Methodology for Part Building Orientation in Additive Manufacturing

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Abstract. This paper presents a methodology to position a part built in additive manufacturing. The proposed methodology handles several criterion including volume of support, surface quality, building time and cost. The objective is to minimise these criteria in each position selected by the user. The weighting of these criteria, chosen by the user, helps to compute an index for each position and leads to a part orientation in order to prioritize a criterion rather than another. The minimum index then gives the best part orientation. This methodology is developed in C++ in the Taal project, a research and development project financed by CT CoreTechnologie.

Keywords: Additive manufacturing, Part orientation, Multicriteria algorithm, Surface quality, Volume of support, Printing time, Printing cost
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1 INTRODUCTION

Additive manufacturing is a process increasingly used in all industries: automobile, aerospace [16], medical [8] and electronics. The principle of this manufacturing consists in stacking layers of materials on the top of each other to create the desired part. Materials like metal, plastic or composite can be used in the form of powder, liquid or solid form for plentiful process assembly.

In additive manufacturing, a part will always be printed according to Z-axis, however its positioning on the machine's tray, called part building orientation, is not unique. This positioning has to respect some important rules established for additive manufacturing. Below are the main rules:

- Support must be built for overhangs with a low angle value. This value depends on the process but is mainly set around 45 degrees (angle between horizontal and material)
- Holes axis should be oriented under manufacturing's direction to avoid supports in holes during a printing
- Contacts between part and supports must be minimised to save time during post-processing and to obtain an acceptable surface quality

- Fillets with a low radius need to be removed to avoid manufacturing defaults and add ones between the tray and part to avoid part's material removal during its cleaning
- A wall must have a minimum thickness to be printed which depends on its tilt. In post-treatment cases, it is advised to have more thicken wall for functional surfaces
- Part positioning on the tray should have the lowest height to be quickly printed

Before the printing of a part, the user must define the part building orientation. It is not trivial because the orientation has an impact on several parameters. Among those, you can find part accuracy and surface finish generated by the staircase effect; the volume and complexity of supports created to support the part's overhangs during the printing and its building time and building cost. To find a part building orientation which will help to satisfy all criteria above is not an easy task. In fact, an orientation which gives a very satisfactory surface finish can lead to a long printing time, thus, to a bigger cost. The methodology tackled in this article aims to find a compromise between these different criteria. It aims to help the user to position his part on the machine according to his wish.

After a literature review, this paper will present a methodology for part building orientation in additive manufacturing. The selected criteria used in this methodology will be examined. Then applications and case study will be presented. Finally, a conclusion and a future scope will be discussed.

2 LITERATURE REVIEW

Many methodologies have been developed to find a part orientation in additive manufacturing. Some are based on multi-objective approach considering several parameters like building time, support complexity, surface finish and accuracy. The aim of those studies is to find an orientation which satisfies objectives and produces a functional part. Two solutions are proposed in literature to give orientations candidate for a part:

- One is obtained by rotation around X and/or Y axis with a given angle
- One is collected by selected surfaces which will be the base surfaces when building the part

The four following studies use the first solution to define orientations. Nezhad et al. [15] proposed an Optimized Pareto Based Part Orientation algorithm to satisfy a minimum building time and support volume and a desired surface finish. An adaptive slicing method is integrated to the algorithm in order to answer to a multi objective part orientation where optimized objective functions are simultaneous and independent. This method does not need to handle weights for this multi-objective optimization. Masood et al. [9] developed a generic algorithm based on the minimum volumetric error in the part due to staircase effect. For each orientation, the volume difference between the printed part and the CAD model is computed. The method allows to obtain a higher accuracy and surface finish. Das et al. [2] proposed a part orientation where tolerance errors from staircase effect and volume of support are computed for every orientation and tried to minimise them. Every face with an angle lower than 35 degrees with horizontal needs support and a volume of support is computed with a quadtree based approach. Weights are used with all tolerance errors to find the best orientation. Results representing all orientations are presented on a unit sphere. Phatak and Pande [14] developed a genetic algorithm based strategy and used it to obtain optimum orientation of the parts for RP process. The objective criteria for optimization is considered to be a weighted average of the performance measures such as building time, staircase error and material used. These parameters are computed for each orientation generated this time from angles randomly obtained in the chosen range. An algorithm has been also developed to hollow the oriented CAD model with desired shell thickness suiting the part material and its intended use.

Other studies chose the second solution by selecting faces from the convex part. The selected surfaces are then the base surfaces when building the part. Byun et al. [1] presented a multi-objective approach considering the surface roughness, the building time and part cost. Roughness is computed with formula taking into account particular layer thickness and angle between the normal of a surface and the build direction. An expression allowed to deduce the layer thickness for a maximum roughness value. To select the preference order among the three criteria, weights and TOPSIS method are used. Lan et al. [7] determined the orientation of a designed part to be produced in SLA with three factors: surface quality, building time and support structure. Propositions are established to obtain a good surface quality in maximizing surfaces which are not affected by staircase effect and minimising surfaces with worst quality. Moreover, algorithms are developed to minimise the number of support and the part's height to minimise the building time.

Other study chose a unit sphere to express the global directional space, which is discretized uniformly and completely. Each facet from a STL model is mapped onto the discretized unit sphere. With both, an exhaustive and a GA-based search, Zhang and Li [17] proposed a method to search the optimal building direction from a global directional space that leads to minimised volumetric error in building a part.

Paul and Anand [12] analyzed the effect of part orientation on two types of form errors, cylindricity and flatness errors. An algorithm to calculate the optimal orientation for minimising these errors is developed. Moreover, a voxel-based approach for calculating support structures is integrated to the algorithm to minimise the volume while minimising the cylindricity and flatness errors of the part features. The algorithm also offers the user with option of choosing appropriate weights for each form errors and the total volume of support structures.

Moroni et al. [11] presented an approach to find an orientation for assemblies. In this type of part, the most important is the assembly feature. This is why they choose to focus on these features and not on the whole part. This method starts by identifying cylindrical features and then computes down/upward triangle surface area from the tesselation of these cylindrical features. The aim of the method is to find an orientation where these down/upward faces are minimised. This method only treats cylindrical feature on assembly.

An other methodology based on an observation submits a new approach to find a part orientation. Indeed, it is not a multi-objective approach but only a study of support. Actually, an orientation with less support will be faster produced because less volume is printed. Moreover surface quality will be better, there will be less contact between the part and support. Thus, with a smaller volume of material to print and a shorter time of post-treatment of the part to remove support the cost will be cheaper. In order to minimise support, two solutions are possible: the first one consists in computing the overhang surfaces which need support and the second consists in computing the volume of support. Zwier et al. [18] chose the first case and computed all surfaces which need support during the printing. The candidate orientations are those where triangles from tesselation belong to the part convex hull and are the base surfaces when building the part. Morgan et al. [10] chose the second case where orientation came from rotation around X and Y axis. All triangles from the part tesselation which need support are projected to the tray and form the volume of support. Ezair et al. [4] made in turn a mix of the two methodologies, indeed, they minimise the volume of support with orientations candidate obtained by rotations around axis. Even if the support minimisation is an interesting approach with a fast computation, it does not allow to quantify other parameters.

Half of these studies treats one objective, volumetric error or support, and the second half has two or three objectives and only one deals with part cost. Most of these studies take into account the part quality by different calculation. That is why in our study, we chose to quantify this parameter too but with another approach. A printing cost computation will be introduced in our methodology.

3 METHODOLOGY FOR PART BUILDING ORIENTATION IN ADDITIVE MANUFACTURING

In this study, 4 criteria are considered: surface quality, volume of support, printing time and printing cost. To grasp the problematic and to avoid complicating the issue at the beginning, we selected four major criteria. The objective in our future works is to integrate other criteria.

For each criterion, an amount is computed, and weight is associated to each one. Weights are real included

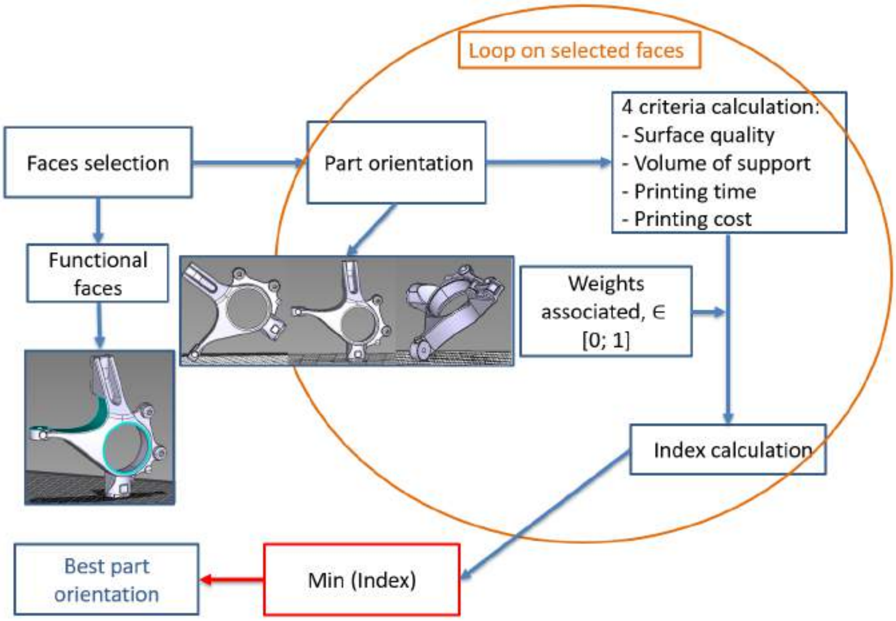

Figure 1: Methodology for the part building orientation.

in $[0;1]$, defined by the user, and allow to obtain a part orientation targeted by the user choice. The more the criterion is important to the user, the bigger is the weight. For example, the user can choose to favour printing time rather than surface quality.

Then, an index is computed with the 4 criteria above.

$$Index = W_{SQ} \times S + W_{VS} \times V + W_T \times T + W_C \times C \tag{1}$$

where:
W_{SQ}, W_{VS}, W_T and W_C are respectively weights for surface quality, volume of support, printing time and printing cost. And S, V, T and C are surface with bad quality, volume of support, printing time and printing cost.

Each amount obtained by a criterion is converted to a base 100, to avoid unit and change issues. An index is therefore calculated and associated to all positions chosen by the user. Thus, the best orientation part will have the smallest index among all computed.

Positions are established by the following way: the user selects faces which are important for him, faces which need a good surface quality. There will have as many tested positions as selected faces. Indeed, when a face is selected, the part orientation is the one where the face is perpendicular to the tray. For that, a normal average of the face is computed and is vertically oriented by rotations. All faces part are going through the same rotations and form the tested position. Thereafter, amounts for each criterion are calculated, which gives an index value for the position. The main reason why we place the selected face perpendicular to the tray is to avoid the staircase effect. Indeed, as you can see on Fig. 3, a vertically oriented face is not affected by this issue contrary to overhang faces. Selected faces could be placed parallel to the tray with their normal downward oriented to avoid the staircase effect. However, this orientation would lead to support creation between the tray and the faces during the printing. Besides, the support creation causes a bad surface quality for faces touching it. The methodology is resumed in the Fig. 1.

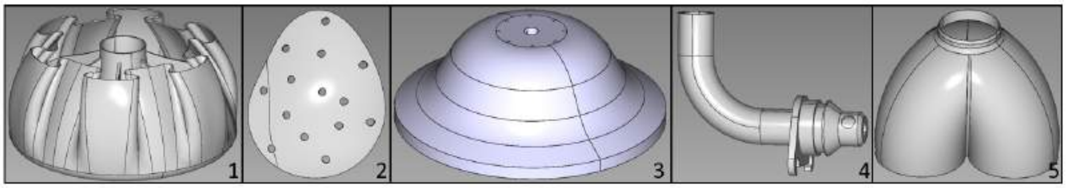

Figure 2: Tested parts for computation's times.

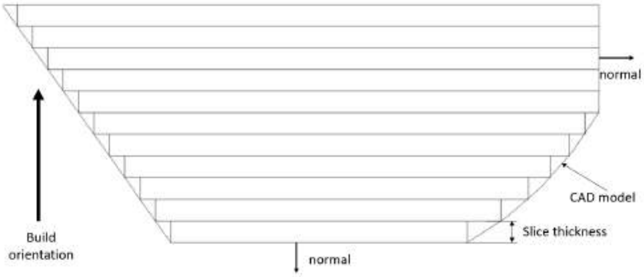

Figure 3: Staircase effects in additive manufacturing.

It is possible to select all faces from a part, but the computed time can be time-consuming. Indeed, three of the four functions used to evaluate criteria depend on the part's tesselation. Therefore, the more the part has faces and the bigger they are, the longer will be the computation time. It is obvious on the following table associated with the parts Fig. 2. The algorithm is faster with part 2 than with part 3, because the first part is very small. The same thing happens with the part 4 and 5. Regarding the part 1, because of the big size and the number of faces, computation has been stopped. A solution to reduce the time-consuming computation will be to simply algorithms. For example, the volume of support computation is very accurate, to save time it would be better to proceed to a coarse calculation. Moreover, a new tessellation of the part with less triangles and the current parallelisation of some algorithms will save time too.

Part	1	2	3	4	5
Number of faces	130	38	38	74	54
Computation time (s)	stopped after 30% computation in 24h	77.901	189.891	1742.2	17370

3.1 Surface Quality

Surface roughness has a big impact on surface finish for parts made by additive manufacturing. This roughness comes from different causes, the main one being the staircase effect. This effect is found on surfaces non-parallel/perpendicular to the XY-plane [7], basis for the print. Thus, a good part orientation should minimise this kind of surface. Moreover, the layer thickness used during the print increases this effect with its big size. The angle between horizontal and material plays a part too, and this is usually accentuated when a support is needed to make the part. The roughness computation on the total part will give us an indication of the part's surface quality.

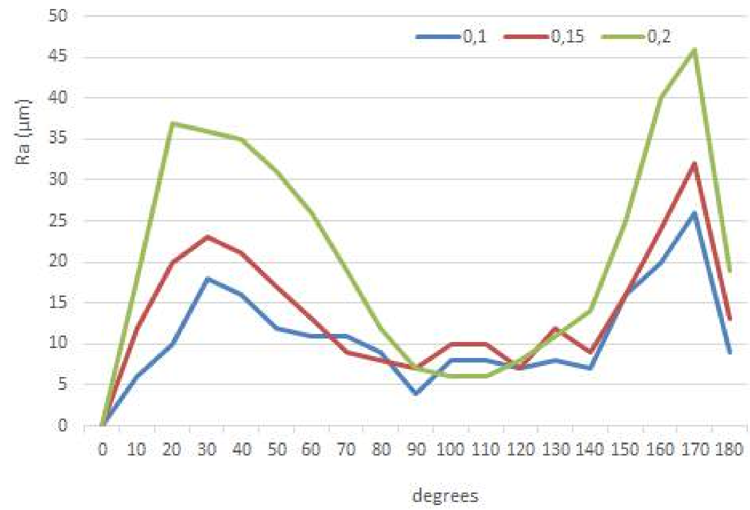

Figure 4: Roughness data obtained by analysis of the printing model Fig. 5 for 3 different layer size (0.2, 0.15 and 0.1 mm).

To evaluate the roughness of the part, we used works from J. Giannatsis and V. Dedoussis [5] on surface roughness estimation. They measured roughness by analysing the printing part Fig. 5 with an inductive digital roughness gauge. The model has been printed three times with a SL-250 ACES with different layers thickness: 0.1, 0.15 and 0.2 mm and allows to retrieve roughness values for angles (between horizontal and material) from 0 to 180 degrees. Thus, with this data, it is possible to know the roughness of each triangle of the tesselation's part.

As we can see on roughness curves Fig. 4, roughness is very high for angles included in $[10; 70]$ and $[145; 175]$ degrees. In order to have a good surface quality, surface amount with angles included in the ranges above needs to be minimised. For this criterion, that is those of surfaces who are computed.

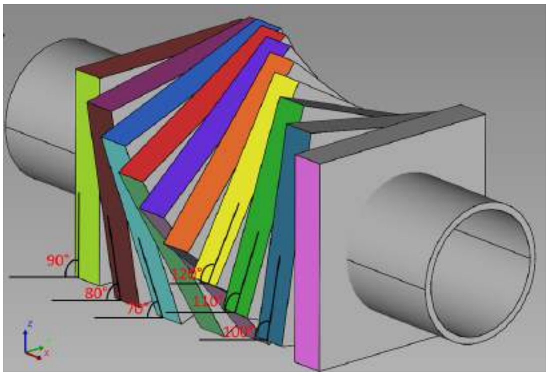

Figure 5: Model used for roughness measurement.

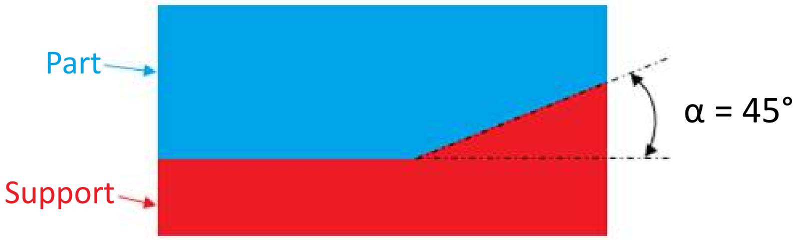

Figure 6: Support according to angle.

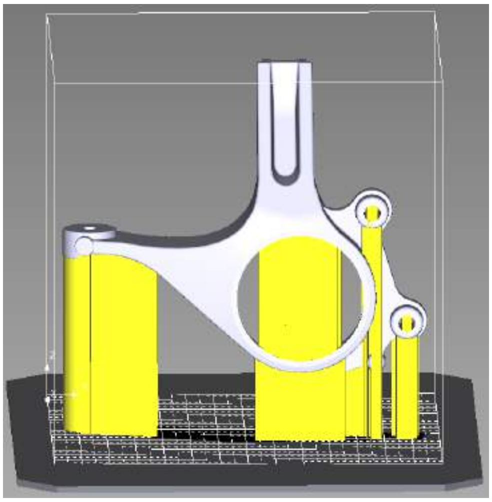

Figure 7: Support created with the above method.

3.2 Volume of Support

In most additive manufacturing processes, overhang needs supports to be printed. In this algorithm, all overhangs with angle lower than 45 degrees are supported, Fig. 6. Thus, a volume of support is computed to represent this criterion.

Volume of support has a big impact on a printed part and should be minimised for a best orientation part. In fact, the more support you need to print a part and the bigger are contacts between supports and part, which impacts the surface quality and post-processing time needed to clean the part. Moreover, this needs more material to the printing which increases the printing cost and time. For this step, the volume of support is computed as follows: it is the sum of projections on the tray of each triangle from the tessellation part with angle (between horizontal and material) lower than 45 degrees. See the example on a part: Fig. 7.

3.3 Printing Time

For this criterion, only printing time is computed, pre-processing and post processing time are not measured. This quantity is based on a formula developed by Di Stefano and Di Angelo [3]. Besides, to take into account total layers' deposition and total delay time between subsequent layers' deposition; they considered the complexity of the geometric model: the presence of holes and the complexity of layers' contours, induce unproductive times for tools movements. That's why layers' contours' depositions and repositioning tool are evaluated in the building time. Here is the formula used in this criterion, it can be duplicated to distinctly deal with time needed to print part and time needed to print support. However, to simplify our calculations, we used the same parameters for both part and support.

$$t_f = \left(\frac{V}{L} - p.W\right).t_s + \left(\frac{b_z}{L}\right).t_W + \alpha.n_{repos} + \beta.p \tag{2}$$

where:

$$\begin{aligned}
V &= volume\ of\ material\ to\ be\ formed;\\
L &= layer\ thickness;\\
p &= length\ of\ layers'\ contour;\\
W &= material\ line\ segments\ width;\\
t_s &= solidifying\ rate\ or\ material\ deposition\ rate\ in\ the\ building\ time;\\
b_z &= prototype\ height;\\
t_w &= delay\ time\ between\ each\ layers'\ deposition\ of\ material;\\
\alpha &= proportionality\ coefficient\ for\ material\ tip\ repositionings\ number;\\
n_{repos} &= number\ of\ tool\ repositioning;\\
\beta &= proportionality\ coefficient\ for\ material\ layers'\ perimeter;
\end{aligned}$$

Let's see in detail the printing time formula:

$\left(\frac{V}{L} - p.W\right).t_s$: time needed to fill inside layers,

$\left(\frac{b_z}{L}\right).t_W$: sum of delays between each layer to build the part,

$\alpha.n_{repos}$: time of tool repositioning,

$\beta.p$: time for layers' contours' depositions.

3.4 Printing Cost

For this criterion, a sum of various costs is made. It takes into account the volume of material needed to print both the part and support, energy used during printing and the part's post-processing.

The cost of material needed for the printing is the sum of part's volume and support's volume (deducted from support's criterion) multiplied by the cost of material per unit. Then with the printing time, computed in the previous criterion, multiplied by the cost of energy, we deduce a cost for energy consumption. Finally, the post-processing cost represents the cost needed to clean surfaces impacted by support. Therefore, we gather all triangle's areas from tesselation part with overhang lower than 45 degrees with horizontal. This is equivalent to the total area needing support to be realized during the print, multiplied by a cost of cleaning, which will give us an approximation of post-treatment cost.

After some cost computations and analysis with costs obtained in commercial company, we saw that the computed cost was very simplistic. It does not integrate things like the cost of the machine, the time spent by an operator for the good functioning of the machine and the time to prepare the part. To this end, another cost formula was developed to be closest to the price proposed by commercial company to print a part. This new formula now takes into account: machine's hourly rate; time required by operator to set up the machine,

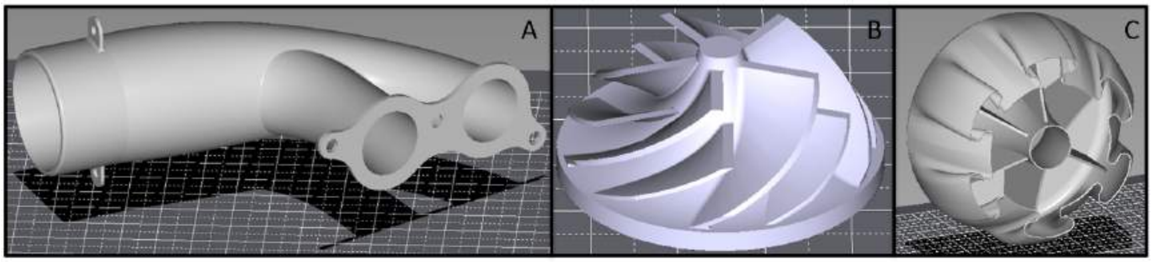

Figure 8: Parts used for cost computation in Table 1.

Part	Price from commercial company	Computed cost	Difference
A	1763 €	1635 €	7.3%
B	400 €	352 €	12%
C	3535 €	3441 €	2.7%

Table 1: Comparison between commercial company cost and computed cost

changing and loading new powder, remove substrate and clean the machine after a build; time and cost needed by operator for the pre-treatment; and the ratio of the part on the tray considering that several parts are printed together.

$$cost = (V_{part} + 0.2 \times V_{sup}) \times P_{mat} + (t_f/60) \times (Cons \times P_{energy} + P_{ratio} \times M_{hr}) + P_{ratio} \times P_{op} \times T_m + 0.25 \times (P_{op} + P_c) + S_{sup} \times P_{pt} \quad (3)$$

where:

$$\begin{aligned}
V_{part} &= volume\ of\ the\ part; \\
V_{sup} &= volume\ of\ support; \\
P_{mat} &= material\ price; \\
t_f &= time\ to\ print\ the\ part; \\
Cons &= machine\ consumption; \\
P_{energy} &= energy\ price; \\
P_{ratio} &= ratio\ part\ area\ tray\ area; \\
P_{op} &= operator's\ hourly\ rate; \\
T_m &= time\ required\ for\ the\ machine\ post\ and\ pre\ treatment; \\
P_c &= cost\ for\ using\ computer\ workstation\ with\ all\ software\ and\ licenses; \\
S_{sup} &= surfaces\ who\ need\ support; \\
P_{pt} &= post\ treatment\ cost;
\end{aligned}$$

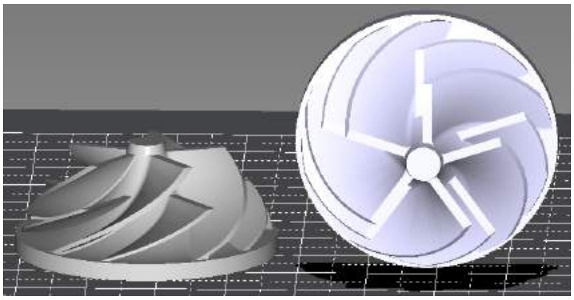

Figure 9: The same part in two different orientations.

Costs computed in the Table 1 with the above formula are oriented for SLM process, parameters such as material price and machine consumption have been chosen by result. Moreover only 20% of the projected support is considered to be close to support done in SLM.

The post treatment cost remains the most important factor in this cost formula. Indeed, according to the part orientation, it helps to be close or very far away from total cost obtained by commercial company. The part Fig. 9 showed this: for two different orientations, the computed cost difference was 231 €. The cost to print the part for the left orientation is more significant than the same part in the right orientation. Even if the building time is the half for the left orientation, the cost leading to this criterion does not explain the cost difference. This is not coming from volume of support neither, in both cases the difference is only of 4 cm^3. The biggest difference comes from surfaces which need support, 90 cm^2 in the left case against 8 cm^2 in the right case. This generates a difference of post treatment cost of more than 200 €.

4 APPLICATIONS AND CASE STUDY

The application and the case study have been realised thanks to the project Taal, Fig. 10. It is a research and development project financed by CT CoreTechnologie. The goal is to develop a software for the preparation of CAD models for additive manufacturing. Among other things, it allowed to simulate roughness on part, to create different kind of support and lattice...

In this section, an industrial work piece has been tested, four different positions (Fig. 11) have been chosen and three cases with different values of weights have been analysed, Table 2. In the first case, Case 1, all weights are equals to 1, thus criteria values can be retrieved, Table 3. Then in the Case 2, we chose to focus on surface quality and printing cost, whereas in the Case 3, printing cost then printing time are mainly targeted. Results are therefore different and are presented in the array Table 4. This table indicates index value computed for each position in each case, and for each case the minimum value coincides with the best orientation. In the two last cases, the best orientation found by the algorithm is not the same. It found the position B for the best part building orientation in the Case 2 and the position A for the Case 3. This result highlights weights power on index value to obtain a different part orientation according to weights values.

However, according to the parts and selected faces which give the orientation for a part, an orientation part can always be the best part orientation whatever the weights. This is explained by the geometry of part, which can give the lowest criteria values for an orientation. Thus, whatever the combination of weights and criteria, the index will always be the lowest for the same orientation.

In a second part, we studied the work piece presented on Fig. 13. Each criterion and index have been computed for the 54 faces of the part with all weights equals to 1. Values are shown in the Fig. 14 where X-axis represents all tested positions, i.e. 54. The four criteria have the same trend as the index curve. It is easy to see the links between the four criteria. As a matter of fact, volume of support varies like the quantity

Studied cases	Case 1	Case 2	Case 3
Surface quality weight	0.2	1	0.6
Volume of support weight	0.2	0.6	0.2
Printing time weight	0.2	0.4	0.8
Printing cost weight	0.2	0.8	1

Table 2: Weights for the three different cases studied.

Position	A	B	C	D
Surface quality	106.761	42.189	119.723	106.445
Volume of support	5.66E-05	5.15E-05	8.12E-05	6.23E-05
Printing time	654.092	1302.57	648.888	1237.72
Printing cost	81.2305	145.308	84.4017	140.441

Table 3: Criteria results for the Case 1 and the four positions.

Position	A	B	C	D
Case 1	52.9982	59.7233	61.5802	71.4474
Case 2	195.801	193.2655	226.3941	250.2314
Case 3	163.51	213.8188	177.9374	241.3443

Table 4: Index values for the three cases and the four positions.

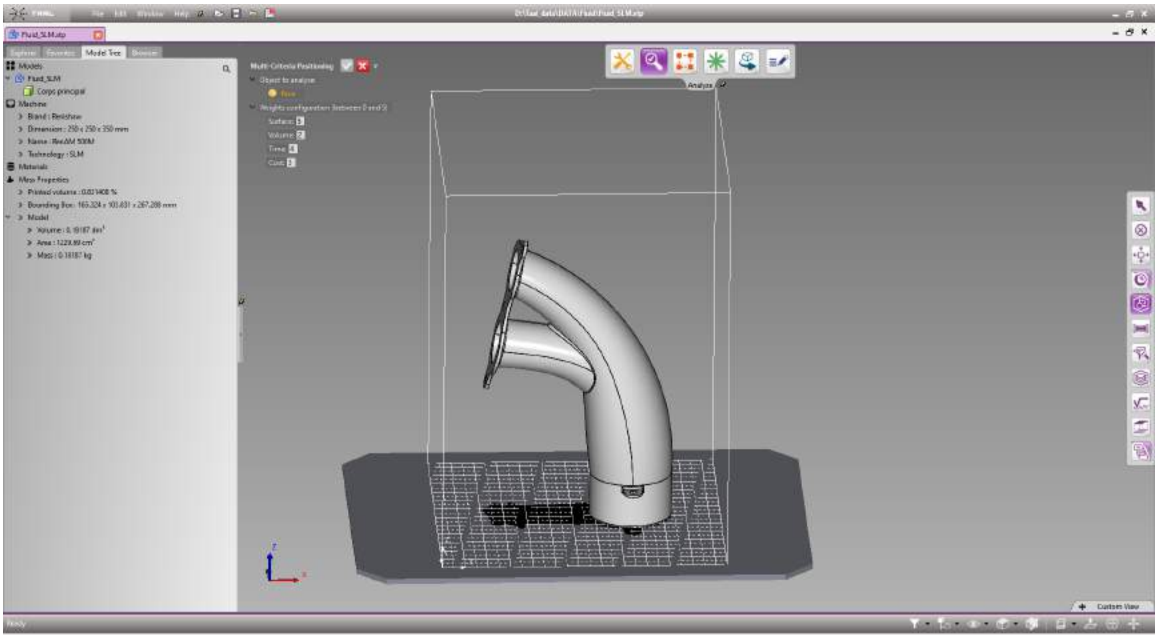

Figure 10: Taal project.

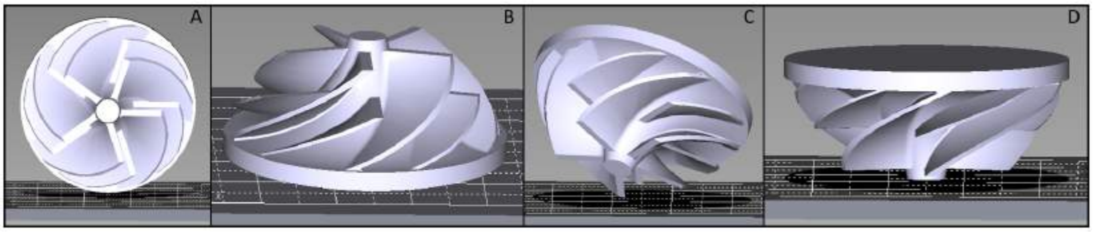

Figure 11: Four positions tested for this part.

of surfaces with bad quality. This is explained by the fact that support is needed for an angle between material and horizontal lower than 45 degrees, yet surfaces with bad quality are surfaces among other with angles included in $[10; 70]$ degrees. Moreover, volume of support influences printing time and printing cost. Indeed, to print a part in an orientation with less support will be shorter to manufacture and less expensive because less material will be printed. The surface quality will be better because there will be less contacts between the part and support and thus the post treatment will be shorter and less expensive. Zwier et al. [18] and Morgan et al. [10] deduce another methodology from this reasoning. The idea to find the part building orientation is to minimise the support. To this end, the first author chooses to minimise overhang whereas the second one finds an orientation where the volume of support is minimised. A second methodology has been developed, based on support minimisation to find a best part building orientation. The part orientation is not chosen by the user who selects faces but for this method, orientations are defined by rotation around X and Y axis. The user however has to choose the rotation angle. In order to find a part building orientation with a minimum of support, surfaces with angles lower than 45 degrees are computed. Results of this methodology are presented in Fig. 12 for the part presented in Fig. 11, where X-axis represents all positions obtained by rotations and for

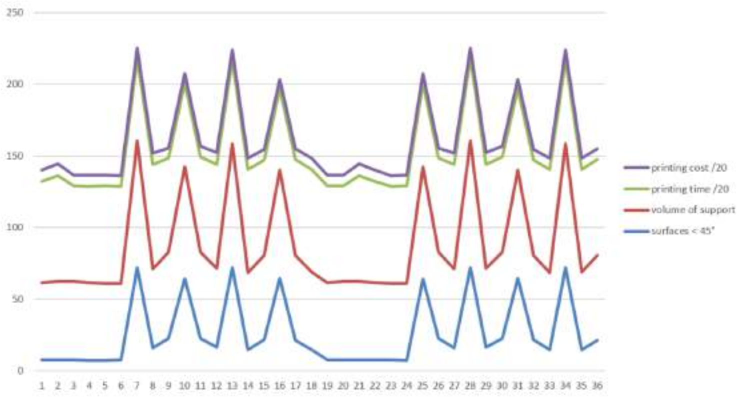

Figure 12: Simplified methodology results.

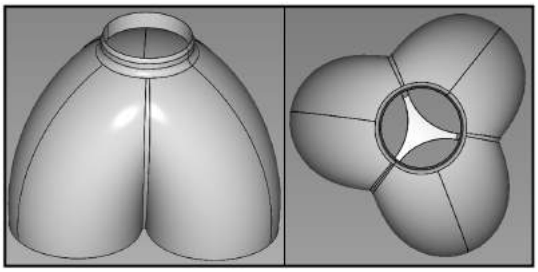

Figure 13: Tested part on its 54 faces.

which criteria are computed, i.e. 36 positions. For these tests, the rotation angle was equals to 60 degrees, it is of course possible to reduce this angle to 5 or 1 degree for example. Moreover, volume of support, printing time and cost have also been computed for the test to see the evolution of this criteria with surfaces which need support. Once more with this methodology, the link between volume of support, printing time and cost is highlighted.

5 CONCLUSIONS AND FUTURE SCOPE

A methodology is proposed for part building orientation in additive manufacturing process, which is based on four essential criteria which are surface quality, volume of support, printing time and cost. The algorithm allows to accentuate or not criteria according to the user wish thanks to weights associated with each criterion. Quite a few orientations are tested, they are defined by the user in selecting faces from the part. For each orientation, an index is computed which depends on computed criteria, different for each orientation. Among these index, the smaller gives the best part building orientation. Methodology has been applied on several industrial cases to verify the accuracy of the different criteria. It is concluded that the weights values play a part in the part building orientation determination. Moreover, the analysis of an industrial case will show links between the four criteria. Other criteria can be easily included in the index computation. Currently, we are adding a criterion which computes all surfaces on a part which need support and host support. The aim is of course to minimise surfaces which are in contact with support in order to obtain a better surface quality and a gain in post-treatment. In future, we could include for example another criterion which evaluates the difficulty to remove support on a part. The goal of this criterion will be to position the part to help the removal of

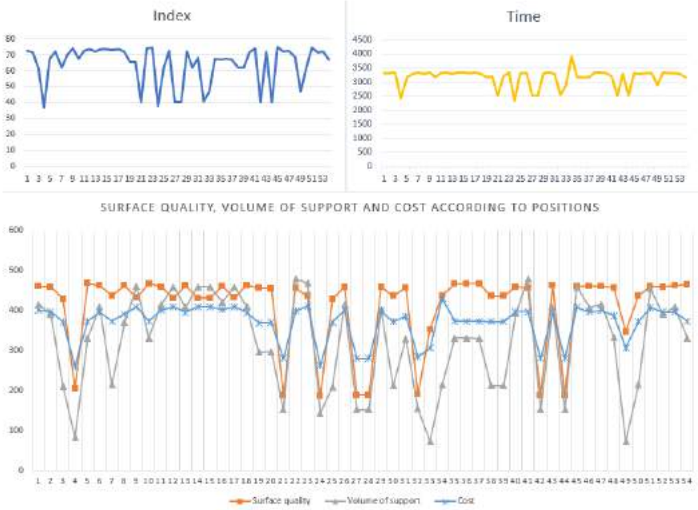

Figure 14: Results of each criterion and index for the 54 faces of the tested part.

support by excluding orientation where support is not removable. A thermal distortion criterion [13] could be added too in order to find an orientation to minimise it. Also, the study of the part building orientation of heterogeneous objects could be interesting by their greater use [6]. Both cases could be approached, multi-material objects which have distinct material domains and functionally graded materials which have continuous material variation in composition and structure gradually over volume. Molds using conformal cooling concept could be studied with this new approach to check cavities condition, roughness and support creation for example.

All parameters and data used in this algorithm are not all the most relevant, but allowed to target choices in part orientation. Indeed, data used to qualify the surface quality have been obtained in 2007 with a SLA process. With machine improvement in quality and the differences between processes, angle's ranges with bad roughness won't be the same and will need to be editable. That is why, we are expanding a methodology to allow the users to obtain their own roughness data according to their machine. Moreover, the use of the average roughness R_a is maybe not the more relevant, the use of the roughness R_z could be more interesting.

In future it would be very interesting to complete the current methodology with a new one based on genetic algorithm. It could be based on orientations obtained by the selections of the best orientations from the previous methodology. Then with cross, selections and mutations, new orientations could born and the four criteria and the index could be computed. Thus, new and better orientations could raise from that and be better. Such an algorithm could be implemented on the modeFRONTIER software.

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