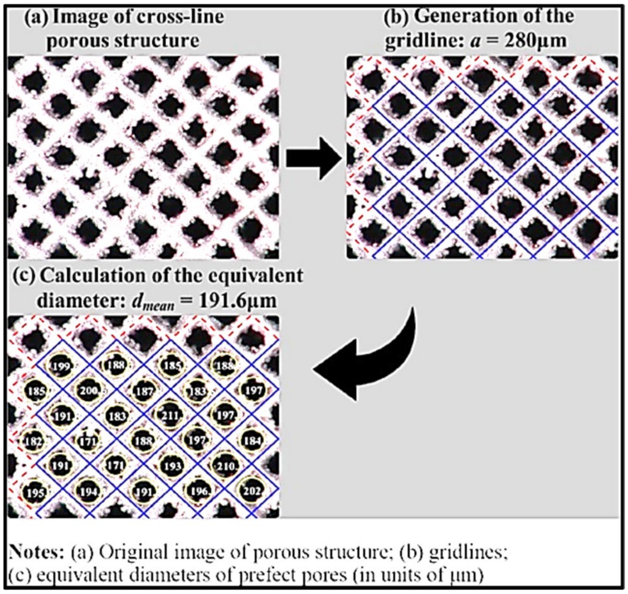


Fig. 4 Porous structure [31]

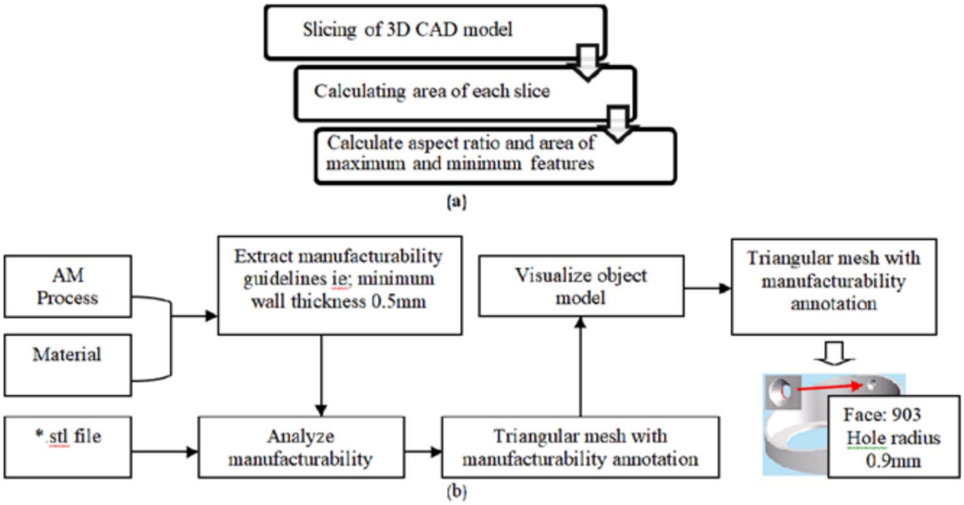


Fig. 3 Manufacturability evaluation [26] **a** steps of evaluation, **b** algorithm of evaluation

$$p = \frac{d^2 mean}{4a^2} \cdot 100\% , \tag{9}$$

where d is the average pore diameter; a is the width of the lattice cell. This equation expresses the proportion of the area occupied by pores within a given unit of area, scaled as a percentage. The result, p, gives a dimensionless percentage value (0–100%) that represents how much of the structure is taken up by spaces versus solid material. This metric is critical in material science, biomedical engineering (e.g., scaffold design for tissue engineering), filtration media, and additive manufacturing of latticed or cellular structures. Higher values of p indicate more porous structures, which could be desirable for permeability, lightweighting, or fluid/gas flow, while lower values reflect denser, mechanically stronger structures. This equation helps quantify the structural function of a design, that is, how it balances mechanical strength and porosity for different applications such as fluid or gas transfer. Porosity can be classified into three levels which are 0, 1, and 2 as shown in Table 1.

A porous structure can be considered as level 1, if it is completely formed and achieved 25% or more; however, it can be regarded as level 0 if it is created uniformly but not recognizable and not measurable as shown in Table 1. Level 2 is an intermediate level of level 0 and level 1, in which the porous structure is measurable, but it is less than 25%.

The 3D CAD model was analyzed on the basis of part orientation and layer thickness optimization in the first step of data set establishment. The main objective of the analysis of part orientation is to avoid or reduce support structure requirements, although it can be modified later according to the overall manufacturability evaluation. In the next step, a data set is created based on 136 lattice structures, which consist of 4 different types of lattices and materials. This data set included unsuccessful manufacturing along with successful manufacturing. In another approach application, software named "DesMod" was introduced to evaluate manufacturability and represent graphically, based on various factors, such as material type, surface quality, features similarity, shape features, complexity of materials, volume-to-surface area, production volume, physical characteristics, and shape complexity factors [5]. The main advantage of this approach is to provide feedback for design modification; however, the disadvantage is that it does not consider the AM process and its important process parameters, such as layer thickness. Manufacturability can be evaluated as the volumetric fraction $\left(\eta V_f\right)$ achieved compared to the 3D CAD model. It can be calculated, as shown in Eq. 10 [32]. It is a dimensionless ratio that reflects the relative error or deviation in volumetric fill. A zero value indicates a perfect match; positive values show excess material (overbuild), and negative values indicate underbuild or porosity.

Table 1 Level of porous structures, and inspection criteria

Level	Inspection criteria	Achieved porosity
0	The porous structure is uniform or partially achieved, but difficult to recognize	Cannot measure
1	The porous structure is completely formed	25(or more)
2	The porous structure can be recognized	Less than 25%

$$\eta \mathrm{V}_{\mathrm{f}} = \frac{V_{f\mathrm{Actual}} - V_{f\mathrm{Design}}}{V_{f\mathrm{Design}}}, \tag{10}$$

where V_f is the volume fraction, $\mathrm{V}_{\mathrm{fDesign}}$ is the designed volume, $\mathrm{V}_{\mathrm{fActual}}$ is the actual volume, achieved in part. Equation 10 is useful for evaluating the precision and fidelity of a manufactured part relative to its intended design, specifically focusing on the solid volumetric fraction, that is, how much of the volume of the part is solid material. This equation is crucial in AM, where ensuring lattice structures or controlled porosity is required. It is used in process validation, design verification, and material performance evaluation. This equation helps to tie together the intended functional performance of a part (such as strength, stiffness, or weight) with the actual performance after fabrication. For example, if a lightweight lattice structure was designed with a specific density for aerospace or biomedical applications, even small deviations in the volumetric fraction can dramatically affect mechanical integrity or biological integration. Thus, this equation gives designers and engineers a quantitative way to assess fidelity, which is a critical checkpoint in the digital-to-physical transition. The main advantage of this study is its focus on quantification; however, the quality of parts is not considered, instead of the volume achieved.

In another approach, the manufacturability of the porous structure is evaluated using the "Archimedes principle" [33]. In this method, the part dipped in the liquid and the percentage of porosity is measured by the ratio of the difference in mass due to buoyancy and the actual mass, as shown in Eq. [11] [33].

$$\varepsilon = \frac{\mathrm{M1} - \mathrm{M2}}{\rho.\mathrm{V}} \cdot 100\%, \tag{11}$$

where $M1$ is the initial mass of the container with liquid; $M2$ is the mass of the container with liquid after dipping the structure; $\rho$is the density of the liquid, and V is the total volume. This equation estimates the porosity (%) of an additively manufactured part using the Archimedes principle, a classical method based on fluid displacement. It is particularly useful for porous structures such as lattices, cell designs, or scaffolds commonly fabricated using the PBF-LB/M process. Equation 11 is crucial for applications where mechanical properties, permeability, or lightweighting are essential. It is also useful to validate the manufacturability of a porous structure by checking how much volume of the void is retained after manufacture. This approach is widely used in the research of lightweight, biomedical scaffolds, filters, and scaffolds.

Part geometries can be divided into two main categories for geometric manufacturability: thin walls, sharp edges and corners, small hole gaps, and sharp inner profiles. Thus, geometric manufacturability can be evaluated by morphological operations, i.e., dilation and erosion, and by image processing software. In this study, the manufacturability of the part is represented as the permeability achieved according to the 'Darcy law', as shown in Eq. 12 [34]. Here, permeability (*K*) can be defined as a measure of the ease with which a fluid can flow through the voids of a porous structure. It is intrinsic to the geometry of the pores, not to the fluid itself.

$$\mathrm{K} = \frac{\Delta \mathrm{P}}{\mathrm{L}} = \frac{\mu v}{\mathrm{K}}, \tag{12}$$

where ΔP is the pressure drop along the length of the porous medium; L is the length of the porous medium in the direction of flow; μ is the dynamic viscosity of the fluid, and v is the superficial velocity of the fluid. Equation 12 describes the flow of a fluid through a porous medium; especially for porous or lattice structures; it helps assess how well a fluid can pass through the part. This equation is especially useful for the design and evaluation of porous components in biomedical, aerospace, or energy applications. It is also useful for comparing different AM design strategies, materials, or process parameters, depending on how they impact the internal structure, which is commonly used in biomedical AM research for bone scaffolds to ensure sufficient blood/nutrient flow. It is also useful in AM-created filtration, fuel cells, and fluid transport components. It can be concluded that the permeability equation provides a critical link between the design of porous structures and the real-world functionality in additive manufacturing. When evaluating the flow performance of the fluid, it helps ensure that manufactured parts meet both manufacturing quality and application-specific needs, especially in fields such as biomedicine, filtration, and thermal management.

Manufacturability can be calculated in terms of the porosity achieved in the lattice cell and the sphericity, as shown in Eq. 13 [35].

$$\text{Sphericity} = \frac{\mathrm{S_s}}{\mathrm{S_p}}, \tag{13}$$

where $\mathrm{S_s}$ is the surface area of the sphere and $\mathrm{S_p}$ is the surface area of the particle. This equation calculates sphericity, which is a geometric measure of the degree to which the shape of an object resembles a perfect sphere. Sphericity is often used to describe the shape of powder particles used in the PBF-LB/M process; it is a dimensionless value, typically between 0 and 1, where 1.0 represents a perfect sphere and less than 1 shows a less spherical or more irregular shape of powder particles, which can lead to poor flow and uneven melting. This value provides a quantitative metric for quality control in both material selection and part analysis. It is important because of its direct impact on the stability and repeatability of the process. In addition, the equivalent diameter of a powder particle ($\mathrm{D_v}$) can be calculated by its volume ($\mathrm{V_p}$), as shown in Eq. 14 [35].

$$\mathrm{D}v = \left(\frac{6}{\pi} V_p\right)^{\frac{1}{3}} \tag{14}$$

It is the diameter of a perfect sphere that has the same volume. This is particularly important in PBF-LB/M, as the powder characteristics are fundamental to building quality. Powder particles are not always perfectly spherical, and this method provides a standardized way to represent them using a single scalar value, i.e., the diameter. Powder flow capacity is considered essential for assessing manufacturability [35]. The morphology of the powder particles and their size distribution are the most critical factors influencing powder flow and manufacturability. It is observed that the density of the powder bed can cause a good packing density, resulting in a higher bulk density in the final part. In this study, the process parameters were evaluated in terms of energy density, as shown in Eq. 15 [35].

$$\text{Energy density (E)} = \frac{\mathrm{P}}{\mathrm{h} \cdot \mathrm{v} \cdot \mathrm{t}}\ \mathrm{J/mm^3} \tag{15}$$

.

where P is the laser power; h is the hatching space; t is the layer thickness. The energy density equation serves as a foundational metric in additive manufacturing in quantifying how laser energy interacts with material. It is essential for process optimization, defect prevention, and ensuring that complex geometries (such as thin walls or porous structures) are manufactured accurately and consistently. This equation is useful in process parameter optimization for AM, especially PBF-LB/M. Energy density has higher values for dense parts and lower values for porous or lattice structures. These values help determine the suitability of a building strategy and whether parts are fully fused, without defects, and accurate in dimensions. The energy density is a key variable when evaluating the manufacturability of a part using AM, which helps predict and prevent defects during build. It allows designers and engineers to fine-tune the process parameters for quality and performance and acts as a bridge between CAD design, material, and manufacturing execution.

In addition, manufacturability can be evaluated by analyzing porosity, cooling rate, and metal vapor in the process [36]. In this approach, computational fluid dynamics (CFD) is used with coding in a software application, named “inhouse TATM-MEX”. The major advantage of this method is the ability to analyze the correlation of temperature with porosity and viscosity; however, the correlation of process parameters is not discussed. In another approach, the manufacturability of hollow-walled lattice struts is evaluated in different build directions [37]. According to this study, a high frequency of failure is observed at the 22.5° build angle with the thinnest wall thickness due to defects in the integrity of the wall. This is particularly the case when a single laser scan path is used.

Manufacturability can also be evaluated by checking the use of material in the part geometries after part production [38]. The main advantage of this study is that it also considers cost; however, it cannot provide detailed information on factors that influence material use, time, and cost. Using the characteristics of the material, manufacturability can be evaluated in terms of the mechanical properties achieved, such as tensile strength and fatigue strength, in addition to porosity. On the contrary, this study does not discuss the correlation of the critical factors that generate these properties [39]. In addition to this, it is observed that the mechanical strength increases with a reduction in layer thickness [40]. A study has observed the correlation between laser parameters that affect manufacturability, such as powder particle distribution, density, and absorptivity [41]. The advantage of this research is that many laser parameters are discussed, which limits the research as well. Another disadvantage of this approach is that the laser parameters cannot be selected or optimized in the same way for different materials.

In a more detailed analysis, the assessment of manufacturability has been divided into seven subcategories, which are the volumetric evaluation, the geometric evaluation, the evaluation of support structures, the feasibility of the build time, the cost evaluation, the required resources and the post-processing requirements, as shown in Table 2 [42]. The evaluation of these subcategories is represented as design readiness levels in each category.

According to Table 2, the volumetric evaluation of parts concerns the feasibility of the volume of parts with respect to the volume of the machine work area, used to process parts. In the geometric evaluation, the feasibility of its production must be checked. The feasibility of the support structure and its built orientation angle must then be analyzed. The feasibility of total build time should be evaluated based on part manufacturing targets based on pre-decided lead time. Cost evaluation must be performed to ensure that excess cost and required resources are analyzed to meet manufacturing and post-processing requirements based on manpower, machines, instruments, and material availability. From a broader perspective, the manufacturability of the AM process is related to all activities of the AM process, as well as familiarity with the process, rather than focusing on a single operation [9]. The study is based on familiarity with the product, knowledge expertise, and methodologies for the technological evaluation of the design before it is released to production, as shown in Eq. 16 [9].

$$\begin{aligned}\mathrm{AMMA} = \mathrm{a}\left(1-\frac{9}{\mathrm{TRL}}\right) + \mathrm{b}\left(1-\frac{10}{\mathrm{MRL}}\right) \\ + \mathrm{c}\ \cdot\ \mathrm{UPD} + \mathrm{d}\ \cdot \mathrm{UFP} + \mathrm{PPP},\end{aligned} \tag{16}$$

where *a,b,c* are the ratio of AM expertise and overall activities; technology readiness level (*TRL*) is maturity and readiness infusion of new emerging technology; manufacturing readiness level (*MRL*) is maturity and readiness infusion of new (emerging) technology; usage to product development (*UPD*) is usage of AM technologies in the phases of product development to assist the overall process; and usage to final production (*UFP*) is usage of AM technologies in the phases of actual production with complementary uses. The advantages of this research are the quantification of manufacturability and the focus on the skill of producing various parts throughout the production stages. This equation represents a composite manufacturability metric that blends technologies, manufacturing readiness, and design-related complexity factors into a single score. It helps decision

Table 2 Manufacturability evaluation criteria [42]

SN	Criteria	Definition
1	Volumetric evaluation	Part volume feasibility checks concerning machine work volume
2	Geometric evaluation	The geometries of the part need to be checked to determine whether they can be produced or not
3	Evaluation of the support structure	Optimal build orientation analyzed to minimize or avoid support structures
4	Feasibility of building time	The build time must be calculated and checked to determine whether it is feasible for machine availability, powder availability, and lead time
5	Cost evaluation	The overall cost must be less than the cost to the customer or according to the target
6	Required resources	The required resources must be checked before starting production
7	Post-processing requirements	Post-processing requirements must be analyzed on the basis of manpower, material, and machine availability

makers understand how easily a component can be manufactured using additive manufacturing technologies such as PBF-LB/M. It is useful for designing validation and manufacturability assessments for new components. It is applicable during feasibility studies for the adoption of AM in high-stakes industries (aerospace, defense, and medical). It allows early-stage risk evaluation by combining readiness metrics with geometry-related manufacturability.

2.3 Summary of existing studies for manufacturability evaluation methodology

Based on the complexity of the part, various studies for the evaluation of manufacturability can be classified into two main categories, which are feature-based and knowledge-based evaluations, as shown in Table 3.

The evaluation of manufacturability is crucial for assessing parts of various shapes. Feature-based evaluation uses software to analyze geometric features, focusing solely on parts without considering process parameters, as shown in Table 3. However, it relies on existing databases, which can be limited. Knowledge-based methods depend on the operator's skills, causing variability. A hybrid approach is also possible in which manufacturability evaluation can be done partially with different approaches, for example, the initial data entered by the operator, and the further assessment with the help of a machine learning algorithm [46, 47]. In another way, initial feature analysis can be performed with the help of software by analyzing 3D CAD files for wall thickness, and the operator performs a further analysis [44]. Studies emphasize the importance of layer thickness, which is easy to control and crucial to achieving desired characteristics in parts [48–50]. It is also observed that the feature-based approach is fast, and less knowledge is required for the method due to the application of software, but it is limited to specific features on parts. The main drawback of this method is that it is based on the previous database, which can be limited to the growing demand for complexity day by day [51]. In contrast, the evaluation of knowledge-based manufacturing is more based on operator skills. The major drawback of this approach is that it can vary from person to person. Therefore, modifying a knowledge-based framework with specific guidelines is highly required to evaluate manufacturability and control the variation in the output generated from person to person [52]. Second, when reviewing existing studies, it is observed that no studies report a numerical framework to evaluate manufacturability by considering the process parameters, that is, layer thickness, which is highly desired by industries [9].

3 The aim and purpose of the study

The purpose of this study is to conduct a preliminary evaluation of manufacturability in additive manufacturing processes by examining the influence of layer thickness and geometrical complexity on overall build time using the PBF-LB/M process. The objective of this study is to develop a numerical framework to evaluate the preliminary manufacturability of geometrically complex parts, facilitating the optimization of layer thickness for improved process efficiency and accuracy. Furthermore, the objective is to contribute to existing methodologies while introducing new insights into the interaction between process parameters and manufacturability.

The purpose of this study is to address the need for a systematic preliminary numerical evaluation of manufacturability considering both geometric complexity and layer thickness. This approach offers a robust framework for assessing the preliminary manufacturability of various parts. Using the relationship between layer thickness and geometric precision, the study emphasizes its critical role in manufacturing results [50, 53–58]. Furthermore, it bridges a research gap by proposing a numerical correlation between manufacturability and geometrical complexity, a key requirement for the advancement of manufacturing practices in the industry [9]. A continuous trend of research interest can be seen in recent years in this field, as shown in Fig. 5.

The search for relevant articles was carried out in the 'Scopus' database using the keywords 'LPBF' and 'SLM', which are widely recognized acronyms for 'laser powder bed fusion' and 'selective laser melting', respectively. These keywords were selected because of their popularity and widespread use in the additive manufacturing research community, as shown in Fig. 5. Additional searches were performed using keywords related to the thickness of the layer as a process parameter in conjunction with the PBF-LB/M process. Terms such as complex, geometries, layer, and thickness

Table 3 Summary of various approaches for the evaluation of manufacturability

SN	Approaches	Advantages	Disadvantages	References
1	Feature-based	Faster and less knowledge is required	It only considers the design aspect, but does not consider the material and process parameters	[26, 43]
2	Knowledge-based	Various aspects can be considered	Requires a certain level of knowledge. The output can vary from person to person. Layer thickness is not considered in the manufacturability evaluation	[9, 29, 32, 35, 42, 44, 45]

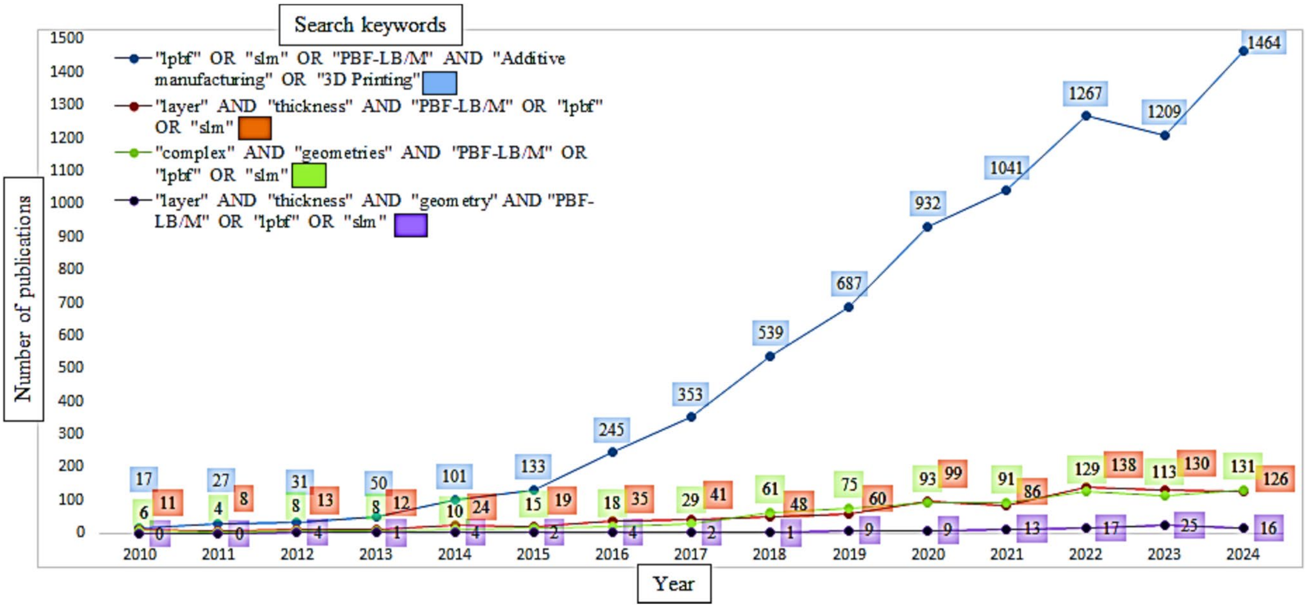


Fig. 5 Recent publications on the effect of layer thickness, and part geometries on PBF-LB/M

were combined with SLM, LBF, and PBF-LB/M to identify studies that investigate correlations or jointly discuss these topics. This approach allowed retrieval of a comprehensive set of research articles focused on geometrical complexity, layer thickness, and manufacturability in PBF-LB/M processes in terms of popularity, by studying these in combination or relatively. We can see a huge scope of research in the PBF-L/B-M process, as the number of publications is very high compared to those of publications under complex geometries and layer thickness relations. According to Fig. 5, the publications in this category are only 1.09% of the total publications in the PBF-LB/M process.

This research can be used to numerically evaluate and compare different types of complex geometrical parts to determine their preliminary manufacturability with the PBF-LB/M process. It can be very helpful for companies to compare and select parts. In the research process, the topic of research was introduced, and then existing related work on manufacturability evaluation was discussed and classified as shown in Fig. 6.

A suitable numerical framework was developed and implemented using real industrial examples to evaluate manufacturability in practical settings. This framework was validated by comparing the manufacturability results with the process cost and the estimated total cost using ‘AMOTool’, a cost analysis tool developed by the company ‘Etteplan Oyj’. The focus on build time was calculated using industrial software tools from ‘Aconity’ and ‘Autodesk Netfabb’, which simulate the PBF-LB/M process based on key parameters such as part orientation, support structures, and laser scanning strategies. Simulation and cost modeling offer a comprehensive view of both process and cost efficiency. By examining how factors such as part geometry and layer thickness affect manufacturability and comparing simulated data with actual case studies, the study strengthens the accuracy and industrial relevance of the proposed framework.

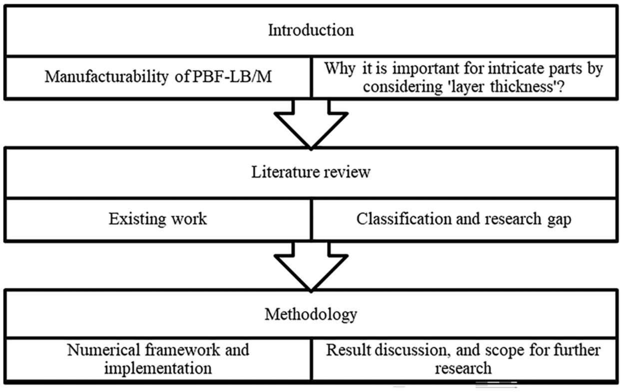


Fig. 6 Flow of research

Although the current study focusses on a limited set of factors, it establishes a solid foundation for future research aimed at developing a more comprehensive assessment framework of manufacturability. Future work will expand on this foundation by incorporating a wider range of parameters, including material properties, quality control criteria, machine characteristics, and additional process variables. This will allow for a more holistic analysis of manufacturability and support more informed decision-making during the early stages of product design and development. Finally, the results are discussed in the context of broader applications, highlighting the potential and need for continued exploration in this area to support the evolving demands of additive manufacturing.

This study has significant scientific relevance as it addresses the challenge of managing and controlling the complexity of parts produced using the PBF-LB/M process. By establishing a correlation between geometrical complexity and the layer thickness process parameter, the research contributes to a deeper understanding of how geometrical complexity influences manufacturability. This knowledge improves the predictive capabilities of the manufacturing process, paving the way for more efficient design strategies for part geometries and layer thickness optimization in additive manufacturing. From an industrial perspective, the study provides a valuable framework for numerically evaluating the preliminary manufacturability of parts produced using the PBF-LB/M process. This approach enables manufacturers to objectively compare the manufacturability of various parts and suppliers, supporting better decision-making in part, supplier selection, and process planning. By linking layer thickness and geometrical complexity to manufacturing results, the study helps industries improve production efficiency, reduce costs, and ensure consistent quality in additive manufacturing.

3.1 Research questions

The following research questions have been formulated to explore and address critical gaps in understanding and evaluating preliminary manufacturability in the PBF-LB/M process. They originate from the need to analyze how the geometrical complexity of components, especially those with intricate, thin-walled features, influences their manufacturability within this additive manufacturing technique. In addition, the layer thickness process parameter mediates the trade-off between surface quality and manufacturing speed warrant examination to support design optimization. Recognizing the importance of early design validation, the research also explores the role of numerical modeling in predicting preliminary manufacturability and its tangible benefits. Furthermore, the integration of a numerical framework raises questions about its ability to optimize design decisions regarding cycle time, precision, and cost. This framework is intended to be applied to various high-demand sectors, such as aerospace, biomedical, and automotive. The adaptability of the method is also examined. Finally, the incorporation of additional process parameters into the framework opens avenues for future research and development. Together, these questions guide the theoretical analysis of current methodologies and foster practical advances in design and manufacturing workflows.

4 Methods

According to the definition, manufacturability is the ability to manufacture easily [7, 8]. This ease can be in terms of quality, time, and cost [9]. However, geometric complexity and layer thickness are independent variables that greatly contribute to the manufacturability of PBF-LB/M, as shown in Fig. 7. Therefore, it can be calculated by the efficiency of the build rate considering the thickness of the layer and the multiplication of the geometric complexity of the part, due to the following multiplicative phenomena [64].

Numerically, Fig. 7 can be expressed as the product of the efficiency of the building rate considering the thickness of the layer and the geometric complexity of the part, as shown in Eq. 17

$$\begin{aligned}\text{Manufacturability} &\\ = \ &\text{Build rate efficiency (by considering layer thickness)}\\ &\cdot \text{Part geometrical complexity.}\end{aligned} \tag{17}$$

Equation 17 describes a composite metric that links two key factors that influence the additive manufacturing process. These are the process performance and design complexity and the ability to assess how manufacturable a part is using the PBF-LB/M process. In this equation, the build-rate efficiency reflects how quickly a part can be built, mainly influenced by the thickness of the layer. Thicker layers result in faster build times but typically lower surface quality, whereas thinner layers improve detail resolution at the cost of slower builds. The geometrical complexity of the parts represents the complexity of the design of a part. It can be quantified using indices such as feature count, curvature variation, thin-wall distribution, or complexity ratios (e.g., thickness ratio, depth ratio, etc.). Multiplying these two factors gives a manufacturability score, which can be used to compare multiple designs. The value is typically dimensionless and relative, meaning that it

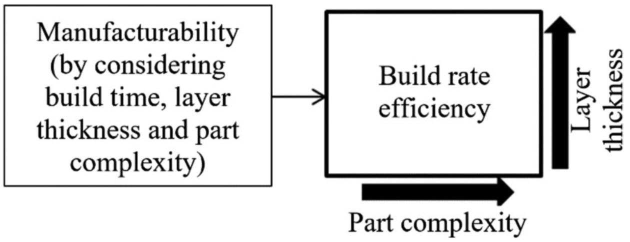


Fig. 7 Manufacturability by considering build time, layer thickness, and part geometrical complexity

is useful for grading parts or identifying which ones are easier or harder to manufacture within a given process setup. In short, this equation serves as a decision support metric that helps balance performance and manufacturability in the design of parts for AM. It supports the narrative that design and process cannot be optimized in isolation. Their interaction is crucial for efficient and effective production. Build rate efficiency can be measured by the percentage ratio of the time required to build part to the ideal or minimum possible time. When considering the thickness of the layer, the minimum possible or ideal time can be achieved by reducing the number of layers to one. The influence of the geometrical complexity of a part on manufacturability can be expressed by the product of the building rate efficiency and the geometrical complexity of a part. This relation can be expressed in Eq. 18.

$$\text{Manufacturability} = \frac{\text{required time to build part}}{\text{ideal time (minimum possible)}} \cdot \text{Part geometrical complexity} \cdot 100\% \tag{18}$$

Here, the percentage ratio of the time required to build the part and the ideal time represent the efficiency of the build rate.

The geometrical complexity of the part can be represented by the volume ratio of the part because the building of the part follows a linear path in PBF-LB/M.

Therefore,

$$\text{Manufacturability} = \frac{\text{required time to build part}}{\text{ideal time}} \cdot \text{Part volume ratio} \cdot 100\% \,. \tag{19}$$

Here, the part volume ratio (C_{PVR}) represents the complexity of the part.

The ideal or minimum possible time to build a part can be evaluated by reducing the number of layers to one. Under this condition, the thickness of the layer will be equivalent to the height of the part.

Thus,

$$\text{Manufacturability} = \frac{\mathrm{v} \cdot \mathrm{h} \cdot \mathrm{t}}{\mathrm{v} \cdot \mathrm{h} \cdot \mathrm{h}} \cdot \mathrm{C}_{\mathrm{PVR}} \cdot 100\% \,, \tag{20}$$

where v is the scan speed, h is the height of the part or the height of the feature in the build direction, t is the thickness of the layer and $\mathrm{C}_{\mathrm{PVR}}$ is the volume ratio of the parts. The minimum thickness of the part can be considered instead of layer thickness because it is correlated, the final part height, and the part volume can be calculated with the help of CAD software, as shown in Fig. 8.

Using the CAD software named 'SolidWorks', the minimum thickness of the part is shown in red, as shown in Fig. 8. The direction of the build is decided according to the minimum height of the build, with the minimum or no support structure required. The height of the part must be calculated in the build direction. The volume of parts can also be evaluated using CAD software, as shown in Fig. 8. The volume ratio can be calculated as the ratio of the volume of parts (V_P) and the volume of the bounding box of parts (V_B), as shown in Fig. 9.

Here V_B can be calculated by multiplying the maximum length (l), maximum width (b), and maximum height of the part in the build direction (h), as shown in Fig. 9. The complexity of the part is considered high when the volume ratio of the part decreases.

Hence, for a single-layer thickness, when all layers of the building are the same.

$$\text{Manufacturability} = \frac{\mathrm{t}}{\mathrm{h}} \cdot \frac{\mathrm{V}_\mathrm{P}}{\mathrm{V}_\mathrm{B}} \cdot 100\% \,. \tag{21}$$

For multiple or varying layer thicknesses, the average layer thickness t_{av} can be considered for the complete building of the part.

$$\mathrm{t}_{\mathrm{av}} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{t}_\mathrm{i}}{\mathrm{n}}, \tag{22}$$

where n is the number of layers; t_i is the thickness of the i^{th} layer.

Therefore,

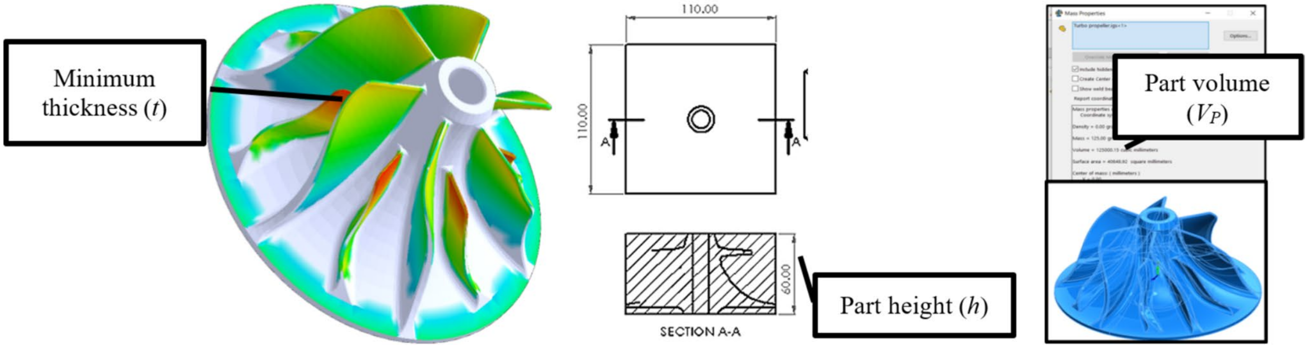


Fig. 8 Evaluation of minimum part thickness (t), part height (h), and part volume (V_P) with the help of CAD software

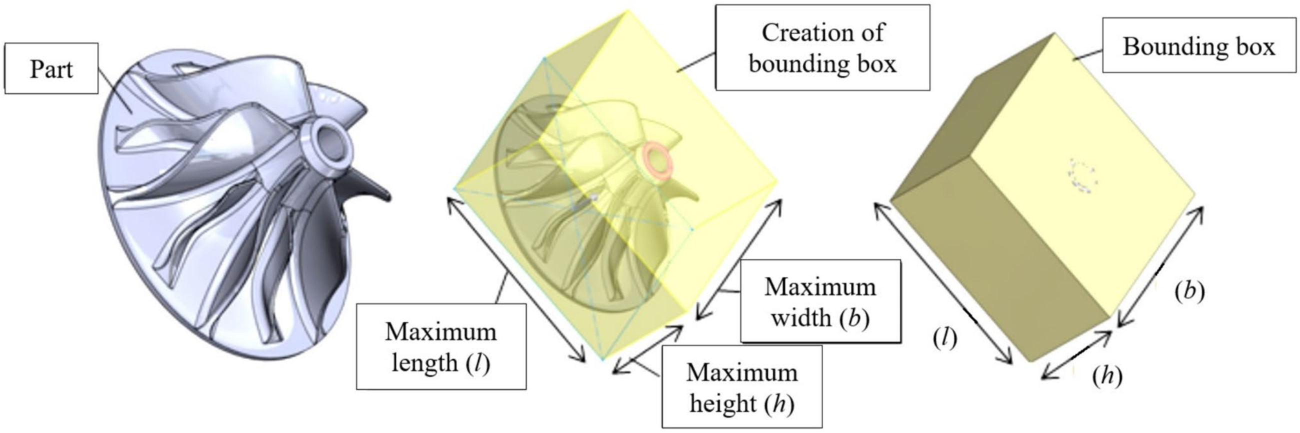


Fig. 9 Part and its bounding box

$$\text{Manufacturability (multi - layer)} = \frac{t_{av}}{h} \cdot \frac{V_P}{V_B} \cdot 100\% . \tag{23}$$

Step-by-step guidelines can be described as shown in Fig. 10.

Figure 10 presents a systematic framework for evaluating preliminary manufacturability in the context of PBF-LB/M. It defines a quantitative method based on geometric and volumetric attributes extracted from CAD models. The first step geometry extraction (using CAD software) involves gathering the necessary geometric data from the CAD model of the part, the thinnest wall or section of the part, the vertical extent of the part in the build direction, part volume, and bounding box volume, which is typically calculated as the art length, width, and height. The minimum thickness of the part can be calculated instead of directly using layer thickness because they are proportional to each other, as shown in Fig. 10; however, the average thickness

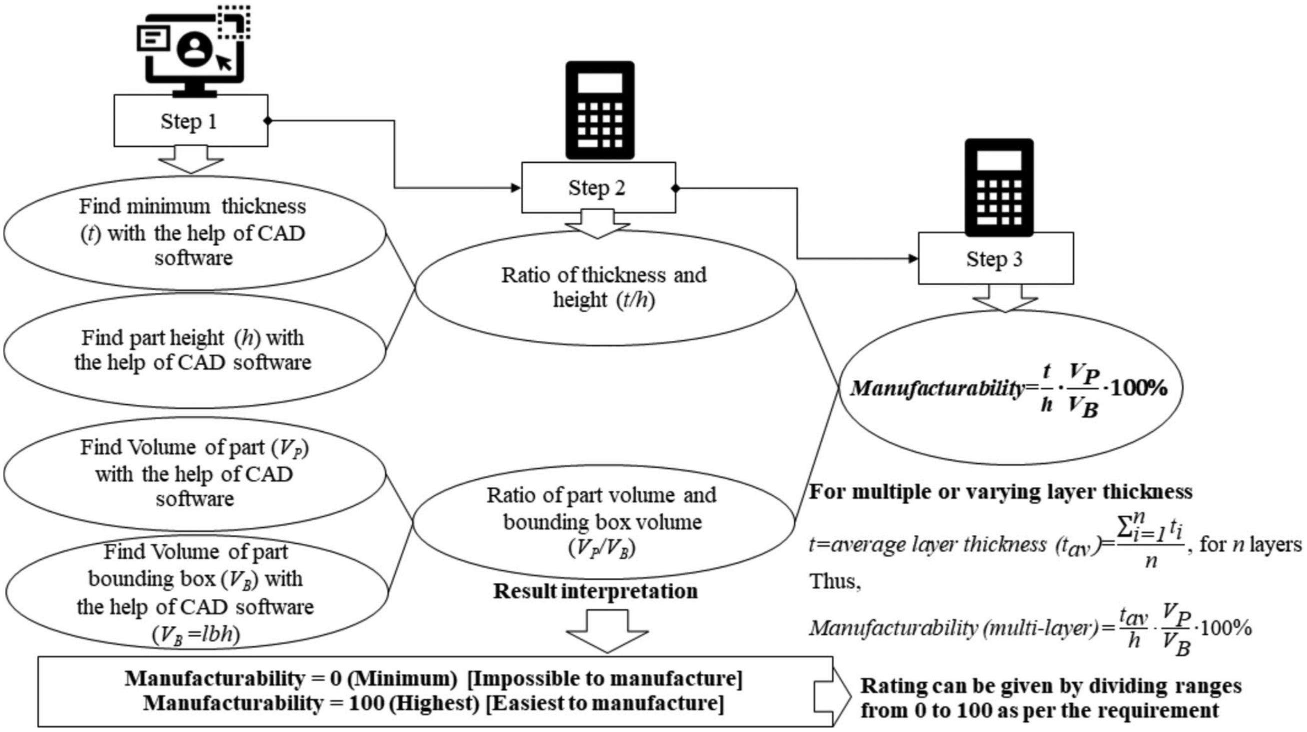


Fig. 10 Numerical framework to evaluate the preliminary manufacturability of complex geometrical parts considering the thickness of the layer with PBF-LB/M

and part height ratio can be considered for multilayer thickness conditions. Using Step 1, the thickness-to-height ratio and the volume-to-bounding-box volume ratio of the part must be calculated, which represents the density of the material or the use of space. A low ratio suggests complex or sparse geometries that may be more difficult to fabricate. The framework blends part geometry and process efficiency to create a quantifiable manufacturability score. It enables quick comparison between multiple designs without detailed simulations. The ratio of the volume of the part and the volume of the part bounding box was calculated, and all these values were added to Eq. 21 to obtain the manufacturability as a percentage. The results can then be interpreted on a scale from 0 to 100, representing the lowest to highest levels of manufacturability, respectively.

The preliminary manufacturability evaluation was conducted in 13 different parts, each varying in complexity and representing a variety of industries and applications. These parts were carefully selected to cover a wide spectrum of design features and functional requirements, ensuring a comprehensive analysis. A key criterion in selecting these parts was their ability to be manufactured without the need for support structures, emphasizing self-supporting designs optimized for AM. The 3D CAD models of all parts were sourced from an open-source platform, "https://grabcad.com", as illustrated in Fig. 11. This platform provides a vast collection of publicly shared CAD files, making it a valuable resource for testing and research. Each part used in the evaluation presents unique geometries and challenges that contribute to a comprehensive assessment of the manufacturing framework. Parts include components from sectors such as automotive, aerospace, medical, and machinery. By incorporating such a diverse set, the framework aims to simulate real-world manufacturing conditions and constraints. The varying levels of complexity in the parts also allow for analysis across different difficulty levels in design and production. This approach not only strengthens the robustness of the framework but also enhances its practical relevance. Ultimately, the inclusion of various parts helps generate interest and familiarity among users and readers, encouraging a wider adoption of the developed methodology.

For the practical implementation of framework, process cost and the total cost were calculated using an online tool called 'AMOTool', developed by 'Etteplan Oyj', a well-known company in the field of additive manufacturing. The required input parameters, such as part height (mm), part volume (cm^3), and surface area (cm^2), were obtained with the help of CAD software such as 'SolidWorks' and entered into the tool. To maintain consistency, other parameters were kept constant, i.e., the number of parts that fit on the build plate was set to one piece, the number of stacking layers was set to one, the estimated added support volume was fixed at 5%, the estimated post-processing (PP) cost was set to zero, and the estimated annual production volume was set as one.

Furthermore, the part build time simulated with the 'Aconitity and 'Netfabb' software in actual build conditions under assumptions, as shown in Table 4.

Table 4 shows the build time simulation criteria with the 'Aconity MIDI + ' machine using the PBF-LB/M process that involves a detailed workflow starting with the import of 13 STL models into the 'Autodesk Netfabb' software. Each part is reoriented to reduce height and support requirements, with surfaces classified using overhang angles of 42º (critical) and 39º (non-critical) to guide support placement. The parts are raised 2 mm above the build platform to aid post-processing. The machine was operated with a 150 W laser and a 0.08 mm spot size, scanning speed at 900 mm/s, and used 316L stainless steel powder. Slicing is done with 30 µm layers and a rotating strip infill pattern to balance the heat distribution. 'Netfabb' generates a sliced file containing toolpaths and metadata, which is then loaded into 'Aconity' machine software where only machine-specific parameters like gas flow and recoater speed are added. This setup allows for a reliable build time estimate, as most variables are predefined in the simulation.

5 Results and discussion

The preliminary evaluation of the manufacturability of the cases was carried out based on the framework created, as shown in Eq. 21 The evaluation results are illustrated in Table 5.

Table 5 compares 13 cases (referenced in Fig. 11) by analyzing key parameters affecting manufacturability in additive manufacturing, including part volume, bounding box volume, part height, minimum thickness, build-rate efficiency, part volume ratio, and an overall manufacturability value. The manufacturability value is calculated by multiplying the build-rate efficiency by the part volume ratio, providing a consolidated metric of production efficiency as shown in Eq. 21. The comparison reveals that parts like case 13 (FBCC unit cell) exhibit high manufacturability due to efficient space usage and favorable geometry, while parts like case 1 (GE model 24v3) score lower due to bulkier design and less efficient build characteristics. The analysis underscores that compact geometry, optimal material distribution, and high build-rate efficiency are critical to improving manufacturability.

The cost of the process and the total cost were calculated using an online tool called 'AMOTool', developed by 'Etteplan Oyj', as shown in Table 6.

Table 6. shows that parts with larger volume and surface area, such as various GE brackets and the turbo propeller,

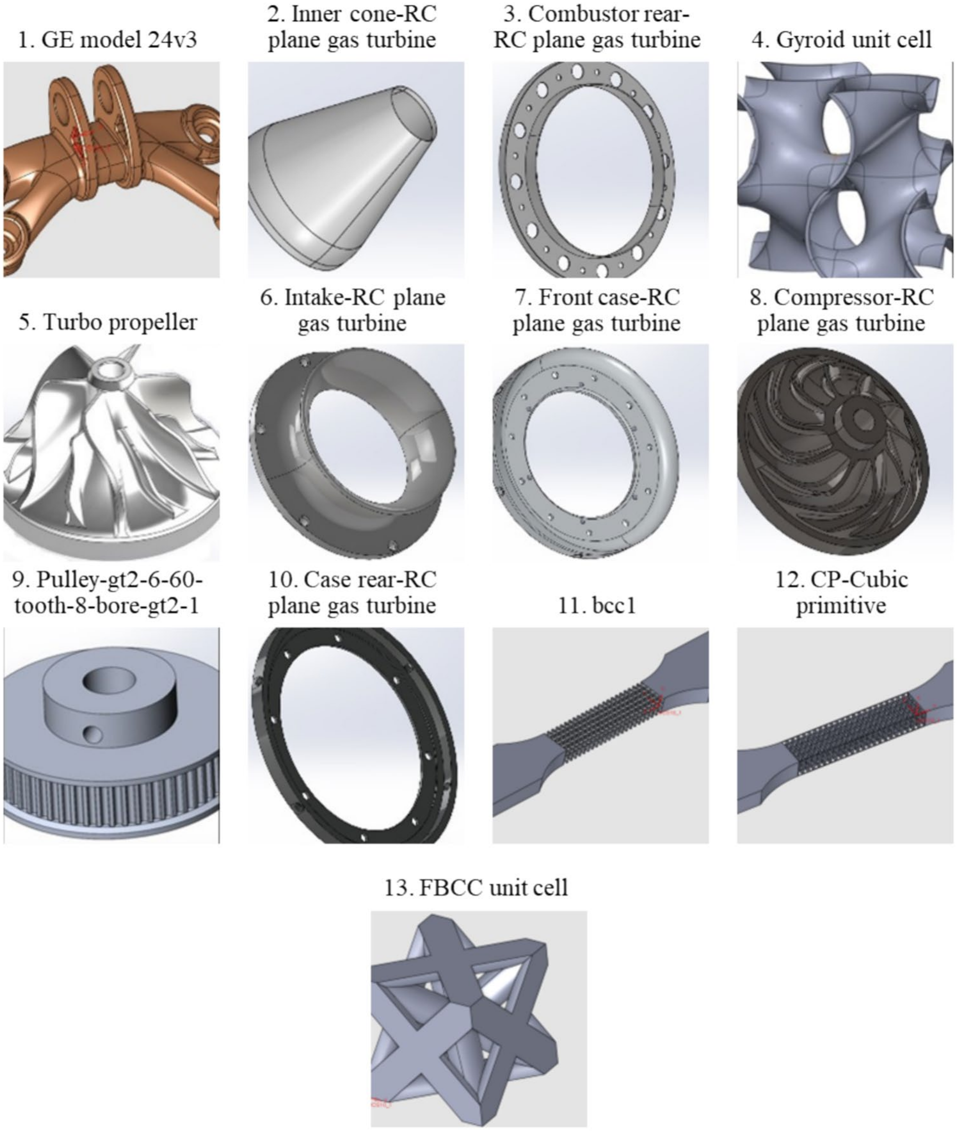


Fig. 11 Cases of complex geometrical parts for manufacturability evaluation

1. GE model 24v3
2. Inner cone-RC plane gas turbine
3. Combustor rear-RC plane gas turbine
4. Gyroid unit cell
5. Turbo propeller
6. Intake-RC plane gas turbine
7. Front case-RC plane gas turbine
8. Compressor-RC plane gas turbine
9. Pulley-gt2-6-60-tooth-8-bore-gt2-1
10. Case rear-RC plane gas turbine
11. bcc1
12. CP-Cubic primitive
13. FBCC unit cell

Table 4 Build-time simulation criteria

Machine name	Laser power (W)	Spot size (mm)	Distance between the part and build platform (mm)	Scanning speed (mm/s)	Material
Aconity MIDI+	150	0.08	2	900	316L

show higher costs, although some small, intricate parts like the lattice node and gyroid unit cell also command notable expenses due to complexity. Parts cover various applications, including gas turbines, implants, and structural components, illustrating a broad spectrum of design and manufacturing considerations.

To ensure the reliability of the preliminary assessment of manufacturability, the focus must be on the consistency and precision of the way manufacturability is calculated. There must be no external factors, such as errors in input data or miscalculations, that might reduce reliability. The correlation between manufacturability and the calculated values of the dependent variables such as layer thickness, part height, part volume, and volume of the bounding box was checked to ensure consistency. It must be clear that in the case of measurement of these variables, uncertainties can produce inconsistent results in manufacturability. After recalculating the manufacturability of each part and comparing it with the previous value, the recalculated values closely match the values provided in most cases, indicating that the evaluation of manufacturability is reliable. The difference in calculating minimum layer thickness is very small or negligible, which may arise from considering

Table 5 Preliminary evaluation of manufacturability

Case	Part name	Part volume (V_P) mm^3	Bounding box volume (V_B) mm^3	Part height (h) mm	Minimum thickness (t) mm	Build rate efficiency (t/h)·100%	Part volume ratio (V_P/V_B)	Manufacturability = Building rate efficiency ·Part volume ratio
1	GE model 24v3	100,000	1,200,000	62.5	0.05	0.08	0.08	0.01
2	Inner cone-RC plane gas turbine	1390	54,200	40.0	0.40	1.00	0.03	0.03
3	Combustor rear-RC plane gas turbine	1280	46,200	8.00	0.40	5.00	0.03	0.14
4	Gyroid unit cell	244	3050	14.5	0.40	2.76	0.08	0.22
5	Turbo propeller	125,000	726,000	60.0	1.15	1.91	0.17	0.33
6	Intake-RC plane gas turbine	12,000	96,700	23.6	0.75	3.18	0.12	0.39
7	Front case-RC plane gas turbine	13,400	92,900	12.0	0.50	4.17	0.14	0.60
8	Compressor-RC plane gas turbine	23,700	71,400	24.5	1.00	4.08	0.33	1.36
9	Pulley-gt2-6–60-tooth-8-bore-gt2-1	12,300	25,600	15.8	0.97	6.17	0.48	2.97
10	Case rear-RC plane gas turbine	5720	38,000	5.00	1.00	20.0	0.15	3.01
11	bcc1	25,000	37,800	7.68	0.32	4.17	0.66	2.76
12	CP-Cubic primitive	24,100	37,800	7.68	0.32	4.17	0.64	2.66
13	FBCC unit cell	856	1730	12.0	1.50	12.5	0.50	6.19

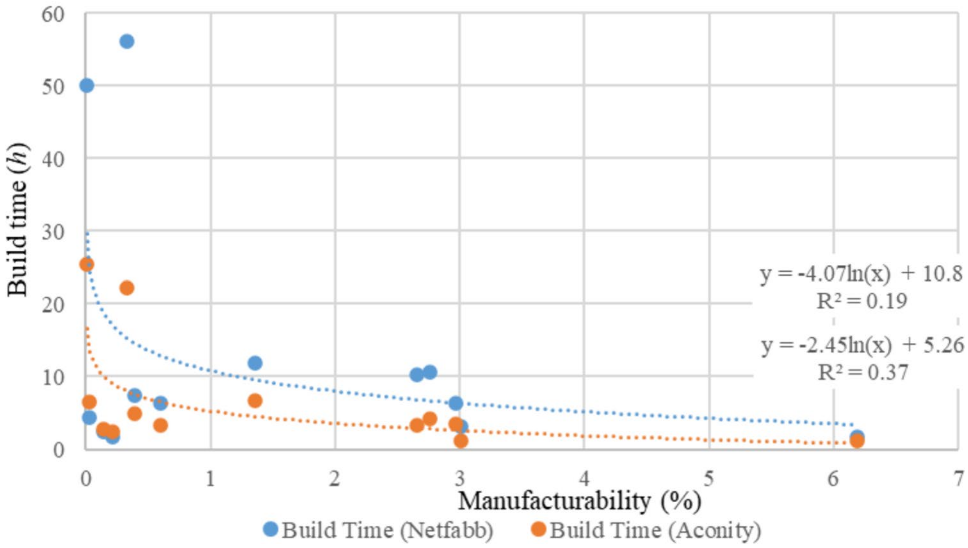
Table 6 Process cost and total cost calculation of case studies

Case	Part name	Part height (h) mm	Part volume (V_P) cm^3	Surface area cm^2	Process cost (€)	Total cost (€)
1	GE model 24v3	62.5	101	528	832	1160
2	Inner cone-RC plane gas turbine	40.0	1.39	70.4	136	346
3	Combustor rear-RC plane gas turbine	8.00	1.28	66.5	39.0	249
4	Gyroid unit cell	14.5	0.24	12.9	47.0	256
5	Turbo propeller	60.0	125.0	409	938	1290
6	Intake-RC plane gas turbine	23.6	12.0	105	157	380
7	Front case-RC plane gas turbine	12.0	13.4	141	137	362
8	Compressor-RC plane gas turbine	24.5	23.7	75.3	222	460
9	Pulley-gt2-6–60-tooth-8-bore-gt2-1	15.8	12.3	51.2	127	351
10	Case rear-RC plane gas turbine	5.00	5.72	81.3	62.0	278
11	bcc1	7.68	25.0	181	197	436
12	CP-Cubic primitive	7.68	24.1	139	185	423
13	FBCC unit cell	12.0	0.86	13.4	43.0	253

sharp corners and edges, which depend on post-processing planning in different companies and purposes. The correlation between the build-rate efficiency and the volume ratio of the part appears logical and consistent, supporting the validity of the evaluation method. To quantify reliability, the build time was compared with the manufacturability to check the reliability of the framework as shown in Fig. 12.

Figure 12 shows the relationship between manufacturability and build time, using data from two different software tools: Netfabb and Aconity. The build times from Netfabb are represented by blue dots, whereas those from Aconity are shown as orange dots. To capture the trend in each dataset, a logarithmic curve was fitted to Netfabb and Aconity. Both trend lines show a negative relationship, which means that

Fig. 12 Comparison of manufacturability, and build time

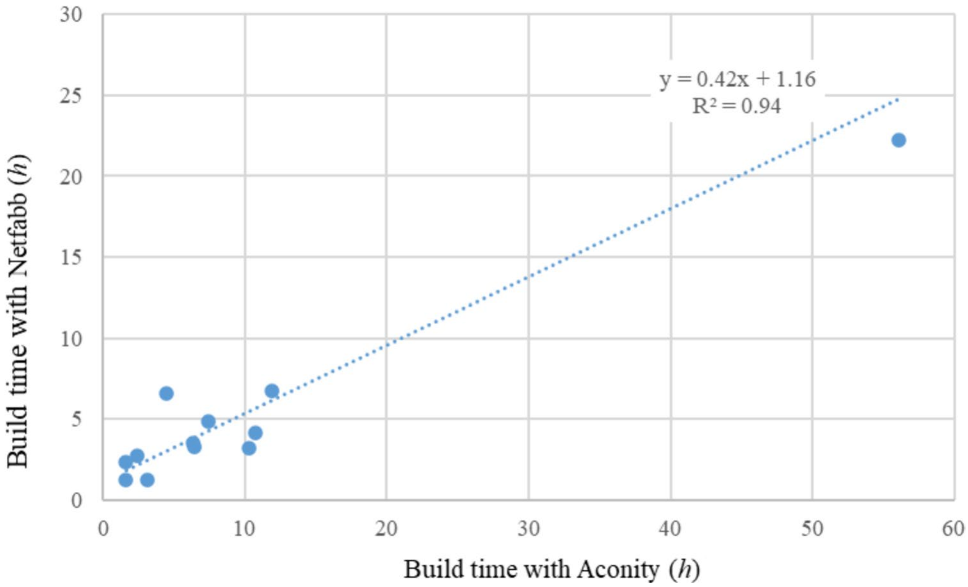


as the manufacturability increases, the build time tends to decrease. This supports the reliability of the manufacturability framework, particularly with the Aconity software, as it demonstrates a clearer and more consistent link between manufacturability scores and reduced build times. The comparison of build time between Netfabb and Aconity was made, as illustrated in Fig. 13.

Figure 13 presents a scatter plot comparing the build time estimates generated by Aconity and Netfabb software. In this figure, the x-axis represents the build time estimated by Aconity (in hours), while the y-axis shows the corresponding build time estimated by Netfabb (in hours). Each data point on the graph corresponds to an individual part. A dotted trend line is included to indicate the overall relationship between the two data sets. The trend line shows a strong positive linear correlation, with an R^2 value of 0.94, which is close to 1 suggesting that, in general, as build times calculated by Aconity, they also tend to increase proportionally in Netfabb. However, the correlation is not perfect, particularly at longer build durations of 50.0 h, deviate from the trend line. These deviations may be attributed to differences in the algorithms that each software uses to calculate build times, potential simplifications in one of the tools, or additional processing factors that one software accounts for while the other does not. This analysis highlights both the consistency and variability in the way different software platforms estimate build times for additive manufacturing.

In this study, various research articles on manufacturability evaluations were reviewed. The study was limited to the effect of process parameters on the assessment of manufacturability. The study aimed to establish a preliminary numerical framework to evaluate manufacturability considering

Fig. 13 Comparison of build time with 'Netfabb' and 'Aconity' software



layer thickness as one of the most critical parameters that affects the manufacturability of complex geometrical parts. Several existing studies reviewed various approaches to assess manufacturability; however, no research reported assessing complex geometrical parts considering the process parameter numerically. Therefore, more research is needed to provide a numerical framework for industrial and academic applications to be observed. The primary result of this study was the numerical evaluation of the manufacturability with the most critical process parameter of PBF-LB/M, such as the layer thickness. This study evaluated 30 cases of complex geometric parts, as shown in Table 7. The manufacturability of complex geometric parts is carried out successfully and can be interpreted numerically. Second, the article illustrated various existing studies to evaluate the manufacturability of complex geometrical parts. Several studies have been conducted on manufacturability evaluation, which can be categorized as feature-based and knowledge-based approaches. The results of various methods are represented by color coding, numerical range, and pass or fail basis. The limitations of the existing literature and the advantages of the numerical framework for evaluating manufacturability are shown in Table 7.

Table 7 shows the requirement of the numerical framework to evaluate manufacturability by considering process parameters to obtain accurate results without human knowledge variation; however, no research was carried out in this way. Furthermore, this study revealed that the manufacturability of complex geometric parts can be numerically evaluated considering the process parameters such as layer thickness. Step-by-step guidelines are provided to the user to eliminate the effect of variation in human knowledge on the results, as shown in Fig. 10.

5.1 Multilayer vs. single-layer model

This study is useful for single-layer and multilayer applications. According to Eq. 23, the average layer thickness must be considered for multilayer conditions. The thickness of the top layer can be reduced depending on the complexity requirement of the features. Similarly, the thickness of the bottom layers can be increased according to the requirement of the surface finish [22]

5.2 Ideal manufacturability condition

The ideal manufacturability in the PBF-LB/M process is a theoretical state of 100% efficiency, achieved when the layer thickness equals the part height and the part fully occupies its bounding box, indicating minimal complexity and build time, as shown in Eq. 22. Here, the ideal cycle time serves as a benchmark for the shortest possible build under perfect conditions, helping to identify inefficiencies and guide process optimization and production planning.

5.3 Limitations and implications of research

This research is limited to a preliminary evaluation of manufacturability focused specifically on the effects of layer thickness and geometric complexity in terms of overall build time. Other important factors, such as quality-related aspects, material properties, process parameters, and machine-specific parameters, have not been considered at this stage. The authors acknowledge the significant impact these factors can have on the results of manufacturability and intend to incorporate a more comprehensive analysis of these parameters into future studies.

6 Conclusion

This study reviewed existing research on the evaluation of manufacturability using different approaches and highlighted the importance and limitations of these methods in the evaluation of preliminary manufacturability. Among the key findings, layer thickness emerged as a crucial process parameter, especially in the context of complex geometrical parts manufactured through the PBF/LB-M process. The methodologies reviewed were classified into feature-based and knowledge-based evaluations, with the latter requiring systematic improvements to minimize variations arising from human judgment. To address these concerns,

Table 7 Limitations of existing approaches and advantages of the numerical framework for evaluating manufacturability

Limitation of the existing literature	Advantages achieved
Quantification cannot be done; the result is based on manufacturability or not on color coding in the CAD file [26]	Quantification of the possible result for the comparison of manufacturability between two or more parts is possible
The contribution of the process parameter cannot be evaluated; the manufacturability is based on the complexity of the part [42]	Contribution of process parameters: the thickness of the layer can be evaluated, which is one of the most critical process parameters for the build rate and manufacturability
Manufacturability is based on the complexity of the porous structure; solid structures cannot be evaluated [31]	In addition to porous structures, solid structures can also be evaluated with the same method. Comparison of the manufacturability of the design of parts is easy

a preliminary numerical framework was developed that integrates layer thickness as a key process parameter. The framework includes step-by-step guidelines to ensure consistent execution and was validated by comparing process cost, total cost, and build time simulations using AMOTool, Aconity, and Netfabb software tools, respectively. Experimental results demonstrated that shorter build times are associated with higher manufacturability, reinforcing the effectiveness of the framework.

Furthermore, this study emphasizes the importance of layer thickness and component complexity in evaluating manufacturability and proposes a structured approach that can be applied in both industrial and research settings. The developed framework offers a practical tool to control part complexity during the design stage, helping organizations meet specific goals related to cost efficiency and timely delivery. Looking ahead, there is significant potential to extend this work by incorporating additional influential parameters such as build rate, quality control measures, and post-processing requirements. Such enhancements will be essential to meet the increasing demand for highly complex parts in the additive manufacturing industry, where precision, efficiency, and scalability are continuously evolving [59].

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Declarations

Conflict of interests The authors declare no competing interests.

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