A MULTI-CRITERIA DECISION-MAKING APPROACH TO OPTIMIZE THE PART BUILD ORIENTATION IN ADDITIVE MANUFACTURING

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ABSTRACT

The part build orientation is a manufacturing variable that must be considered when designing a product to maximise AM opportunities. There are several approaches to selecting the best print direction in the scientific literature by considering different criteria. However, most of the studies are focused on specific AM technologies. It is missing a general method that evaluates a widespread number of criteria. Furthermore, such approaches expect designers establish weights for technical criteria that are too specific, especially during the preliminary design steps. Designers are familiar with criteria like cost-effectiveness, productiveness, quality and mechanical strength.

The paper presents a multi-criteria decision-making approach to optimise the build part orientation in additive manufacturing. The method considers five decision-making criteria (cost-effectiveness, rapidity, productiveness, quality and mechanical strength) and seventeen specific technical criteria. TOPSIS is the method used to optimise the build part orientation. A case study of three components exemplifies the five steps of the procedure.

Keywords: Design for Additive Manufacturing (DfAM), Additive Manufacturing, Decision making, TOPSIS, Build Part Orientation

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1 INTRODUCTION AND LITERATURE REVIEW

During the past ten years, the engineering community has become aware of Additive Manufacturing's (AM) potential to revolutionise product development. The working principle of AM is to create layer by layer a three-dimensional object. Finding the best build orientation, along which material is added, is crucial. For example, economic feasibility, quality, and mechanical strength depend on the direction. The orientation difficulty in AM process planning is the decision of the best direction to add materials (Zhang et al., 2017). Determining the part orientation is crucial since it directly impacts component properties such as surface quality (Vasudevarao et al., 2000), mechanical strength, fabrication cost, and build time (Gupta et al., 1999). Thus, part orientation is a problem that design or production engineers face when they want to produce components. To solve the part orientation issues in various AM processes, it is necessary to consider several variables. Often, the optimal direction for one variable is not the best for another. Hence, the optimal direction is the right compromise. The part's optimal orientation comes from a multi-criteria decision approach.

In literature, several multi-criteria methodologies and algorithms have been developed to evaluate the best printing direction for controlling different performances of AM processes. (Singhal et al., 2005) aims to obtain the lowest possible average part surface roughness for Stereolithography-processed parts by selecting the best part deposition orientation. The optimisation issue was minimising surface roughness using a traditional Trust Region method-based approach. Another methodology only for SLA technology is proposed by (Kim & Lee, 2005). The proposed method defines the post-processing time and cost as a function to be minimised. Interest in the optimal printing direction for FFF technology is shown in (Masood et al., 2000). In this case, an analytical methodology is developed to define the optimal orientation according to a single criterion: the volumetric error. Surface quality is the only criterion evaluated exclusively by (Delfs et al., 2016) for SLS technology. The method is based on finding the optimal direction that minimises surface roughness.

(Brika et al., 2017) presents a method in which eight criteria for powder bed fusion by laser (L-PBF) technology are evaluated. They used an integrated technique to optimise the mechanical characteristics (elongation, hardness, tensile and yield strength), surface roughness, the quantity of support structure, and build time and cost. The part's geometry analysis has been utilised to estimate the required support and assess the build time and cost. To solve the multi-objective optimisation issue using a genetic optimisation method, normalised weights are assigned to various objectives based on their relative relevance.

Instead, several technologies were evaluated simultaneously by (Li & Zhang, 2013) to choose the optimal direction using a multi-objective approach. A multi-sphere system was formulated in the methodology to optimise the construction orientation of an AM component. The optimisation considers two criteria: the volume and model height. Then, Pareto analysis is used to identify the optimal part orientation.

The literature review clarifies that finding the optimal component orientation in AM processes is widely investigated. Unfortunately, these studies do not provide methods considering a broad and transversal set of technical criteria applicable across different techniques. Approaches are mainly focused on single AM processes. Furthermore, build part orientation methods rely on too specific technical criteria (e.g., support volume, overhang area, height). Often, designers do not know the relative importance of these criteria to get the best print direction. They are much more familiar with decision criteria related to the design context, like cost, time, productiveness, quality, mechanical strength, etc. Thus, it is requested that designers set weights to these last decision criteria rather than technical ones. Then, the method for selecting the optimal build part direction has to assign these weights to the specific criteria, following a correlation map. Furthermore, designers must compare different AM processes to select the best one. In this phase, the weights should be dynamically assigned to the technical criteria. For example, Selective Laser Sintering does not need support. Thus, this technical criterion is irrelevant to defining the build orientation.

The paper proposes a method for selecting the best build part orientation through a Multi-Criteria Decision Making (MCDM) approach. It allows design engineers to set relative importance to high-level decision criteria. Depending on the AM technology, these weights are transferred to a list of specific technical criteria. This assignment depends on the AM process (e.g., the cross-sectional area gradient is most important for Laser-Powder Bed Fusion). The scores are given to the criteria through

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geometric algorithms, considering the specificity of each AM technology. (e.g., when supports are not required, directions have the same score). The method considers many criteria applicable to almost all the AM processes.

2 BUILD PART ORIENTATION CRITERIA

The definition of the best part orientation during the design phase should consider criteria easily identifiable by designers. Often, design engineers must consider how to orient a part before or during the design phase. For example, with a proposer shape, supports can be avoided, surface quality can be improved, etc. Specific and detailed technical criteria (e.g., the volume of supports and overhang area) must be avoided at this stage because design engineers cannot quickly establish relative weights. Engineers are much more familiar with criteria related to the product's technical specifications rather than the manufacturing process.

2.1 Decision-making criteria

This section presents a list of general decision-making criteria for whose designers can set weight. For each decision-making criterion, it will be possible to link one or multiple technical criteria.

1. *Rapidity*: time required for manufacturing a single part.
2. *Cost-effectiveness*: cost required for manufacturing a single part.
3. *Productiveness*: number of parts to be realised in a certain amount of time.
4. *Mechanical strength*: mechanical strength required by the part.
5. *Quality*: surface quality (e.g., roughness) of the non-machined surfaces.

2.2 Technical criteria

The part orientation should evaluate multiple technical criteria. Here is a list of recommendations that should be considered to optimise production time and cost, productiveness, part strength and quality. Such guidelines result from a scientific survey on building part orientation in additive manufacturing.

1. *Part shadow on build plate [mm²]*: projected area of the part on the build plate. A reduced part shadow improves the nesting of the pieces, thus, the production capacity.
2. *Bounding box on the build plate [mm]*: width and length of the bounding box on the build plate. This criterion is similar to the part shadow that does not account for the external shape of the part.
3. *Print height [mm]*: maximum part dimensions along the print direction. For several production processes, the greater the high, the longer the print time.
4. *Bounding box volume [mm³]*: volume of the bounding box oriented as the build chamber.
5. *Packing density [%]*: percentage of the print volume taken by the printed parts. This value depends on the part shape (e.g., area/volume ratio) and manufacturing process (sometimes, there is a maximum threshold).
6. *Volumetric error [mm³]*: the deviation between the volume of materials needed for model fabrication and that theoretical model occupies. This criterion is linked to the staircase effect and surface roughness. This value is computed for each face and compared with the relative tolerance to verify a suitable direction. The volumetric error for the entire part is the average error on all the faces.
7. *Surface roughness (on non-machined surface) [μm]*: surface finish related to the staircase effect of additive manufacturing, which depends on surface inclination and layer thickness. According to the specific printing process, exact formulas may be used for a more precise evaluation (e.g., for FFF, roughness can be evaluated considering the arithmetical mean deviation of the manufactured profile from the expected smooth profile (di Angelo et al., 2020)). The staircase effect is removed if the surface is machined and cannot be considered in part orientation. As the volumetric error, this parameter is computed for each face to verify compliance with the required roughness. The surface roughness for the entire part is the average roughness on all the faces.
8. *Overhang area (on non-machined surface) [mm²]*: area of the surfaces those normals have an angle from horizontal over a threshold (this value depends on the print technology, material and printing parameters). These surfaces must be supported for some processes to avoid part deformation during the fabrication. The "non-machined" term limits the analysis only to those overhang surfaces that are not machined. For metal and functional parts, surfaces must be

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machined to guarantee tolerances and roughness. If overhang surfaces must be machined, the poor surface quality deriving from the support is not an issue.

9. *Support volume [mm³]*: volume of support structure on overhang surface to prevent deformation.
10. *Volume of supports difficult to remove [mm³]*: quantity of support volumes in regions with limited access. There are many post-processing technologies where supports are removed through chemical and electrochemical techniques. In these cases, it is enough to guarantee a proper media flow to remove material in the supported regions. However, other additive manufacturing processes require mechanically removing supports through tools. In such cases, supports must be located in easily accessible areas for cutting tools.
11. *Cross-sectional area gradient [%]*: to prevent shrink lines, a part should be oriented to avoid abrupt cross-sectional area variation. This criterion measures the maximum percentage variation of the cross-sectional area between two consecutive slices.
12. *Orientation of datum surfaces [°]*: maximum angle between the print direction and surface normal of geometries used as a datum for machining operations. To reduce the deformation of datum surfaces, these must be oriented vertically.
13. *Orientation of holes [°]*: maximum angle between the holes axes and print direction. Through and threaded holes axis should be aligned along the print direction.
14. *Part orientation to the recoater [°]*: angle between the recoater (when existing) and the edges of a part. The direction should be set to avoid having long-walled parts parallel to the recoater. This situation will cause the recoater to run into a significant obstacle suddenly.
15. *Mechanical resistance [°]*: additive manufacturing is inherently an anisotropic process. For example, FFF parts exhibit reduced strength along the build direction caused by the bonding strength between layers. This criterion indicates the angle between the print and force directions.
16. *Process time [min]*: total production time required for printing and post-processing operations.
17. *Process cost [€]*: total production cost required for printing and post-processing operations.

2.3 Constraints

The part orientation must consider manufacturing constraints that depend on the company's business plan (e.g., production volume) and production facilities (e.g., technical features of 3D printers).

1. *Bounding box dimensions [mm]*: the part must be oriented to fit within the print volume.
2. *Target cost [€]*: the total manufacturing cost must be lower than the target cost.
3. *Production capacity [parts/hour]*: the total manufacturing time must be lower than a target to guarantee the required production capacity.

3 METHODOLOGY

This study aims to define a methodology that, depending on the production scenario, provides the optimal orientation independently of the AM technology. In detail, the designer establishes the production context through input. The chosen scenario provides weights (i.e., importance) to the different criteria for the final choice of printing direction (3.1). Next, the criteria values are extrapolated, and the geometric and non-geometric data related to the orientations assumed by the part are collected (3.2). Thus, the collected data is compared with the process constraints, showing the non-executable directions (3.3). The remaining orientations are then evaluated to define the optimal one through the proposed multi-criteria decision-making method (3.4).

3.1 Design and production requirements

The first step of the methodology starts with the input. In detail, the information required is as follows:

- *Component 3D model*: it is the virtual model prototype to evaluate and extract all its geometrical characteristics and unique features. The information extracted will then be necessary for the implementation of the method.
- *AM technology and printer machine used*: to assess the optimal direction is necessary to know the AM process. Its operating principle defines which criteria to consider, how to attribute the value of each one and the relative weight. For example, the presence of supports structure is directly related to the overhang surface criteria. SLA technology requires support in constructing the part, while SLS technology does not. If a piece is to be produced quickly with SLA technology, the presence of supports must be reduced, thus minimising the surface area in the overhang.

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On the other hand, producing a part quickly with SLS technology requires minimising the component's height in the printing direction. In the first case, the overhang surface criterion is more important. In the second case, the height criterion in the z-direction is more critical. It is also essential to define the characteristics of the printer. In detail, information on the dimensions of the printing chamber makes it possible to assess which orientations can be carried out and which can be discarded. In addition, technical data such as machine cost and printing speed are necessary to define criteria such as production cost.

- *Part material*: information on the material influences criteria such as printing cost and time.
- *Orientation angle accuracy*: the part can assume infinite orientations within the printing chamber. This parameter makes it possible to limit alternatives and, thus, how much to rotate the component at each step. A high value allows a low computational load but low accuracy in finding the best orientation. A high value loads the computational phase but allows more precise solutions. It is possible to apply the method several times around the sub-optimal directions initially found, thus keeping the computational load low.
- *Force application direction*: it gives the user an indication of the anisotropy that will occur in parts made in different orientations. This parameter guides the choice based on the possible need for mechanical resistance in a given direction.
- *Process constraints*: this prevents the method from considering printing directions that do not satisfy certain conditions as optimal. The conditions are printing chamber width, length and height, production time and production cost. The first three relate to the printer's characteristics and eliminate orientations that exceed the size of the printing chamber. The last two assist if the user has unique requirements. For example, the necessity to produce a part quickly or to evaluate if building a prototype with AM technologies is economically competitive against the traditional method.
- *A minimum number of parts per printing volume*: it allows the user to evaluate the printing of a batch of parts. By setting the minimum number of elements, the user asks the method to propose only those solutions that allow a more significant number of pieces than the one set.
- *Definition of printing context*: the user defines the scenario in which to print the component through five macro areas: (i) *rapidity*, (ii) *cost-effectiveness*, (iii) *productiveness*, (iv) *high quality* and (v) *mechanical strength*. Therefore, the user expresses the importance of the different macro areas by rating from 1 to 10.

3.2 Criteria evaluation

After introducing the different inputs, all the technical seventeen criteria are valorised by elaborating the input data. Here is an excerpt of how to evaluate some of the criteria listed in §2.2.

1. *Total process cost*: the total process cost was defined by developing and implementing analytical cost models for the different technologies. (Mandolini et al., 2023) presented the analytical cost model structure example used to evaluate the process cost. Cost models are based on process time estimation. By correlating machine, energy and material costs, cost information can be described by four cost items:

$$C_{tot} = C_{material} + C_{machine} + C_{operator} + C_{energy} \tag{1}$$

   This criterion is strongly related to the macro area of the economy.
2. *Total process time*: this parameter considers machine set-up time, build time and time for post-processing operations. In this study, only set-up and build time were evaluated. The values were extracted directly from the analytical cost models. Alternatively, they can be obtained from 3D printing software tools. This criterion is strongly related to macro-area rapidity.
3. *Bounding box on the build plate*: the size of the shortest and longest side of the component on the printing plate. It allows evaluation of how many parts can be placed on the printing plate at each orientation. It also provides an assessment of the component fit in the chamber platform. This criterion is strongly related to productivity.
4. *Print height*: each orientation defines different heights of the component. This criterion strongly correlates with speed and economy.
5. *Overhang area*: criterion that defines which surfaces need support. This criterion is strongly correlated with quality and rapidity

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6. *Bounding box volume*: depends on the projected area on the printing platform and the height assumed by the component. So this criterion defines the volume that encloses the piece at each orientation. This criterion allows the packing density to be determined.
7. *Packing density*: a factor is identified by a percentage. It indicates the actual footprint of the part inside the printing chamber. It is calculated by taking the ratio between the volume of the component and the footprint volume. This criterion is of considerable importance when printing not just one piece but a group. It is, therefore, strongly related to productivity and the economy.
8. *Support volume*: criterion that defines the volume of support required for each orientation. This information is obtained directly from the software, depending on the technology used. This criterion is strongly correlated with quality and rapidity.
9. *Mechanical resistance*: it is evaluated with the load's direction and the deposition layer at each orientation. The mechanical strength of the bond between each layer can be weaker than the mechanical strength within the layer itself. So, the resistance score is maximum (10, on a scale from 1 to 10) when the layer is parallel with the load direction. A perpendicular arrangement gets the minimum score (value 1). This criterion is strongly related to the macro area's mechanical strength.

Criteria 3, 4, 5, 6, 7 and 8 can be evaluated using 3D printing or nesting software.

3.3 Manufacturing constraints

This step makes it possible to assess which orientations are not executable and must be eliminated. In detail, all orientation information calculated in the criteria evaluation step is compared with the process constraints defined in the input. The method then assesses whether the values for each orientation are within the acceptable range. Directions that obtain a positive evaluation in all comparisons are still valid for the next steps.

3.4 Multi-criteria optimisation

This step is the main phase of the method and leads to the definition of the optimal direction. The objective is to identify the best direction based on several criteria; therefore, a multi-criteria choice method is required. The proposed methodology is based on the TOPSIS method (Technique for the order of Preference by Similarity to Ideal Solution). This system offers as optimal the alternative that is geometrically closer to the positive and negative ideal solution (Behzadian et al., 2012). The positive one maximises the benefit criteria and minimises the loss criteria. In contrast, the negative one maximises the loss criteria and minimises the benefit criteria. The two ideal positive and negative solutions are identified by analysing the data within a matrix.

This step consists of 6 sub-steps:

1. The first step is to collect, for each orientation, all the criteria values defined in §3.2 within a matrix. Each criterion is represented by a column vector enclosing all the importance of the different directions for that criterion.
2. Then each column vector (i.e. each criterion) is normalised.

$$b_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \tag{2}$$

   The normalisation takes place through the ratio of the value of the i-th orientation of the j-th criterion (a_{ij}) and the vector column modulus $\sqrt{\sum_{i=1}^{n} a_{ij}^2}$, with n number of orientations. The value b_{ij} is the normalised value of the i-th orientation of the j-th criterion. All values are then normalised, resulting in a new matrix with normalised column vectors.
3. In step 3.1, the importance of being associated with each macro-area is expressed as input. Each macro-area is linked, depending on the technology, to different criteria. Therefore, the input provided is transmitted to the criteria as weights. In this sub-stage, the importance of each criterion (p_k) is multiplied by the normalised value of each orientation (b_{ij}) contained in that criterion:

$$c_{ij} = b_{ij} \cdot p_k \tag{3}$$

   A new weighted matrix is obtained by operating for each value of the normalised matrix.

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4. Next, the optimal solutions for each criterion are found. Each criterion is a function for which the value that maximises or minimises it is sought. For example, the process time criterion should be kept as low as possible, so it should be minimised. The packing density criterion should be maximised. Therefore, for each column vector of the weighted matrix, two orientations are identified: the one that maximises that criterion and one that minimises it. These represent the ideal solutions (positive and negative) of each criterion.
   So, for each weighted value of the orientation (c_{ij}) contained in the criterion column vector, the geometric distance ($d_{ij}^{+;-}$) is calculated against the coefficients of the positive (s_{ij}^{+}) and negative (s_{ij}^{-}) ideal solution.

$$d_{ij}^{+} = \left(c_{ij} - s_{ij}^{+}\right)^2 \text{ and } d_{ij}^{-} = \left(c_{ij} - s_{ij}^{-}\right)^2 \quad (4), (5)$$

5. The values obtained at sub-step 5 are shown in two tables; one for the distance with the positive ideal solution and one with the negative ideal solution. Thus, the geometric distance with the different criteria can be observed for each orientation. At this point, the geometric distance between the positive ideal solution (S_i^{+}) and the negative ideal solution (S_i^{-}) of each orientation i is calculated.

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} d_{ij}^{+}} \text{ and } S_i^{-} = \sqrt{\sum_{j=1}^{n} d_{ij}^{-}} \quad (6), (7)$$

6. The last step provides the optimal orientation. It is obtained through the following expression:

$$V_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \quad (8)$$

   where the optimal alternative is the one that obtains a higher score of V_i. A table indicates the best orientation (i.e., the optimal solution). Repeating the method around the optimal solution and refining the angular accuracy is possible.

4 CASE STUDY

4.1 Problem

The case study was set in cooperation with a 3D printing company that has provided the components and established the two scenarios (rapidity and mechanical strength, Table 1).

Table 1. Weights for the rapidity and mechanical strength scenarios

Scenarios	**Related Technical Criteria**	**Objective**	*Weights of scenarios on the technical criteria*			
			Rapidity Scenario		**Mechanical Scenario**	
			Evaluation	**Weight**	**Evaluation**	**Weight**
Rapidity	Process Time	Minimise	6	0.6	1.33	0.13
Cost-effectiveness	Process Cost	Minimise	2	0.2	1.33	0.13
Productiveness	Packing Density	Maximise	1	0.1	1.33	0.13
Mechanical strength	Mechanical resistance	Maximise	1	0.1	6	6

Table 1 shows the technical criteria used to evaluate the considered scenarios; the objective criterion function gives their correlation with the related scenarios. For example, the rapidity scenario minimises the process time criterion as the objective function. So, in this case, process time has the highest weight. Mechanical resistance is the most critical technical criterion for the mechanical strength scenario. So it has the highest importance. It should be noted that the "High quality" scenario was not considered in the case study. No algorithms and tools were available to obtain information about the component roughness for various configurations.

These two scenarios were evaluated through three components (Table 2), processed with four AM technologies and four materials. Thus, 12 case studies were analysed. The technologies and materials considered are Laser Powder Bed Fusion (L-PBF) and Inconel 718; Direct Energy Deposition (DED) and AISI 316; Selective Laser Sintering (SLS) and Polyamide PA; Fused Filament Fabrication (FFF) and ABS.

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Table 2. Case study components

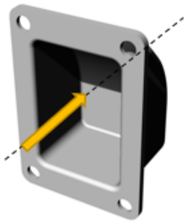
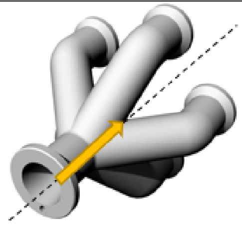
Wheel	Cup	Manifold
		

Table 2 shows the direction of the loads (torques and forces) to evaluate mechanical strength.

4.2 Results and discussion

This chapter presents the intermediate results of the method steps for component "Cup" with L-PBF technology and the rapidity scenario. The final optimum orientations are given for the remaining technologies by considering both scenarios. Table 3 shows the directions considered (those not meeting the process constraints are already excluded) and the criteria defined in Chapter 3.2 with the corresponding calculated values. The orientations represent the relative position between the component and the printing plate. The technical criteria shown in Table 3 were collected using Netfabb (by Autodesk) and reported in a Microsoft Excel spreadsheet. Once the data collection (step 1) is complete, the matrix is normalised (step 2) using equation (2). Next, the weighted matrix (step 3) is constructed using equation (3) by associating the weights with the criteria in Table 3.

Table 3. Data collection for component "Cup" with L-PBF technology, Inconel 718 material

				Technical Criteria										
				Manufacturing Constraints										
				Process Time [h]	Process cost [€]	Width Bounding Box Smaller Size [mm]	Length Bounding Box Larger size [mm]	Print height [mm]	Overhang area [mm²]	Part shadow [mm²]	Bounding box volume [mm³]	Support volume [mm³]	Packing density [%]	Mechanical resistance
Row	Orientations			60 [h]	5500 [€]	250 [mm]	250 [mm]	325 [mm]	-	-	-	-	-	-
	x	y	z											
1	0	0	0	44,5	€ 4.707	60	90	130	4771,60	4295,41	558403,30	162074,00	22,75%	10
2	90	0	0	47,1	€ 3.528	90	130	60	9178,20	11332,00	679920,00	218239,80	18,68%	4
3	180	0	0	54,6	€ 5.192	60	90	130	4532,00	4295,39	558400,70	249488,90	22,75%	10
4	0	90	0	57,1	€ 4.568	60	130	90	8732,60	5457,67	491190,30	290686,30	25,86%	4
5	0	180	0	54,6	€ 5.192	60	90	130	4532,00	4295,41	558403,30	249498,40	22,75%	10
6	0	0	90	44,5	€ 4.707	60	90	130	4771,60	4295,41	558403,30	162074,00	22,75%	10
7	0	0	180	44,5	€ 4.707	60	90	130	4771,60	4295,41	558403,30	162074,00	22,75%	10
8	45	45	45	26,9	€ 3.786	104,36	150,85	125,68	137,30	10291,99	1293497,30	12505,40	9,82%	7
9	45	45	135	26,9	€ 3.786	104,36	150,85	125,68	137,30	10291,99	1293497,30	12505,40	9,82%	7
10	45	135	45	26,0	€ 3.744	104,36	150,85	125,68	305,50	10292,70	1293586,54	4867,50	9,82%	7
11	135	45	45	26,4	€ 3.958	97,75	150,85	136,30	32,00	9208,19	1255076,30	2845,00	10,12%	7
12	45	135	135	26,0	€ 3.744	104,36	150,85	125,68	305,50	10292,65	1293580,25	4867,70	9,82%	7
13	135	45	135	26,4	€ 3.958	97,75	150,85	136,30	32,00	9208,25	1255084,48	2844,60	10,12%	7
14	135	135	45	26,5	€ 3.966	97,75	150,85	136	128,70	9210,99	1255457,94	4145,10	10,12%	7
15	135	135	135	26,5	€ 3.966	97,75	150,85	136	128,70	9211,04	1255464,75	4154,10	10,12%	7

Table 4 represents the results of the different steps. Table 4, from A to D, represents a normalised, weighted matrix. This step identifies the criteria' positive and negative ideal solutions according to the weights initially set.

In detail, through equations (4) and (5), the geometric distances of each orientation and each criterion from the positive and negative ideal solution are calculated (step 4). The positive and negative geometric distances of each analysed direction from the positive and negative ideal solution are then calculated (step 5) using equations (6) and (7). Results are shown only for the positive solution in Table 4, column E. Once the geometric distances of each orientation have been defined, the optimum direction is evaluated (step 6) using equation (8). Table 4, column F provides the values.

As seen in column F, the optimal solution is the one with orientation (45°,135°,135°). The optimal orientation is rated similarly to another direction (45°,135°,45°). This result is because the two orientations are the same but with a 90° rotation about the z-axis. The method could be reapplied for a detailed study of the best solutions to find the optimal printing direction.

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Table 4. Results of different steps for "Cup"

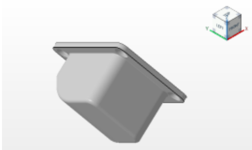
				A	B	C	D	E	F
			Criterion	Process Time	Process cost	Packing density	Mechanical resistance		Results
			Weights	0,60	0,20	0,10	0,10		
Row	Orientations								
	x	y	z						
1	0	0	0	0,00380	0,00016	0,00002	0,00001	0,06310	0,43703
2	90	0	0	0,00495	0,00000	0,00008	0,00042	0,07386	0,34916
3	180	0	0	0,00912	0,00031	0,00002	0,00001	0,09723	0,20802
4	0	90	0	0,01082	0,00012	0,00000	0,00042	0,10656	0,16822
5	0	180	0	0,00912	0,00031	0,00002	0,00001	0,09723	0,20800
6	0	0	90	0,00380	0,00016	0,00002	0,00001	0,06310	0,43703
7	0	0	180	0,00380	0,00016	0,00002	0,00001	0,06310	0,43703
8	45	45	45	0,00001	0,00001	0,00042	0,00014	0,02394	0,44285
9	45	45	135	0,00001	0,00001	0,00042	0,00014	0,02394	0,81068
10	45	135	45	0,00000	0,00001	0,00042	0,00014	0,02371	0,81642
11	135	45	45	0,00000	0,00001	0,00042	0,00014	0,02371	0,81068
12	45	135	135	0,00001	0,00001	0,00042	0,00014	0,02394	0,81649
13	135	45	135	0,00000	0,00002	0,00041	0,00014	0,02374	0,80649
14	135	135	45	0,00000	0,00001	0,00042	0,00014	0,02371	0,81042
15	135	135	135	0,00000	0,00002	0,00041	0,00014	0,02374	0,81070
	Objective Criteria Function			Minimise	Minimise	Maximise	Maximise		
	Ideal positive solution			0,0870	0,0374	0,0331	0,0321		
	Ideal negative solution			0,1910	0,0551	0,0126	0,0117		

For the same component but the remaining technologies, the optimal directions are listed in Table 5. It is important to note that for each technology and each scenario, the criteria may have different importance (i.e. weights).

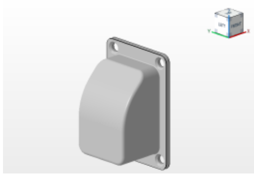
Table 5. Optimal build print directions for component "Cup", L-PBF process

	Rapidity	Mechanical strength
L-PBF	45°,135°,135°	0°,0°,90°
DED	180°,0°,0°	180°,0°,0°
SLS	90°,0°,0°	180°,0°,0°
FFF	135°,135°,135°	0°,0°,0°

Rapidity
45°,135°,135°



Mechanical strength
(0°,0°,90°)



The proposed study aims to develop an approach that can provide the optimal printing direction regardless of the technology used, considering the fundamental criteria of 3D printing. Currently, studies in the literature focus on developing algorithms focused on specific technologies and criteria. This method overcomes this limitation and lays the foundations for creating a tool that assists the designer from the early design stages. The procedure was tested with four different AM technologies. From the results, it is possible to observe that the optimal direction changes depending on the technology and the production context (scenario). Furthermore, the results achieved lend credit to the method. For example, for the mechanical strength scenario, the directions obtained for L-PBF and the others align with the theoretical concepts in Chapter 2. The proposed approach currently needs to be more automated. The data fueling each criterion were extrapolated and calculated manually, which is a limitation of the method.

5 CONCLUSIONS

The paper presented a multi-criteria decision-making method for defining the build print orientation in additive manufacturing. The approach consists of five high-level decision-making criteria (i.e., rapidity, cost-effectiveness, productiveness and mechanical strength), whose relative importance can be set by designers. These criteria are linked to many specific technical ones (e.g., print height, bounding box volume, overhang area) connected to the geometry of the printer part. Such a solution allows design engineers to easily set weights to a few high-level criteria rather than many specific ones. The methodology was conceived to be independent of AM technology. Furthermore, the paper

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presented a vast list of technical criteria by summarising those available in the literature. The TOPSIS method was used as an MCDM method.

A case study based on three components, four AM technologies and four materials was included to exemplify the method. Not all the technical criteria were considered since the unavailability of algorithms for evaluating them. Moreover, the methodology should be improved to manage better those technical criteria whose values change on the surface (i.e., volumetric error and surface roughness).

Future work on this subject should aim to improve the build orientation methodology by considering a multi-step approach. At first, a set of sub-optimal directions should be computed by considering simple (quick to assess) technical criteria and rough angular resolution. Then, optimal orientations will be evaluated by considering the remaining technical criteria and refining the angular resolution. Genetic algorithms may help the entire methodology by reducing the computational effort. The procedure can be structured with alternative MCDM approaches (e.g., AHP- Analytical Hierarchy Process) to evaluate what is the best performing.

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