Computer-Aided Design, Vol. 30, No. 5, pp. 343–356, 1998

Printed in Great Britain
0010-4485/98/$19.00+0.00

ELSEVIER

PII: S0010-4485(97)00083-3

Part orientation and build cost determination in layered manufacturing

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As more choices of materials and build processes become available in layered manufacturing (LM), it is increasingly important to identify fundamental problems that underlie the entire field. Determination of best build orientation and minimizing build cost of a part are two such issues that must be considered in any LM process. By decoupling the solution to these problems from a specific LM technology, not only can the solution be applied to a variety of processes, but more realistic cost comparisons of parts built on different machines become possible. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: part orientation, build cost, layered manufacturing

INTRODUCTION

The rapidly expanding field of layered manufacturing (LM) sees more options for designers in the choice of materials and processes each year. Models can be built from wide selections of materials, including plastic, ceramic, metal and paper, using an equally large variety of processes; for example, fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), laminated object manufacturing (LOM), solid ground curing (SGC) and many others which can be found in Ref. [1]. Two of the most basic problems of all LM processes are determining the optimal build orientation and minimizing manufacturing cost. In this paper, we propose methods for calculating cost and orientation of parts and show how these two problems are associated. The orientation problem is analyzed from a generic view, so that the solution is not specific to any given process or material. Also, a general cost model is discussed that can be applied to a broad spectrum of LM methods. We then show how it can be customized for specific LM processes. While cost and orientation methods are developed independently, geometrical information determined by the orientation calculation can be utilized by the cost model, so not only can a cost for a single part orientation be calculated but multiple orientations selected by the orientation calculation can be compared to determine the cheapest. Further, costs of manufacturing with different LM processes can be compared to find the least costly orientation and LM process.

The work in this paper builds on concepts introduced in an earlier paper[2] where the orientation problem was considered for processes that required an external support structure. The influence of part accuracy, hollow parts and processes that do not need support are now considered for orientation. Also, cost calculations are incorporated, extending the analysis further.

ORIENTATION

Determination of the optimal part orientation is a fundamental problem in LM. Several approaches have been proposed. Lan *et al.*[3], Frank and Fadel[4], and Cheng *et al.*[5] have developed methods for determining orientation for SLA, Thompson and Crawford[6] proposed a method for SLS, and Allen and Dutta[2] explored a method that applies to several processes.

The basic methodology of building parts layer by layer is common to all LM processes. By identifying these factors common to all processes, an approach that is not bound to any one process can be developed. Orientation has a significant effect on many key characteristics which determine the final part's cost. Identifying these characteristics allows us to better understand their influence on part cost so that it can be minimized. Also, by automating orientation selection, operator interaction with the problem is removed, reducing possible errors. The general orientation characteristics (GOCs) we consider to affect part cost are as follows.

(1) The height of the part in the build direction. For many processes, the height is directly related to the total build time and hence final cost.
(2) For processes that use external support structure, the following are considered.

- Total volume of support material used. The support structure does not contribute towards the finished part, wasting both build time and material.
- Total area of contact of the part with the support structure. Reducing contact area decreases the time and the cost of removing supports and finishing surfaces.

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Paper Received: 24 July 1997. Revised: 25 October 1997. Accepted: 25 October 1997

(3) The quality of selected faces (or total surface area) measured by surface accuracy. How a part is oriented determines which faces are subjected to the staircase effect and which are in contact with supports. Both these factors deteriorate the surface quality of the manufactured part, increasing time and cost for finishing the surface.

Two factors not considered in this paper are part strength, for all processes, and drainage, for parts manufactured from liquid. Since relatively few parts are used for functional testing, mechanical properties of the build material are ignored. Drainage is a special case that is limited to few LM technologies and is not considered further. Information on part strength for SLS can be found in Ref. [6] and Cheng *et al.*[5] consider trapped volumes in determining orientation for SLA.

Calculation of the GOCs and their effect on part cost is influenced by the LM process. For example, in processes that need support, such as SLA, the volume of the support structure and the area of contact with the part are important, but for SLS, which does not require supports, these factors are not. As another example, compare FDM with Sanders Prototype ModelMaker. Both use supports, however, in our experience, surface quality where they contact the model is much worse for FDM than Sanders. So, each process influences each of GOCs differently, which may produce different orientation and cost results. Hence, a process profile for each LM process is created to mimic its effect on the GOCs. To maintain neutrality from process type, general process characteristics (GPCs) which are present in more than one LM methodology and, hence, could be viewed as generic to a group of processes, are chosen. The GPCs which we consider here are:

(1) enabling/disabling generation of a support structure for processes that do and do not need support;
(2) enabling/disabling calculation of the base support structure for processes that need to support the base of the part and those that do not;
(3) maximum overhang angle without support;
(4) defining a factor for surface inaccuracy where supports contact the model.

By divorcing process selection from any one specific factor, general profiles for the LM process are created using the appropriate GPCs. For example, FDM would have a maximum overhang angle of 60°, enable support structure and select a high inaccuracy factor, but would disable base support structure. On the other hand, SLA would also enable support structure but have a lower inaccuracy factor, select a maximum overhang angle of 70° and enable a base support structure. Using this approach, process profiles for new LM processes can also easily be added because they too should share some of the GPCs.

GOCs can be individually used to rank a selection of orientations according to minimum height, minimum volume of support, minimum area of contact with support or maximum accuracy of total surface area or selected facets. From these rankings the 'winner' decides the build direction.

While this selection technique may be appropriate in limited situations, e.g. where the orientation maximizes the accuracy on an important face, a more useful approach is to determine the lowest cost orientation. Because orientation directly effects price, several orientations need to be compared to find the lowest cost. Extending this concept further, orientation costs on different LM processes can also be compared to select the best machine as well as the orientation. This selection will, of course, vary from part to part because of the differences in process and part geometries.

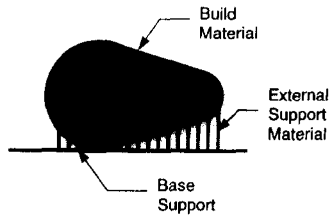


Figure 1 Cross-section through a solid part showing external support

For companies with different LM machines, the strategy for selecting which machine to manufacture a part on could be based upon lowest cost, availability of machines, customer requirements for the final manufactured part, etc. For simple part geometries, determining the best orientation manually is often self evident. However, when more complex parts are considered, accurate selection of the orientation and machine is more difficult and prone to error.

Currently, an automated technique allowing manufacturers to compare costs is not available. A cost model that applies to a broad range of LM machines would allow calculation of the cost of a predetermined orientation on different machines. However, without a method of comparing different orientation's costs directly, practical implementation of the cost model is limited. Hence, consolidation of the cost model and orientation module provides the ability to investigate costs of a wide variety of orientations. Only then can the best orientation and machine selection be achieved, which:

- reduces manufacturing costs by reducing orientation and machines selection errors, consequently producing cheaper parts;
- automates the machine and orientation selection process;
- allows better cost estimation of parts.

Orientation selection and support computation is explained in the previous paper[2] for solid models. Support structures for hollow models, accuracy calculations and the cost model are elaborated further in the following sections.

Support structure

For support calculation, the part can either be considered a solid or a closed hollow surface. Generally, it is taken to be solid with only an external support structure, as shown in *Figure 1*. If the same part is now thought of as hollow, the

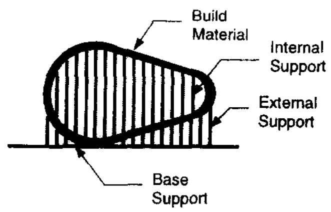


Figure 2 Cross-section through a hollow part showing internal and external support

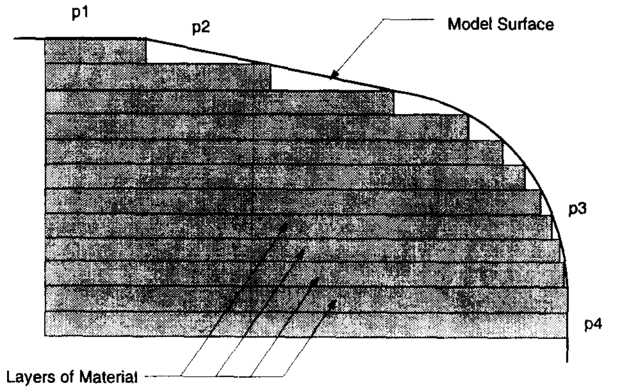


Figure 3 Variation of the layered manufactured part's surface with the true surface due to the staircase effect

support structure replaces the interior filled region, as in *Figure 2*. The latter method is useful when the interior 'makeup' of the model is unimportant and the LM process uses less material for supports than in normally manufacturing the part. This approach reduces the total volume of material used when compared to the former method, with the additional benefits of decreasing the build time and cost. The information about support is calculated via a 'rays structure' which has been explained previously in Ref. [2]. It also holds information about the surface area of the contact with supports, volume of supports and surface accuracy.

Accuracy calculation

A major source of part inaccuracy is due to the staircase effect. The manufactured horizontal and vertical surfaces (*p1* and *p4* respectively) match the CAD model's surface exactly as shown in *Figure 3*. Practically, inaccuracies of the process introduce some error but for this analysis they are considered negligible when compared to stair step errors and, therefore, can be ignored. Near vertical surfaces, such as *p3*, are significantly less affected by inaccuracy than the near horizontal surface, *p2*. So, to maximize surface accuracy, a surface should be oriented either horizontally or vertically. This is not always achievable, so it is then preferable to orient it as near vertical as possible.

The staircase effect is used as the basis for developing an accuracy measure. *Figure 4* shows an enlargement of a plane, P, built at an angle $(90-\theta)^\circ$ to the build direction. The maximum distance from the manufactured part's surface perpendicular to the CAD model surface is known as the cusp height, h. This depends on the angle θ and the layer thickness, z_t. Thicker layers and/or high values of $\cos\theta$ will

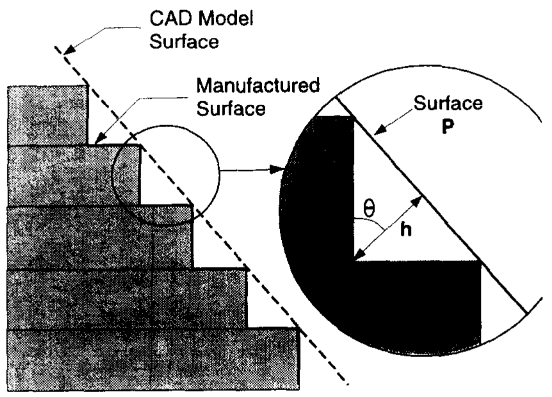


Figure 4 Close-up of cusp height error

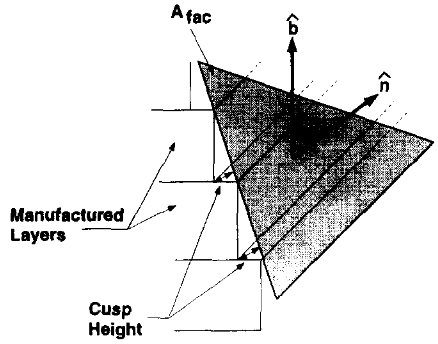


Figure 5 Accuracy of one triangular facet of an STL file

produce larger values for cusp height and consequently a more inaccurate surface will result. So, cusp height can be written as

$$h = \begin{cases} z_t|\cos\theta| & \text{for } |\cos\theta| \neq 1 \\ 0 & \text{if } |\cos\theta| = 1 \end{cases} \tag{1}$$

By using cusp height to measure accuracy of a part, the surface quality can be determined from part geometry, build direction and layer thickness. However, eqn (1) applies to a 2D plane as illustrated. Accuracy measures based on cusp heights for freeform surfaces need further development and are not considered in this paper. (For more detailed discussion of cusp heights, see Ref. [7].) Instead, we use an STL file which is a faceted approximation to the true CAD surface and is commonly used in the LM field. Also, as described in Ref. [2], our orientation and support structure determination requires the computation of convex hulls, also a faceted object.

Consider a single facet on a surface, shown in *Figure 5*. The angle between the surface unit normal, $\hat{\mathbf{n}}$, and a unit vector in the build direction, $\hat{\mathbf{b}}$, is given by their dot product and is equivalent to θ in *Figure 4*.

$$|\cos\theta| = |\hat{\mathbf{n}}.\hat{\mathbf{b}}| \tag{2}$$

Therefore, cusp height and, hence, accuracy can be determined for a triangular facet by rewriting eqn (1) as

$$h = z_t|\hat{\mathbf{n}}.\hat{\mathbf{b}}| \tag{3}$$

However, a 3D part consists of multiple facets in different directions and each may have a different cusp height. So, a facet's accuracy must be weighted comparative to all the other facets. The 'zone of influence' for a facet's cusp height is determined by the area over which it acts. Hence, facet area, A_{fac}, is used as a relative weighting function to other facets. This gives a weighted cusp height for each facet of

$$h_{\text{w}} = hA_{\text{fac}} \tag{4}$$

So, considering two facets, if one has a larger area than the other then its cusp height is more influential than the smaller

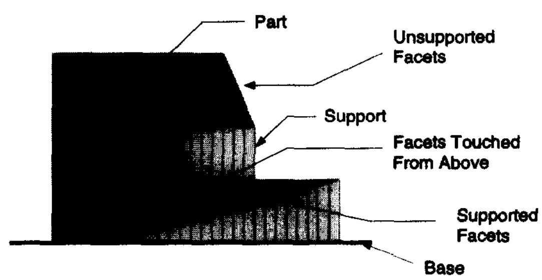


Figure 6 Three cases of accuracy

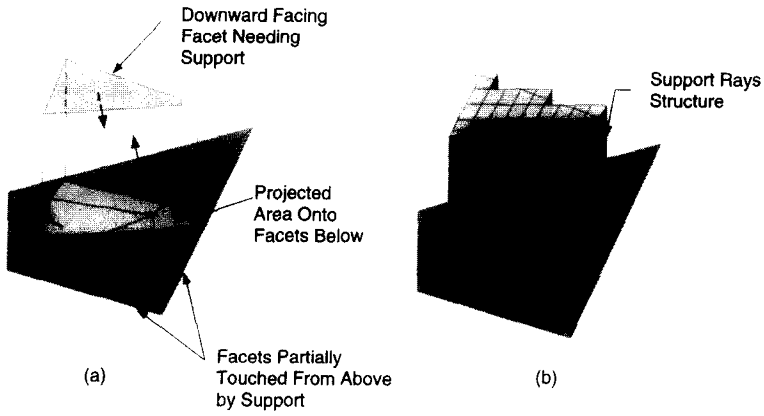


Figure 7 Facets partially touched from above and the support rays structure

facet. Therefore, when calculating orientation, the larger facet will preferentially be oriented to have a lower cusp height than the smaller since it affects the accuracy over a larger area on the manufactured model's surface.

Part accuracy based on weighted cusp height, defined in eqn (4), alone is not enough to determine the part orientation. There are three cases, illustrated in *Figure 6*, which need to be considered:

- unsupported facets;
- supported downward facing facets;
- facets touched from above by the support structure.The accuracy of unsupported facets is given by the weighted cusp height in eqn (4).

For supported facets, not only is the surface affected by the staircase effect but the contact with the support adds additional inaccuracy. It is assumed that when supports touch the surface of the part then the cusp height for the facet is increased by an additional amount, R, which is independent of the facet's angle and therefore constant, i.e. contact with support is equally bad for all facets. So, the weighted cusp height of one supported facet, $h_{w_{sup}}$, is

$$h_{w_{sup}} = (h + R)A_{fac} \tag{5}$$

If the value of R is zero, then the accuracy of the facet's surface is determined only by the stair stepping effect, i.e. it is the equivalent of being unsupported.

For the third case when support touches from above only, a partial area of a supported facet may be projected onto a facet below it as in *Figure 7a*. In order to determine the area of contact a 'rays structure' is used to approximate the support in *Figure 7b* explained in Ref. [2]. *Figure 8* shows a support ray intersecting the facet below a supported facet. $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are unit vectors in the x and y directions. Unit vector $\hat{\mathbf{b}}$ is parallel to the build direction and $\hat{\mathbf{n}}$ is a unit normal to the facet being intersected by the ray. The dimensions of the ray are p and q in the x and y directions. Consider vectors $\bar{\mathbf{x}}$, $\bar{\mathbf{b}}_x$ and $\bar{\mathbf{x}}'$

$$\bar{\mathbf{x}} = p\hat{\mathbf{x}} \tag{6}$$

$$\bar{\mathbf{b}}_x = -\left(\frac{\hat{\mathbf{n}}.\bar{\mathbf{x}}}{\hat{\mathbf{n}}.\hat{\mathbf{b}}}\right)\hat{\mathbf{b}} \tag{7}$$

$$\bar{\mathbf{x}}' = \bar{\mathbf{x}} + \bar{\mathbf{b}}_x \tag{8}$$

and similarly for $\bar{\mathbf{y}}$, $\bar{\mathbf{b}}_y$ and $\bar{\mathbf{y}}'$. So, the surface area of

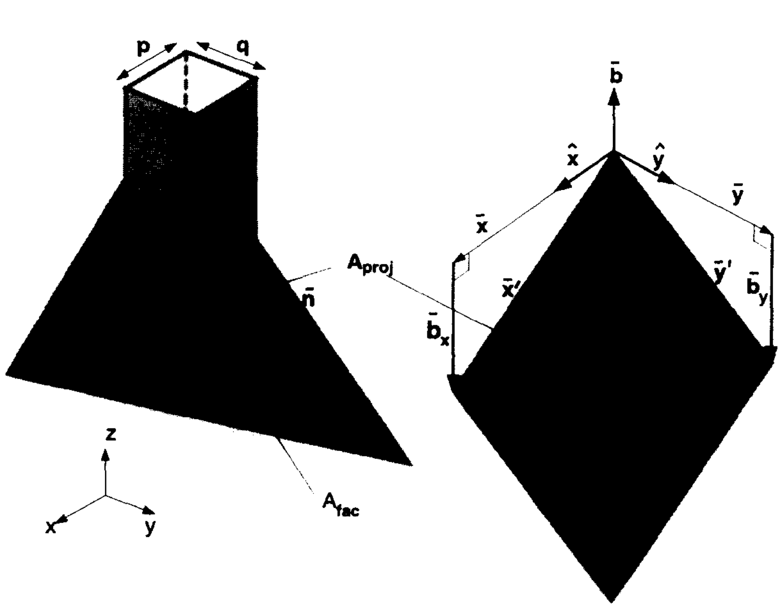


Figure 8 One support 'ray' touching a facet from above

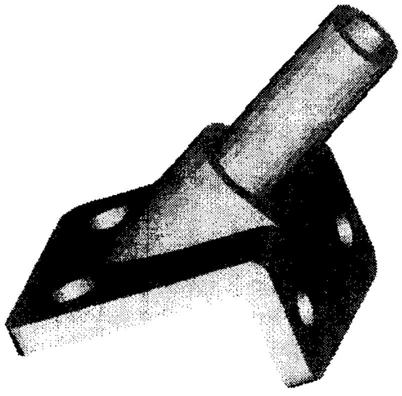


Figure 9 A bracket

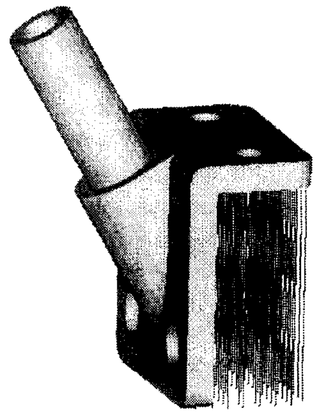


Figure 10 Maximized overall surface accuracy

contact of the ray with the facet is,

$$A_{\text{proj}} = |\bar{\mathbf{x}}' \times \bar{\mathbf{y}}'| \tag{9}$$

This only gives an approximated area of contact because the projected area may 'run over' into an adjacent facet. This error can be reduced by using more rays by decreasing p and q, but at the expense of increased computation. Another error that may occur is when a ray intersects a facet that is near perpendicular to the build direction. The calculated projected area may be greater than the facet area A_{fac}. To prevent this, the maximum projected area is limited to the area of the facet. In summary,

$$A_{\text{proj}} = \begin{cases} |\bar{\mathbf{x}}' \times \bar{\mathbf{y}}'| & \text{for } A_{\text{proj}} \leq A_{\text{fac}} \\ A_{\text{fac}} & \text{if } A_{\text{proj}} > A_{\text{fac}} \end{cases} \tag{10}$$

So, cusp height due to support from above, $h_{\text{w}_{\text{ab}}}$, for each ray, is

$$\text{h}_{\text{w}_{\text{ab}}} = RA_{\text{proj}} \tag{11}$$

Now, the total weighted cusp height, H_{w}, for the whole surface can be determined. If there are N facets in the model, N_{sup} of them are downward facing supported facets and $(N - N_{\text{sup}})$ are unsupported, the total weighted cusp heights for supported, $H_{\text{w}_{\text{sup}}}$, and unsupported, $H_{\text{w}_{\text{un}}}$, facets are given by

$$H_{\text{w}_{\text{un}}} = \sum_{i=1}^{N-N_{\text{sup}}} h_{\text{w}_i} A_{\text{fac}_i} \tag{12}$$

$$H_{\text{w}_{\text{sup}}} = \sum_{j=1}^{N_{\text{sup}}} \left(h_{\text{w}_j} + R\right) A_{\text{fac}_j} \tag{13}$$

The total weighted cusp height for contact from above is given by

$$h_{\text{w}_{\text{ab}}} = \sum_{k=1}^{N_{\text{rays}}} RA_{\text{proj}_k} \tag{14}$$

where N_{rays} is the total number of rays. If facets along a ray do not need support then the area A_{proj} is zero.

Total weighted cusp height is the sum of $H_{\text{w}_{\text{un}}}$, $H_{\text{w}_{\text{sup}}}$ and $H_{\text{w}_{\text{ab}}}$, i.e.

$$H_{\text{w}} = \sum_{i=1}^{N-N_{\text{sup}}} h_{\text{w}_i} A_{\text{fac}_i} + \sum_{j=1}^{N_{\text{sup}}} \left(h_{\text{w}_j} + R\right) A_{\text{fac}_j} + \sum_{k=1}^{N_{\text{rays}}} RA_{\text{fac}_{\text{proj}k}} \tag{15}$$

Finally, total weighted cusp height is averaged by the total surface area of the part to give an average weighted cusp height

$$H_{\text{av}} = \frac{H_{\text{w}}}{\sum_{i=1}^{N} A_{\text{fac}_i}} \tag{16}$$

This value, H_{av}, is used to rank the part accuracy of different orientations. By calculating accuracy on a facet by facet approach, not only can an accuracy be calculated for the entire part surface area, but also for individual surfaces allowing parts to be oriented based on the accuracy of one or two faces instead of the whole surface. The following example illustrates how different orientations are selected when considering the accuracy of the entire surface and a selected surface.

Example—surface selection for accuracy

The part* shown in *Figure 9* has no immediately obvious 'best' orientation for a LM build. The selections shown in the following diagrams are determined by an implementation of the accuracy method in our software known as the orientation module (ORM). Further discussion of the use of this module is included in the section *Orientation Module*. The ORM generates a set of orientations from the faceted three-dimensional convex hull of the part. From these, a list of candidate orientations to be used for testing is distilled by selecting a user-defined number of orientations with the largest 'footprint'. The footprint can be described as the shadow of the convex hull projected onto a plane perpendicular to the build direction. A detailed discussion of this method is included in Ref. [2].

For this example, 10 candidate orientations were selected. Using the maximum accuracy sorting criteria for the entire surface with R equal to 2.0, gives the orientation in *Figure 10* from the list of candidate orientations. Because R is high, the main factor that deteriorates surface quality is contact with supports, it is therefore desirable to minimize this contact area. Other orientations have larger support surface areas of contact and, hence, (in general) a smaller global accuracy. Faces untouched by support also affect the accuracy but their contribution is much less influential for this particular orientation.

* This part was obtained from the NIST repository at: http://elib.cme.nist.gov/pub/subject/pptb/repository/

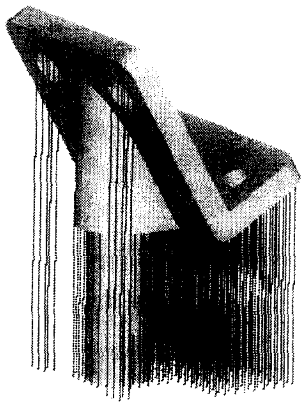


Figure 11 Maximized accuracy of selected faces

Now consider the tubular location pin protruding from the bracket. Maintaining high surface quality may be a critical factor for manufacturing this part because it must be inserted accurately into another component. Building the part in the orientation of *Figure 10* produces cusp heights on its surface which reduce its accuracy and may interfere with the mating of the part. By selecting only the pin's surface for the accuracy calculation, the build direction shown in *Figure 11* is selected by the ORM. The peg's surface is vertical and hence has zero theoretical cusp height and maximum accuracy. Therefore, when building it in this direction, the location pin's surface will be as accurate as possible within the limits of the manufacturing process while the unselected surfaces touched by the support will be deteriorated significantly.

COST MODEL

Generic cost model

The generic cost model equation considers the overall stages for layered manufacturing in a non-process specific way. Methods can therefore be used as a framework to create process-specific equations. The cost equation is divided into three stages of a LM part's life; the prebuild preparation, build, and postprocessing stages. Costs involved with each of these stages, C_{pre}, C_{build}, C_{post}, respectively, are all considered when trying to determine the total part cost, C_{tot}. It is assumed that each stage's process costs are independent of each other and not performed in parallel. Therefore, total cost can be calculated as the linear sum of prebuild, build and postbuild costs,

$$C_{tot} = C_{pre} + C_{build} + C_{post} \tag{17}$$

Prebuild cost

The prebuild preparation stage involves all preparation work necessary before manufacturing a part. It is assumed that an error-free file compatible with the LM software has already been produced, e.g. an STL file. Assuming one operator, paid C_{oper1} cost per unit time, performs all the tasks in this stage, he/she must spend time, T_{pos}, positioning and scaling the part. Process parameters including layer thickness, road width, material type, etc. are entered into the LM software taking time T_{param}. Time is further spent generating support structures, T_{supp}, and slicing the file, T_{slice}. Finally, road paths are automatically generated by the software in time, T_{path}. For these activities there is an additional cost dependent on using a computer, C_{comp}. Once the part is prepared, the LM machine is set-up to begin building. It is warmed up, support and build material loaded/unloaded, the z axis height set, the x–y positioning zeroed, diagnostics performed, the build platform leveled and any cleaning or additional testing are done, taking a total time of T_{setup}. Hence, the total cost of this prebuild stage is,

$$C_{pre} = (T_{pos} + T_{param} + T_{supp} + T_{slice} + T_{path}) \times (C_{oper1} + C_{comp}) + T_{setup}C_{oper1} \tag{18}$$

Build cost

After preparation, the part data is sent to the LM machine to be manufactured. Build cost is defined as the product of build time, T_{build}, and cost/unit time for running the machine, C_{build}, plus the cost of materials used during manufacturing. Running costs include machine depreciation, power consumption, maintenance operator supervision (if needed), etc. Build time can be further subdivided into manufacturing time, T_{man}, and idle time, T_{idle}.

$$T_{build} = T_{man} + T_{idle} \tag{19}$$

The manufacturing time is when the part and support are being manufactured. Idle time relates to non-productive time, such as z axis movement, waiting for commands due to queue starvation, cooling times, leveling, non-manufacturing movement of the nozzle/laser/head/knife, cleaning, milling, etc. Build time is heavily dependent upon both the LM manufacturing process and orientation. By minimizing the support volume, less material is deposited so, in general, T_{man} is smaller. By minimizing height, the number of layers of material is less but tends to increase the average cross-sectional area of each slice. While this increases the time to build each layer there are fewer layers and idle time decreases because less non-productive time is wasted waiting between layers. This, in general, reduces the overall build time. Therefore, orientation is critical in determining build time and, hence, cost. A generic equation for build time for all LM processes does not currently exist, so T_{build} must be determined on a process by process basis. Examples of build time estimation, are developed in the sections *Cost Model for Fused Deposition Modeling* and *Cost Model for Stereolithography* for FDM and SLA, respectively.

Support and part material are not always the same, so their costs, C_{part} and C_{supp}, respectively, are calculated separately giving the total build cost as,

$$C_{build} = T_{build}C_{build} + C_{part} + C_{supp} \tag{20}$$

where C_{build} is the cost of running the machine.

Postprocessing cost

The final postprocessing stage's cost, C_{post}, depends upon time to remove supports, T_{rem}, and finish the model's surface, T_{fin}, to obtain the desired surface quality. These operations are manually performed, so cost is calculated from the latter two terms and the cost of employing an operator, C_{oper2}, to perform these tasks. This stage is also heavily dependent on orientation since, if the surface quality is poor, more time is required to finish the surface to the desired tolerance. Also, orienting a part to minimize support structure will reduce the time to remove them.

Some processes may require extra operations during this stage, such as curing, cleaning, sintering, applying a protective coating, adding metal inserts, etc. The total cost for these operations is dependent on the time to

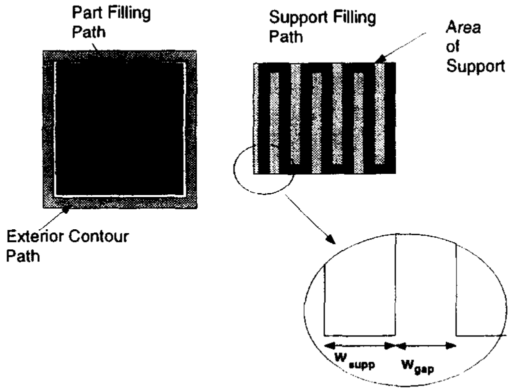


Figure 12 The difference between raster fill patterns for the part and the support

perform the process, T_{fproc}, and the cost of operating the process, C_{fproc}, which includes depreciation of a machine, power usage, operator wages, etc. The cost of any extra materials, C_{ppmat}, used during these operations in removing supports, polishing or further processing must be also be included. Hence, total postprocessing cost is given by

$$C_{\mathrm{post}} = (T_{\mathrm{rem}} + T_{\mathrm{fin}})C_{\mathrm{oper2}} + T_{\mathrm{fproc}}(C_{\mathrm{fproc}} + C_{\mathrm{oper2}}) + C_{\mathrm{ppmat}} \tag{21}$$

Eqns (18), (20) and (21) are used to further develop customized cost equations for specific processes in the next two sections. Summing these three equations gives the total part cost as in eqn (17). It should be noted that the generic cost equations are designed to be general enough so that they can be specialized for many LM technologies. For this paper, FDM and SLA were chosen to illustrate the procedure of specialization. Similar methods can be used to create process specific equations for other LM techniques (e.g. SLS, Sanders Prototype ModelMaker, etc) from the general equations.

Cost model for fused deposition modeling

Prebuild cost

This cost model is based upon the Stratasys 3D Modeler. Considering the prebuild stage for fused deposition modeling (FDM), an STL file is loaded into the FDM software where it is scaled, positioned and process parameters entered to set road width, layer thickness, material type, etc. The part is sliced, supports generated and road paths calculated, after which the part is ready to be sent to the Stratasys machine. The machine is prepared by loading spools of material onto the back of the machine, changing the nozzle size, raising the machine to the operating temperature and purging and checking material flow. Finally, the z height of the platform has to be manually set. After this, the part is ready to be built. Using eqn (18) this can be summarized as

$$(C_{\mathrm{pre}})_{\mathrm{FDM}} = [(T_{\mathrm{pos}})_{\mathrm{FDM}} + (T_{\mathrm{param}})_{\mathrm{FDM}} + (T_{\mathrm{supp}})_{\mathrm{FDM}} + (T_{\mathrm{slice}})_{\mathrm{FDM}} + (T_{\mathrm{path}})_{\mathrm{FDM}}][(C_{\mathrm{oper1}})_{\mathrm{FDM}} + (C_{\mathrm{comp}})_{\mathrm{FDM}}] + (T_{\mathrm{setup}})_{\mathrm{FDM}}(C_{\mathrm{oper1}})_{\mathrm{FDM}} \tag{22}$$

where the subscript FDM signifies the process.

Build cost

For build cost, an estimation of the build time is required. A fairly accurate estimate can be calculated using FDM software, but this would require slicing the part file and generating roads. If multiple orientations are being compared then this is time consuming and increases preparation time. So, another method to estimate build time using the part geometry and orientation supplied by our orientation module is discussed.

Building a layer of material of a part has several stages. The part's external contours are drawn and the interior filled with a tightly rastered pattern. Support structure is deposited, also in a raster pattern but spaced wider than that used to fill the part interior, as shown in *Figure 12*. An approximation for the time, $(t_{\mathrm{part}_i})_{\mathrm{FDM}}$, to lay part material for the ith layer is determined from the cross-sectional area, A_{part_i}, the nozzle velocity in the x–y plane, $(v_n)_{\mathrm{FDM}}$, and road width of the material, $(w_{\mathrm{part}})_{\mathrm{FDM}}$, shown in eqn (23). This method underestimates the true time because the acceleration and deceleration of the nozzle and its changing direction are not taken into account.

The equation for the time to deposit the support structure for the ith slice is similar to eqn (23) except that the support does not fill the entire area, A_{supp_i}. Supports are deposited less densely in widely spaced raster patterns compared to the closely packed raster in the part interior, shown in *Figure 12*. The approximate fraction of A_{supp_i} filled with support material, d_{FDM}, is given by eqn (24) where $(w_{\mathrm{supp}})_{\mathrm{FDM}}$ is the road width of the support and $(w_{\mathrm{gap}})_{\mathrm{FDM}}$ is the spacing between adjacent roads.

In addition to time spent laying support and part material, non-productive time is spent moving the nozzle between roads, $(t_{\mathrm{move}_i})_{\mathrm{FDM}}$, e.g. from the end of a path of support to the beginning of a path of part material. The total time to build a single layer, $(t_{\mathrm{lay}_i})_{\mathrm{FDM}}$ is calculated by eqn (26). After completing a layer, more idle time is spent moving the table to a new z height taking time, $(t_{z\mathrm{move}})_{\mathrm{FDM}}$. Also, the tip of the head is wiped every m layers in time, $(t_{\mathrm{wipe}})_{\mathrm{FDM}}$. Assuming constant slicing, the total number of layers, N_{lay}, is calculated from the height of the part, H, in the build direction and the layer thickness, z_t, as shown in eqn (27). The total approximate build time is found by summing the total time spent building all the layers, all z movement and total tip wiping time shown in eqn (28).

$$(t_{\mathrm{part}_i})_{\mathrm{FDM}} = \frac{(A_{\mathrm{part}_i})_{\mathrm{FDM}}}{(w_{\mathrm{part}})_{\mathrm{FDM}}(v_n)_{\mathrm{FDM}}} \tag{23}$$

$$d_{\mathrm{FDM}} = \frac{(w_{\mathrm{supp}})_{\mathrm{FDM}}}{(w_{\mathrm{supp}})_{\mathrm{FDM}} + (w_{\mathrm{gap}})_{\mathrm{FDM}}} \tag{24}$$

$$(t_{\mathrm{supp}_i})_{\mathrm{FDM}} = d_{\mathrm{FDM}}\frac{(A_{\mathrm{supp}_i})_{\mathrm{FDM}}}{(w_{\mathrm{supp}})_{\mathrm{FDM}}(v_n)_{\mathrm{FDM}}} \tag{25}$$

$$(t_{\mathrm{lay}_i})_{\mathrm{FDM}} = (t_{\mathrm{part}_i})_{\mathrm{FDM}} + (t_{\mathrm{supp}_i})_{\mathrm{FDM}} + (t_{\mathrm{move}_i})_{\mathrm{FDM}} \tag{26}$$

$$N_{\mathrm{lay}} = \frac{H}{z_t} \tag{27}$$

$$(T_{\mathrm{build}})_{\mathrm{FDM}} = \sum_{i=1}^{N_{\mathrm{lay}}}(t_{\mathrm{lay}_i})_{\mathrm{FDM}} + N_{\mathrm{lay}}(t_{z\mathrm{move}})_{\mathrm{FDM}} + \frac{N_{\mathrm{lay}}}{m}(t_{\mathrm{wipe}})_{\mathrm{FDM}} \tag{28}$$

The cost of the material used to manufacture the part is calculated from the volume of material deposited and its cost per unit volume. 3D Modeler uses the same material for both support and part material, so the cost of material used is

$$(C_{\mathrm{mat}})_{\mathrm{FDM}} = z_t (C_{\mathrm{part}})_{\mathrm{FDM}} \sum_{i=1}^{N_{\mathrm{lay}}} (A_{\mathrm{part}_i} + d_{\mathrm{FDM}} A_{\mathrm{supp}_i}) \qquad (29)$$

where $(C_{\mathrm{part}})_{\mathrm{FDM}}$ is the cost per unit volume of the material used. Therefore, total build cost is

$$(C_{\mathrm{build}})_{\mathrm{FDM}} = (T_{\mathrm{build}})_{\mathrm{FDM}}(C_{\mathrm{build}})_{\mathrm{FDM}} + (C_{\mathrm{mat}})_{\mathrm{FDM}} \qquad (30)$$

where $(C_{\mathrm{build}})_{\mathrm{FDM}}$ is the cost of running the FDM machine. This is the same as eqn (20) with C_{part} and C_{supp} being combined into $(C_{\mathrm{mat}})_{\mathrm{FDM}}$.

Postprocessing cost

The final stage, postprocessing, consists of removing support structures and finishing the surface. Empirical measures are used to approximate support removal time, $(T_{\mathrm{rem}})_{\mathrm{FDM}}$. It is assumed that $(T_{\mathrm{rem}})_{\mathrm{FDM}}$ is mainly dependent on both contact surface area of supports due to overhang, $(A_{\mathrm{over}})_{\mathrm{FDM}}$, and area of facets touched from above $(A_{\mathrm{ab}})_{\mathrm{FDM}}$. Supports which are attached to the part at both the top and bottom are much harder to remove than if there is only one point of contact at the top. Since the ability to remove supports depends upon the skill of the operator and processing equipment, an empirical weighting system is suggested in eqn (31), where W_i are weighting factors based on experimental data.

$$(T_{\mathrm{rem}})_{\mathrm{FDM}} = W_1(A_{\mathrm{over}})_{\mathrm{FDM}} + W_2(A_{\mathrm{ab}})_{\mathrm{FDM}} \qquad (31)$$

Total postprocessing time, $(T_{\mathrm{fin}})_{\mathrm{FDM}}$, is dependent upon the total part surface area $(A_{\mathrm{tot}})_{\mathrm{FDM}}$ and area of contact with supports, $(A_{\mathrm{supp}})_{\mathrm{FDM}}$. Support contact area will take longer to process because its surface is rougher.

$$(T_{\mathrm{fin}})_{\mathrm{FDM}} = W_3[(A_{\mathrm{tot}})_{\mathrm{FDM}} - (A_{supp})_{\mathrm{FDM}}] + W_4(A_{\mathrm{cont}})_{\mathrm{FDM}} \qquad (32)$$

So, total time to finish the manufactured FDM part is

$$(C_{\mathrm{post}})_{\mathrm{FDM}} = [(T_{\mathrm{rem}})_{\mathrm{FDM}} + (T_{\mathrm{fin}})_{\mathrm{FDM}}](C_{\mathrm{oper2}})_{\mathrm{FDM}} \qquad (33)$$

Comparing with eqn (21), there are no other postprocessing operations so T_{fproc} and C_{fmach} are ignored and the cost of the finishing materials, C_{ppmat}, is considered negligible.

By using eqns (22), (30) and (33) in eqn (17), the total cost of manufacturing a part on an FDM machine is determined.

Cost model for stereolithography

Prebuild cost

Part preparation involves some different tasks on the SLA250 than FDM. For each part, a support STL file must be generated and then process parameters are selected such as overcure, wait times, layer thicknesses, build style, etc. After setting the parameters, the support and part STL files are sliced and road paths generated. Finally, the part and support files are merged together to be sent to the machine. Preparing the stereolithography (SLA) machine to start building may require topping up the vat build material or changing it if a different resin is used. The laser is warmed up and diagnostics are performed. Once everything is ready, building the part can progress. Prebuild preparation cost, $(C_{\mathrm{pre}})_{\mathrm{SLA}}$, is derived from eqn (18)

$$\begin{aligned}(C_{\mathrm{pre}})_{\mathrm{SLA}} = {} & [(T_{\mathrm{pos}})_{\mathrm{SLA}} + (T_{\mathrm{param}})_{\mathrm{SLA}} + (T_{\mathrm{supp}})_{\mathrm{SLA}} \\ & + (T_{\mathrm{slice}})_{\mathrm{SLA}} + (T_{\mathrm{path}})_{\mathrm{SLA}}][(C_{\mathrm{oper1}})_{\mathrm{SLA}} \\ & + (C_{\mathrm{comp}})_{\mathrm{SLA}}] + (T_{\mathrm{set-up}})_{\mathrm{SLA}}(C_{\mathrm{oper1}})_{\mathrm{SLA}}\end{aligned} \qquad (34)$$

where the subscript SLA denotes the stereolithography process.

Build cost

During the building of the part, each cross-section is drawn with the laser, curing the liquid resin. Fairly accurate build time estimators are available[8] but these require processing of the part to generate laser paths, this is then interpreted to give an estimate build time. This is adequate if the part is in the orientation that is desired, but when trying to calculate the build time for multiple orientations then an alternative needs to be found. Estimation of an accurate build time for SLA from geometry alone is difficult. There are many variables such as laser paths, cure depths and differences between actual and theoretical laser velocities which are difficult to determine accurately and may vary from system to system. Since it is not the purpose here to develop an accurate build estimator but to illustrate the use of the cost model, a simplistic build time estimation based on part geometry is used until more accurate models are formulated.

There are many different parameters that affect the cured depth of each laser path. Contours on exterior surfaces are usually cured deeper than the interior filling patterns. Upward and downward facing flat surfaces, near flat surfaces and vertical walls all have variable cure depths which can be specified by the user and when the cure depth changes, the line width also changes. Filling the interior of the part, i.e. build style, has several different methods depending on material and end part use. Further, the part need not necessarily be built with constant layer thickness. Also, process variations during building such as power fluctuations and pauses due to queue starvation cannot be predicted increasing the build time error. Considering all these factors would add excessive complexity to the analysis. So, to simplify the problem, it is assumed that all vectors are drawn with the same cure depth, i.e. constant layer thickness, and only one vector scan is performed to cure the interior of the part and the part is uniformly sliced. From Ref. [9], the velocity of the laser, V_s, and cured line width, L_w, is given by

$$V_s = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \left(\frac{P_L}{w_0 E_c}\right) \exp\left(-\frac{C_d}{D_p}\right) \qquad (35)$$

$$L_w = 2w_0\sqrt{\frac{C_d}{D_p}} \qquad (36)$$

where P_L is the power of the laser, w_0 is $\frac{1}{e^2}$, the laser beam radius, C_d is the cure depth, and the critical exposure and penetration depth, E_c and D_p, respectively, are properties of the resin being cured. By assuming constant cure depth, line width is also constant. Therefore, time to cure one layer of resin, $(t_{\mathrm{part}_i})_{\mathrm{SLA}}$ is

$$(t_{\mathrm{part}_i})_{\mathrm{SLA}} = \frac{A_{\mathrm{part}_i}}{L_w V_s} \qquad (37)$$

where A_{part_i}, is the cross-sectional area of a cured layer.

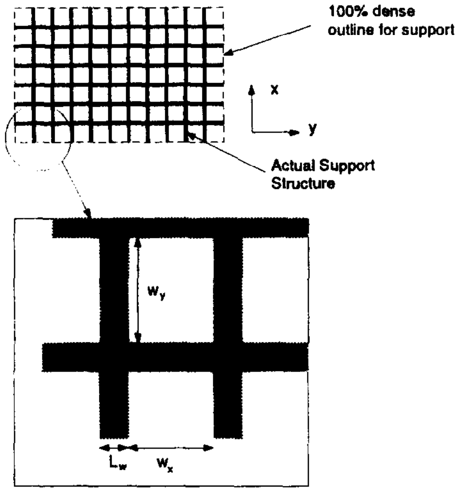


Figure 13 Relationship between cross-sectional support area and required support structure

The cross-sectional area of support is determined from the orientation calculation, A_{supp_i}. It assumes that it will be filled with 100% dense support material. However, for SLA this is not needed because there is a limited distance at which supports can be spaced without the surface deforming. The support structure is assumed to be built in a cross-hatch pattern as in *Figure 13*; other styles exist but only this one is used in the calculation. If $(w_{x\text{gap}})_{\text{SLA}}$ and $(w_{y\text{gap}})_{\text{SLA}}$ are spacings in the x and y direction, respectively, the density of the support structure, d_{SLA}, and the time to cure the supports, $(t_{\text{supp}_i})_{\text{SLA}}$, are

$$d_{\text{SLA}} = 1 - \left(\frac{(w_{x\text{gap}})_{\text{SLA}}(w_{y\text{gap}})_{\text{SLA}}}{[(w_{x\text{gap}})_{\text{SLA}} + L_w][(w_{y\text{gap}})_{\text{SLA}} + L_w]} \right) \tag{38}$$

$$(t_{\text{supp}_i})_{\text{SLA}} = \frac{d_{\text{SLA}} A_{\text{supp}_i}}{L_w V_s} \tag{39}$$

These approximate times for drawing support and part cross-sections do not take into account time to jump from the end of one path to the beginning of another. This is acceptable since the jump time is negligible when compared to idle time and time spent curing the resin. Again, drawing of external contours is ignored as with FDM for simplicity. So, total manufacturing time $(t_{\text{man}_i})_{\text{SLA}}$, for the ith layer, is

$$(t_{\text{man}_i})_{\text{SLA}} = (t_{\text{part}_i})_{\text{SLA}} + (t_{\text{supp}_i})_{\text{SLA}} \tag{40}$$

With constant slice thickness, the number of layers is given by eqn (27) and total manufacturing time is

$$(T_{\text{man}})_{\text{SLA}} = \sum_{i=1}^{N} (t_{\text{part}_i})_{\text{SLA}} + (t_{\text{supp}_i})_{\text{SLA}} \tag{41}$$

In between drawing each layer, the machine idles while it prepares the next layer of resin to cure. This idle time is composed of several stages, each having a user defined time length. Once the current layer is finished, the part is deep dipped into the resin in time, t_{dip}, where it stays in the dipped position for time, t_{postdip} after which the part is then elevated out of the resin in time t_{elev}. A blade sweeps over the surface of the resin N_{sw} times with a sweep interval of t_{sw} for each pass. Finally the part is lowered back into the resin bath, t_{low}, and waits, t_{zwait}, to complete the idle time. This happens between all, N_{lay}, layers of the part. So, total idle time is

$$(T_{\text{idle}})_{\text{SLA}} = (N_{\text{lay}} - 1)(t_{\text{dip}} + t_{\text{postdip}} + t_{\text{elev}} + N_{\text{sw}} t_{\text{sw}} + t_{\text{low}} + t_{\text{zwait}}) \tag{42}$$

SLA only uses one material to build both the part and support. So, the total volume of support, $(V_{\text{supp}})_{\text{SLA}}$, and the part, $(V_{\text{part}})_{\text{SLA}}$, as well as the cost/unit volume $(C_{\text{mat}})_{\text{SLA}}$, will determine the part cost.

$$(V_{\text{part}})_{\text{SLA}} = z_t \sum_{j=1}^{N} A_{\text{part}_j} \tag{43}$$

$$(V_{\text{supp}})_{\text{SLA}} = z_t \sum_{k=1}^{N} A_{\text{supp}_k} \tag{44}$$

$$(C_{\text{mat}})_{\text{SLA}} = z_t (C_{\text{mat}})_{\text{SLA}} \sum_{j=1}^{N} (A_{\text{part}_j} + A_{\text{supp}_k}) \tag{45}$$

and, the total cost for the building stage on SLA equipment is

$$(C_{\text{build}})_{\text{SLA}} = [(T_{\text{man}})_{\text{SLA}} + (T_{\text{idle}})_{\text{SLA}}](C_{\text{build}})_{\text{SLA}} + (C_{\text{mat}})_{\text{SLA}} \tag{46}$$

where $(C_{\text{build}})_{\text{SLA}}$ is the cost of running the machine per unit time while building the part. This equation is the same as eqn (20) except support and part material are the same so their individual costs are combined into $(C_{\text{mat}})_{\text{SLA}}$.

Postprocessing cost

Once the part is finished building it is ejected from the resin and any excess liquid on the surface is removed. This cleaning time, $(t_{\text{clean}})_{\text{SLA}}$, depends on the surface area of the part A_{surf}. The larger the area, the longer the cleaning. A simple approximation is to assume a linear relationship between time to clean and surface area, shown in eqn (47). The part is still in a green state and needs to be fully solidified by curing it in an ultraviolet oven. The time the part is in the oven, $(T_{\text{cure}})_{\text{SLA}}$, is assumed to depend upon its volume and likewise, linearly related where W_6 and Q are constants.

$$(T_{\text{clean}})_{\text{SLA}} = W_5 A_{\text{surf}} \tag{47}$$

$$(T_{\text{cure}})_{\text{SLA}} = Q + W_6 (V_{\text{mat}})_{\text{SLA}} \tag{48}$$

After the part is solidified, supports are removed and the surface is finished. The same relationships used for FDM (eqns (31) and (32)) are applicable here except different constants are used, i.e.

$$(T_{\text{rem}})_{\text{SLA}} = W_7 (A_{\text{over}})_{\text{SLA}} + W_8 (A_{\text{ab}})_{\text{SLA}} \tag{49}$$

$$(T_{\text{post}})_{\text{SLA}} = W_9 [(A_{\text{tot}})_{\text{SLA}} - (A_{\text{cont}})_{\text{SLA}}] + W_{10} (A_{\text{cont}})_{\text{SLA}} \tag{50}$$

Giving the total postprocessing cost for SLA as

$$(C_{\text{post}})_{\text{SLA}} = [(T_{\text{clean}})_{\text{SLA}} + (T_{\text{rem}})_{\text{SLA}} + (T_{\text{post}})_{\text{SLA}}] \times (C_{\text{oper2}})_{\text{SLA}} + (T_{\text{cure}})_{\text{SLA}} (C_{\text{cure}})_{\text{SLA}} \tag{51}$$

where $(C_{\text{cure}})_{\text{SLA}}$ is the running costs of the curing equipment and $(C_{\text{oper2}})_{\text{SLA}}$ the price of employing a skilled technician to finish the part. Comparing with eqn (21), postprocessing material costs are considered negligible and two other tasks apart from support removal and finish are performed.

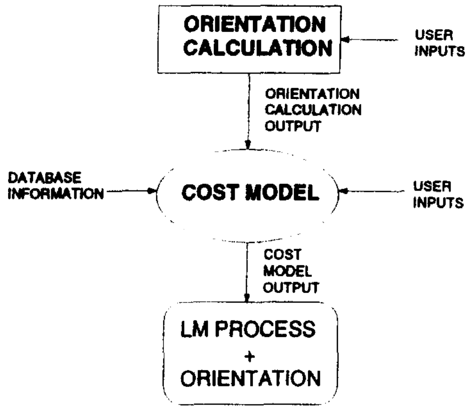


Figure 14 Relationship of orientation and cost model

Cleaning the part and curing are included in eqn (21) by the term

$$T_{\text{fproc}}[C_{\text{fproc}} + (C_{\text{oper2}})_{\text{SLA}}] \qquad (52)$$

For cleaning, no extra equipment is necessary so C_{fmach} is zero and, for curing, operator supervision is not required so C_{oper2} is ignored. The total cost of manufacturing a part on SLA can be calculated by substituting eqns (34), (46) and (51) into eqn (17).

By using the generic cost equations from the section *Generic Cost Model*, practical cost equations for FDM and SLA have been developed. These two process cost equations can now be applied to faceted models to compare costs of manufacturing parts in different orientations on both of these machines which is explored further in the section *Orientation Module*.

RELATIONSHIP OF ORIENTATION TO COST

Although the methods for orientation selection and cost models were developed separately, they are linked. Orientation is a very important factor that affects the build and postprocessing costs. In the cost equations there are factors such as layer thickness, road widths, operator wages, etc. which are predefined user inputs. Others, such as the weighting functions can only be determined by a database of experimental information. Several other factors are dependent upon the model, such as cross-sectional area of the supports and part for each slice, surface area in contact with supports, etc. These unknown cost model inputs can now be resolved because they are calculated by the output of the orientation calculation illustrated in *Figure 14*.

Using GPCs, the output of the orientation information can be tailored to represent a specific LM process and a set of candidate orientations prepared. For build cost inputs, the 'rays structure' and the part geometry gives the height of each orientation and cross-sectional areas of each layer of support and part. In the postprocessing stage, the surface areas of contact with support due to overhang, facets touched from above and total surface area and volume have been precalculated by the orientation.

An example illustrating the use of the output from the orientation module for the cost models for both SLA and FDM is given in the section *Example 1—Cost*. This shows the usefulness of information calculated from the orientation as input into a cost model. Also, in *Example 2—Volume and Contact Area of Supports* the effect of different orientations selected by GOCs alone on cost of manufacturing a FDM part is shown.

IMPLEMENTATION AND EXAMPLES

Orientation module

A suite of software tools to assist in LM is currently under development in the University of Michigan CAD/CAM Laboratory.[10] These tools include modules for variable slicing,[7,11] constructing CAD models from image and density data[12] and automatically controlling wall thickness in thin-walled parts.[13] The software that computes an object's best orientation, referred to as the orientation module (ORM), is part of that suite.

The ORM is viewed as a tool that will allow a manufacturer to automate part orientation to suit their needs before sending it to a layered manufacturing machine. This software acts as an additional step in the much larger manufacturing process. Further, using the cost function capability, the best machine, as well as the best orientation, to build a part for least expense can be identified. For example, the following scenario may describe a typical design cycle using the ORM in layered manufacturing.

(1) Design the part on a CAD system.
(2) Use the orientation module to pick the best orientation and the machine on which to build the part for least cost. Save the part in this new orientation.
(3) Using the adaptive slicing module, generate an adaptively sliced file for the oriented part.
(4) Send this slice file to the machine identified by the orientation module where the part will be manufactured, adaptively sliced and optimally oriented for the lowest cost.

The ORM was written in C++ and uses ACIS libraries for solid modeling and Qhull[8] for convex hull calculations. It runs on HP, Sun and Silicon Graphics workstation platforms and accepts either STL or ACIS SAT files as input. A screen shot of the interface is shown in *Figure 15*.

Process profiles can be selected prior to reading a part. A user-defined number of part orientations are selected by the ORM to be used for comparison. It is assumed that the best orientation will be contained within the set of orientations with the largest 'footprint' projected on the support platform. In addition to the orientations generated by the ORM, the user has the choice to add additional orientations allowing their direct comparison with ORM selected candidates. Orientations are then ranked using one of the following GOCs:

- minimizing the part's height;
- maximizing the stability of the object by selecting the largest base convex hull;
- minimizing the volume of support to reduce excess time and cost to deposit wasted material;
- minimizing total surface area of contact with support to reduce support removal and finishing time;
- maximizing the surface accuracy of the part for better part quality which will reduce the finishing time.

We are aware that multiple options could be selected but this then turns orientation selection into an optimization problem in which the relative importance of each factor must be determined. In the current version of the ORM, this has not been implemented.

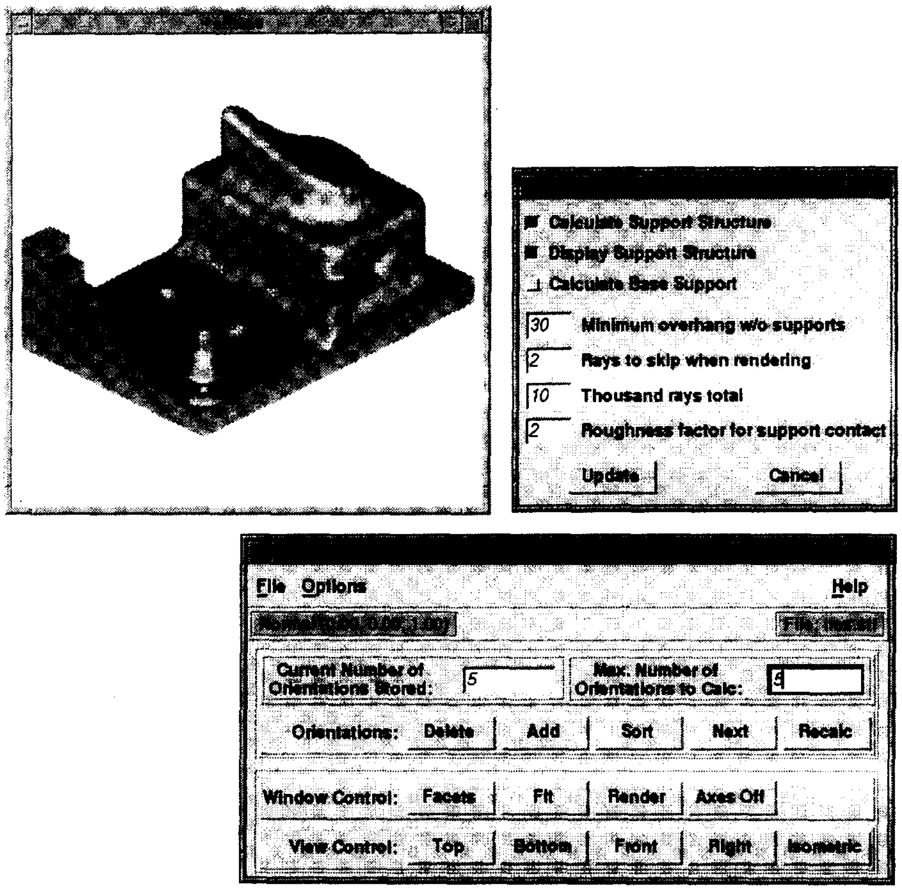


Figure 15 Screen shot of orientation module interface

The user also has the option to use the list of orientations ORM calculated as input into the cost calculation. From that, the cheapest orientation and which machine to manufacture a part on can be calculated.

Examples

Example 1—cost

Figure 16 shows three possible orientations generated by the ORM for a simplified cup with a total surface area of 9.06 in^2 and a volume of 0.64 in^3. A cost analysis can be performed on each using the previously developed cost model equations for FDM and SLA. Accurate information about various cost parameters, such as machine running costs and weight factors are unknowns for this analysis and so, where these are encountered, reasonable assumptions are made to their values.

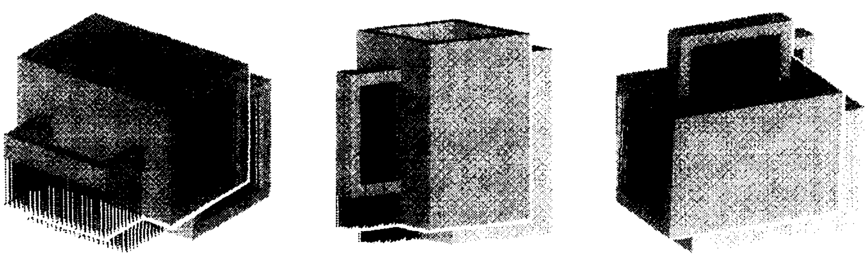
At present, the ORM does not provide slice information for the cost model, so manual calculation of build time using the equations developed in the sections *Cost Model for Fused Deposition Modeling* and *Cost Model for Stereolithography* are used to generate the appropriate information by the ORM about orientations for the cost model, the following process profile GPCs are used for FDM:

- enabled support structure;
- disabled base support structure;
- maximum overhang angle of 60°;
- support contact factor of 2.0.

SLA uses the profile GPCs:

- enabled support structure;
- enabled base support structure;
- maximum overhang angle of 70°;
- support contact factor of 0.5.

On the FDM machine, the part is manufactured from P301 at a cost of \$1 per in^3, with a road width of 0.020 in, a layer thickness of 0.010 in and nozzle velocity of



(A) (B) (C)

Figure 16 Three cup orientations

Table 1 FDM parameters for building a cup in three orientations

	Orientation		
	A	B	C
Total prebuild time (h)	0.33	0.33	0.33
Maximum height (in)	1.0	1.5	1.5
Total build time (h)	2.6	2.3	3.0
Volume of support (in^3)	0.46	0.046	0.47
Total volume of material (in^3)	1.10	0.686	1.11
Support area of contact for overhang (in^2)	1.26	0.18	1.24
Support area of contact from above (in^2)	1.07	0.075	1.27
Total support removal time (h)	0.27	0.03	0.30
Total finishing time (h)	1.12	0.77	1.15
Average weighted cusp height (in)	0.034	0.0038	0.0357

0.7 in s^{-1}. The support structure was assumed to have the same road width and the gap between roads was 0.020 in. The tip is wiped every layer and is included in the idle time between layers, along with the z movement and nozzle starting and stopping giving an average of 20 s idle per layer. The operating cost of the FDM is assumed to be $20 per hour.

For SLA, SL 5170 resin was used with $D_p = 0.0048$ in, $E_c = 13.5$ mJ cm^{-2} with a cost of $2 per in^3. The same layer thickness of 0.010 in was used as with FDM with $w_0 = 0.005$ in and laser power of 100 mW, giving a laser velocity of 34 in s^{-1} with a line width L_w of 0.015 in. For the supports, $w_{SLA_{xgap}}$ and $w_{SLA_{ygap}}$ are considered the same at 0.485 in. The total idle time in between each layer is 54 s which includes deep dipping, layer wiping, z movement, etc. Running the SLA machine is assumed to cost $35 per hour, and a cost of $15 per hour is assumed for the curing equipment.

File preparation time for manufacturing for both processes is equal at 20 min with a cost of using the computer of $1 per hour. Also, readying the machine takes 10 min for an operator employed at $20 per hour. The same operator is employed to perform the finishing functions.

Weighting factors have been chosen such that they emphasise the differences between each system. For support removal of a FDM part (eqn (31)), W_1 is 0.08 h in^{-2} and W_2 is 0.16 h in^{-2} and from the equivalent equation for SLA (eqn (49)), W_7 is 0.03 h in^{-2} and W_8 is 0.06 h in^{-2}. Supports are easier to remove for SLA than FDM so the weighting functions are less. Now considering the finishing equations (eqns (32) and (50)) for FDM and SLA respectively, W_3 is 0.08 h in^{-2} and W_4 is 0.25 h in^{-2}, since finishing the areas where supports touch takes longer for FDM. With SLA, the surfaces tend to be better quality so finishing takes less time, W_9 is 0.05 h in^{-2} and W_{10} is 0.08 h in^{-2}. Finally, weighting factors for cleaning the surface (eqn (47)) and curing time (eqn (48)) need to be assigned for SLA. W_5 is set to 0.007 h in^{-2}, Q to 0.5 h and W_6 to 0.05 h in^{-2}.

Table 2 SLA parameters for building a cup in three orientations

	Orientation		
	A	B	C
Total prebuild time (h)	0.33	0.33	0.33
Maximum height (in)	1.0	1.5	1.5
Total build time (h)	1.54	2.28	2.29
Volume of support (in^3)	0.078	0.020	0.144
Total volume of material (in^3)	0.718	0.66	2.08
Support area of contact for overhang (in^2)	2.76	1.18	2.74
Support area of contact from above (in^2)	1.07	.751	1.27
Total support removal time (h)	0.14	0.09	0.18
Total finishing time (h)	0.56	0.51	0.57
Total cleaning time (h)	0.63	0.63	0.63
Total curing time (h)	0.5	0.5	0.5
Average weighted cusp height (in)	0.0143	0.0047	0.0150

Table 3 Summary of costs for each process stage and total cost

	Orientations					
	A		B		C	
	FDM	SLA	FDM	SLA	FDM	SLA
Total prebuild cost ($)	10	10	10	10	10	10
Total build cost ($)	55	58	46	81	60	84
Total post processing cost ($)	28	34	16	32	43	35
Total cost ($)	93	102	72	123	113	129

Table 1 shows the list of variables calculated from the orientation module and cost model for the FDM calculation. Likewise, *Table 2* summarizes them for SLA. *Table 3* shows the direct comparison of the costs of each stage. For SLA, orientation A is the cheapest because it minimizes the height of the part reducing the amount of time spent idle while the machine prepares the next layer. For FDM, the idle time is not as significant and the amount of support and finishing costs play a more important role in determining part cost. Orientation B minimizes the amount of supports that are required so the build time is reduced. So, when determining the lowest cost method of producing the cup between the two system, the part should be built on FDM in orientation B because it has the lowest overall cost.

Example 2—volume and contact area of supports

The orientation of the part† shown in *Figure 17* would probably be selected by most people as the 'best' orientation to build the part. However, using the orientation module it is shown that for different criteria other less obvious orientations will produce better parts. If minimum surface area of contact with supports or maximum part accuracy is desired, then orientation B shown in *Figure 18* would be best used. However, this produces an increased amount of support material not present in orientation A, which increases the total build time and material usage. If the user wishes to minimize the amount of excess material due

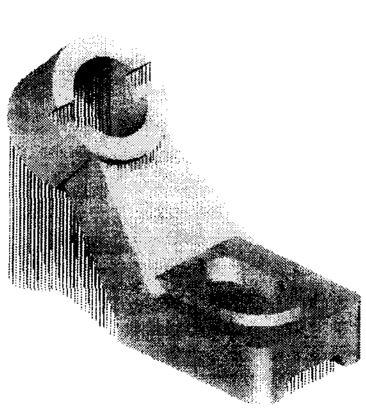


Figure 17 Orientation A: default orientation

† This part was obtained from the NIST repository at: http://elib.cme.nist.gov/pub/subject/pptb/repository/

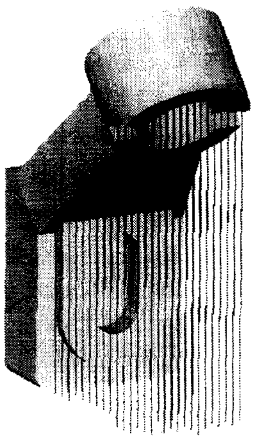


Figure 18 Orientation B: minimized support surface area contact and overall surface accuracy

to supports, then the part should be built in orientation C shown by *Figure 19*.

The cost of each of these orientations has been calculated for manufacturing on an FDM machine. The same parameters are used as in the previous example, where the total volume of the part is 8.8 in^3 with a surface area of 28.07 in^2. The values used by the cost calculation are displayed in *Table 4* and the resulting stage costs are summarized in *Table 5*. The cheapest orientation is the default, A. However, there is little difference in cost with orientation C, so either could be justified in being selected on a lowest cost basis. If higher part accuracy is required, then orientation C should be used but if minimizing build time is more important, orientation A should be selected. Maximum accuracy is the most expensive to manufacture with a lot of material and build time wasted manufacturing support. This is the price paid for higher accuracy of this part.

Table 4 Parameters used by cost calculation for FDM costs

	Orientation		
	A	B	C
Total prebuild time (h)	0.33	0.33	0.33
Maximum height (in)	3.83	5.74	2.29
Total build time (h)	28.7	39.2	30.6
Volume of support (in^3)	4.30	8.30	1.83
Total volume of build material (in^3)	13.1	17.1	10.6
Support area of contact for overhang (in^2)	10.2	7.37	8.07
Support area of contact from above (in^2)	0.72	1.13	1.04
Total support removal time (h)	0.93	0.80	0.81
Total finishing time (h)	4.8	4.3	4.5
Average weighted cusp height (in)	0.078	0.067	0.074

Table 5 Summary of costs for each process stage and total cost

	Orientation		
	A	B	C
Total prebuild cost ($)	10	10	10
Total build cost ($)	583	793	621
Total post processing cost ($)	115	102	106
Total cost ($)	708	905	737

SUMMARY

Our earlier work on part orientation has been extended to include surface accuracy of the part and determining the lowest cost orientation when comparing processes.

Although determining the best orientation of a part may be considered simple, it has been shown that even for some of these parts the 'obvious' orientation may not necessarily be the best. Conversely, for complex geometries, where an orientation is not immediately obvious, the best orientation can easily be determined using the ORM without operator intervention. The generic nature of the solution allows this methodology to be applied to a broad range of existing LM processes as well as easily being extensible to new ones.

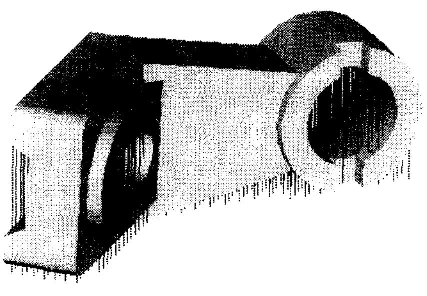


Figure 19 Orientation C: minimized volume of supports

Furthermore, a methodology has been developed for creating cost models for LM processes. The interdependence of orientation on cost has lead to the consolidation of the cost model and orientation to generate a procedure for determining the lowest cost orientation and process for a part. From the general model, customized cost equations for specific LM processes are created.

This generic approach is ideal for the current state of the LM technology. New processes are continually being introduced with the same basic layer-by-layer approach to LM but slightly different ways of producing the part. This method allows these new processes to be easily incorporated into the ORM without the need to change existing code or methodologies. Development of cost models, especially estimating the build time, is, of course, process dependent but because the general cost equation is used as the building blocks for process specific equations, common cost factors exist between process equations.

ACKNOWLEDGEMENTS

Financial support received from the Office of Naval Research Grants N00014-95-1-0767 and N00014-97-1-0245 is gratefully acknowledged.

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