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ORIGINAL ARTICLE

J. Giannatsis · V. Dedoussis

Decision support tool for selecting fabrication parameters in stereolithography

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Abstract The selection of fabrication (build) parameters is the most important task performed by the operator of a layer manufacturing (LM) system. In order to select the best parameter configuration for a part, the operator should be able to compare different alternatives and evaluate them under specific constraints, in terms of fabrication cost and quality. In the present paper, a software decision support tool for build parameters selection in stereolithography is presented. Build orientation and layer thickness are proposed as the primary parameters for the definition of candidate solutions, which are evaluated according to a weighted multi-criteria objective function. As the objective function criteria, the build time, surface roughness and process error are employed. The criteria estimation is based on experimentally derived analytical equations or computed from the STL representation of the part. To further enhance the evaluation process, the software tool exports VRML models that incorporate surface roughness or stairstepping data through colour codification.

Keywords Layer manufacturing · Stereolithography · Build parameters · Build orientation · Surface roughness · VRML applications

1 Introduction

Since their introduction in the early 1990s, layer manufacturing (LM) technologies, or rapid prototyping (RP) technologies as they are also called, evolved to a common and invaluable tool for many companies worldwide, providing fast and cost-effective solutions to the needs of fabricating concept models, prototypes [1–3] and small-batch manufacturing tools [4, 5] for new products, thus, accelerating and enhancing the product development process [6]. During the last few years, the use of LM technologies has also expanded to other applications, such as the on-demand fabrication of medical products and models [7], small-batch manufacturing (or rapid manufacturing) [8] and architectural modelling [9], which extended their use and established them as a dynamic and distinctive group of manufacturing technologies.

Stereolithography, fused deposition modelling (FDM), selective laser sintering (SLS), laminated object manufacturing (LOM) and 3D printing (3DP) are some of the most widely known and used LM technologies [10]. The operation of all LM systems is based on the same basic principles; the fabrication of parts layer-by-layer without the need for any special manufacturing tools or fixtures. The differing factor between them is the material and the physical method employed for the formation and addition of successive layers. Part fabrication in LM is a "bottom–top" direction operation and, hence, the term "building" is very often used instead of fabricating.

The entire manufacturing process using LM technologies comprises of three distinct phases [11]; the pre-fabrication phase, in which the LM machine operator selects the appropriate fabrication (build) parameters and performs several data-preparation tasks (slicing, support generation etc.); the "build" phase, during which the part is fabricated by the LM system and the post-fabrication or "finishing" phase, in which part cleaning, surface polishing and other tasks (post-curing, infiltrating etc.) are performed.

Since the LM system operation during fabrication is entirely automated, the build parameters selected values define, to a great extent, the machine time (build time) cost, the surface quality and the dimensional accuracy of the part, as well as the expected time and effort required in the finishing phase. Layer thickness and build orientation are two of the most important parameters that must be defined prior to fabrication with most LM systems [12]. Other operator-dependent parameters are mostly technology-

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J. Giannatsis · V. Dedoussis (✉)
Center for Product Development and Rapid Prototyping,
Department of Industrial Management and Technology,
University of Piraeus,
80 Karaoli & Dimitriou Str.,
18534 Piraeus, Greece
e-mail: vdedo@unipi.gr
Tel.: +30-210-4142320
Fax: +30-210-4142356
e-mail: ggian@unipi.gr

dependent and vary according to the layer formation method and the materials used.

In order to select or define the appropriate values for the build parameters for a part, the operator takes into consideration its geometrical and morphological features and, most importantly, its intended use. Functional prototypes or casting patterns (e.g. for vacuum casting) should exhibit high fabrication quality, as expressed in terms of dimensional accuracy and surface finish, in order to allow reliable functional testing and reproduction of the part. Concept models on the other hand, which are mostly employed for design review purposes or as communication tools, should be fabricated at minimum cost and time. Since the building cost and quality are inversely related, the operator usually seeks to achieve the best compromise between the two.

In the absence of a formal procedure for the estimation of fabrication quality, cost or time, parameter selection is based on the experience of the operator and on rather simple and "reasonable" assumptions and rules. For example, it can be reasonably assumed that, the thinner the layer is, the bigger the build time due to the higher number of layers. Hence, if the minimum cost is required, the maximum layer thickness must be selected. On the contrary, when maximum accuracy is required, the minimum possible layer thickness should be employed. In a similar manner, orientation rules can be derived that prohibit the presence of stairstepping—the stair-wise effect of surfaces inclined with respect to the build orientation—in surfaces containing important features. These simple assumptions and rules are primarily of comparative nature (e.g. orientation "A" is better than "B" in terms of cost). However, they are not very helpful in cases where conflicting decision situations arise, such as when two important features have different optimum orientations or in the case where certain quality or cost constraints must be controlled. Furthermore, parameter selection based on such simple rules and experience does not guarantee optimality, in view also of the large variety and geometric complexity of parts fabricated usually with LM methods. The development of specific support tools that estimate build cost and quality and facilitate reliable pre-fabrication evaluation of specific parameters configurations could, therefore, prove to be a valuable aid for the operator. These tools could be also used in other tasks besides parameter selection, such as the scheduling of machine operations and, thus, contribute to the best utilisation of the relatively expensive LM systems.

In order to develop reliable operator decision support tools, accurate and reliable estimation models of fabrication quality, cost and time as functions of build parameters need to be constructed, a task that requires a detailed study of the particular technology under investigation. In the present work, a software decision support tool for the pre-fabrication phase of the stereolithography process is presented. The development of this tool has been based on detailed analysis and experimental investigation of stereolithography; however, the methodology presented herein, as well as the structure of the decision support tool developed, could be also applicable to other LM technologies with similar characteristics, like SLS. The proposed software tool can be used for the evaluation of different sets of build parameters during the parameter selection phase, as well as an aiding tool for other pre-fabrication tasks, like quotation offer and job scheduling.

2 Previous work

As noted previously, one of the most important build parameters, in terms of cost and quality, common to all LM technologies is the build orientation. Thus, the problem of finding the best build orientation for a part given a set of fabrication constraints or requirements, usually referred to as the orientation problem, has attracted the attention of many researchers. The orientation problem, like the build parameters selection problem, is, by definition, a multi-criteria optimisation problem. The most simple and intuitive approach to address the multi-criteria nature of the problem is to classify and rank the various conflicting criteria or goals according to their importance and try to assess them separately or consecutively.

This approach is followed by Allen and Dutta [13], who focus on stereolithography and choose, as a primary criterion, the total amount of surface area of the part that comes into contact with supports (supported area) and seek to minimise it. The best orientation is chosen from a set of candidate orientations, which consists of all orientations that have a face of the convex hull of the object as the base. Bablani and Bagchi [14] propose three criteria that can be minimised independently, namely, the process error, the process planning error (as a measure of stairstepping) and the number of layers. The proposed algorithm evaluates one of the above criteria through gradual rotation of the object around one or more axes and by a specified interval. The method of assessment of candidate orientations by rotation around user-specified axes is proposed also by Masood and Rattawong [15]. In the proposed system, an algorithm to minimise the amount of volumetric error is employed. The volumetric error is calculated through slicing of the candidate orientations.

Frank and Fadel [16] propose an expert system which is based on the optimum orientation rules of various geometrical features (planar, cylindrical etc.), in which stairstepping in the corresponding surfaces is minimum. They propose a simple decision matrix that may be used effectively in the case of one critical feature, which is useless, however, if two or more features with different optimum orientations are considered. A similar approach is proposed by Yew et al. [17], who focus on the problem of trapped volume and propose an advisory system that identifies problematic orientations from the 3D model of the part.

Cheng et al. [18] employ the method of progressive multiple objective optimisation, considering the maximum surface quality as the primary objective, minimum building time as secondary and (if required) part stability as third. Surface quality is assessed directly via the CAD model of the part according to the orientation of its surfaces and a predefined weighted scheme, while the build time is assessed indirectly by the number of layers. The orientations with a planar surface of the part as the base are considered as candidate solutions.

Mahji et al. [19] present a set of geometric algorithms that may be used to find the optimum orientation of a part minimizing the stairstep error (its maximum or mean value), the supports volume or the total supported area. All algorithms can be employed to any polyhedral model, except the minimum supports volume algorithm, which is applicable only to convex polyhedral models.

Thompson and Crawford [20] investigate the orientation problem in the case of SLS, where they identify four criteria for the selection of optimum orientation: the part height, the total area of stairstepped surfaces, the total area of supported surfaces and the mechanical strength. To find the best orientation, one of the above criteria is selected as the primary criterion and is optimised through an appropriate optimisation algorithm. Pham et al. [21] describe in detail a feature-based decision support system that helps the stereolithography operator to select the best orientation among a set of candidate orientations considering cost, time, problematic features, optimal orientation of critical features, overhang area and support volume. Lang et al. [22] propose total area of stairstepped (worst-quality) surface, part height and volume of the support structure as the criteria and present algorithms that find the optimum orientation (the one that minimises any of the criteria) among a set of candidate orientations. Candidate orientations are defined by the planar faces of the convex hull of the object.

In the above presented studies, the orientation problem is investigated independently. All other parameters are considered to be as either constant or not significant, as in the case of layer thickness. In many studies, the layer thickness is assumed to obtain a standard and constant value; thus, the height of the part for a particular orientation is employed as a measure of build time (as implicitly defined by the number of layers). Another consideration of the orientation problem that indirectly addresses the issue of layer thickness selection is to employ adaptive slicing methods, in which the layer thickness does not have a constant value, but varies according to a specified accuracy tolerance that is usually associated with stairstepping [23]. The approach of adaptive slicing is used by Hur and Lee [24] for the calculation of the required number of layers in their proposed orientation selection support system. Other proposed criteria for the orientation selection are the total area of stairstepped surfaces, the volume of supports and the "trapped" volume. Xu et al. [25] also propose adaptive slicing as an answer to the trade-off problem between cost and accuracy. The number of layers, the total area of down-facing surfaces and part stability are considered as criteria for orientation selection. An objective function that considers the three criteria according to a user-defined weight is used for the selection of the optimum orientation.

The problem of build parameter selection, in general, is addressed in much fewer studies than the orientation problem. McClurkin and Rosen [26] present a decision support system for stereolithography that helps the user to select appropriate values for process parameters in order to achieve fabrication goals for accuracy, surface finish and build time. In order to construct prediction models that relate quantitatively the fabrication goals to build parameters, namely, part height (which is directly associated with orientation), layer thickness and hatch spacing, a profound experimental analysis according to response surface methodology is used. Multi-objective optimisation is achieved using the compromise decision support problem (DSP) method.

Choi and Samavedam [27] describe a virtual reality system for modelling and parameter optimisation for SLS technology that does not suggest an optimum solution, but can be used for parameter fine-tuning. The system incorporates mathematical estimation models for accuracy, build time and orientation efficiency, and visually simulates the building process, thus, helping the operator select appropriate parameters depending on the build requirements. They identify part orientation, layer thickness and hatch spacing as the key control parameters that influence the specified requirements significantly.

3 Features of the decision support system

3.1 Stereolithography parameters

Following the classification proposed by Schaub et al. [28] in the present work, we consider as build parameters all those process variables that are directly controlled by the operator. In the aforementioned stereolithography optimisation study, as well as in similar studies [29, 30], build orientation, layer thickness, hatching space, hatching style and vat positioning are identified as the most influencing build parameters in terms of accuracy and quality. In all of the above studies, the type of resin and its properties are considered constant, a reasonable assumption in view of the practical difficulty of changing the resin in a single stereolithography machine. In the present study, build orientation and layer thickness are considered to be the two primary parameters, since they implicitly define several variables associated with cost and accuracy, the most important being: the number of layers required, the presence and intensity of stairstepping on part surfaces, the volume of the required support structures and the total area of the supported surfaces (Fig. 1).

Since the proposed system can handle, at the moment, a single part, it is assumed that this is positioned in the centre of the platform, the best possible position in terms of accuracy. Scanning consists of two procedures, contouring or border scanning and hatching. During contouring, the scanning control mechanism directs the laser beam to "draw" and solidify the borders (contour) of each layer. Layer hatching is carried out according to a predefined hatching style, which, for the investigated stereolithography system (EOS, Stereos Desktop S), is of rectangular type. Rectangular hatching style involves the "drawing" of closely spaced parallel vectors or line segments in the *X*-

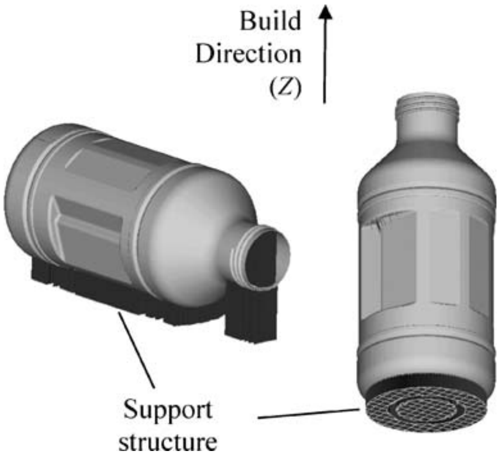


Fig. 1 Possible build orientations for a bottle with the appropriate support structure

wise and *Y*-wise sense, with *X* and *Y* being the two axes defining the machine's platform plane (Fig. 2). The hatching style is also considered constant due to limitations of the specific stereolithography system under investigation.

Likewise, the hatching space (*hs*) is assigned a low and constant value (0.05 mm) to ensure high accuracy and low post-processing shrinkage of the parts [31, 32]. Secondary build parameters, namely, curing depth and hatch velocity, are directly related to the layer thickness (*Lth*) value. The curing depth (*Cd*) is defined as the depth to which resin solidification occurs, given a certain amount of laser-induced energy. For every value of layer thickness, an optimum curing depth is specified through special experimental procedures, to ensure proper solidification and coherence of successive layers, as well as to minimise distortion and the effect of residual stresses [33, 34]. According to the optimum curing depth value and the curing resin properties (critical energy and penetration depth), scanning velocities for every layer thickness are computed [31]. Resin properties as well as shrinkage and beam width compensation are defined via diagnostic testing [35] and they are considered constant.

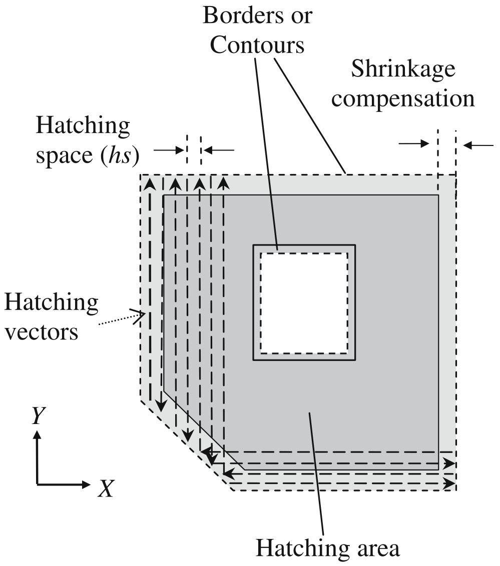


Fig. 2 Schematic representation of the basic scanning build parameters

Layer thickness is considered constant during building and may take three values: 0.10 mm, 0.15 mm and 0.20 mm. These three values are the most commonly used. Variable layer thickness (via adaptive slicing) is not considered. According to the experience of the authors, employing variable layer thickness during the simultaneous building of different parts with variable geometry and form (a practice which is usually followed in order to maximise the effective utilisation of the system) results in several difficulties and complications in stereolithography.

Another important aspect of the build parameter selection problem is the type of geometric representation that the system should process. This decision affects the way of defining candidate orientations and evaluating various geometric properties of the part (volume, surfaces areas etc.) that need to be computed. In some of the previous studies examined, the native CAD system representation is used, because this sort of representation offers the advantage of relatively simple identification of critical or problematic features. In other studies, however, STL is proposed for the representation of part geometry. The STL format is a relatively simple format for triangular tessellated representation of part geometry. Due to its simplicity, it is the de-facto standard for geometric data transfer from various CAD systems to RP control equipment and software [36]. In order to ensure the general applicability of our methodology, STL is used in the proposed system.

Based on the STL representation of the part, candidate orientations for evaluation are defined through the identification of relatively large planar surfaces, which are, in turn, considered as base surfaces for the build orientation. Other candidate orientations may also be considered selectively by the operator, so as to ensure the maximum accuracy of critical features. For each one of the candidate orientations, three candidate solutions (in accordance with the three different values of the layer thickness considered) are defined, in order to form the candidate orientation–layer thickness pairs that are evaluated by the present system.

3.2 Candidate solutions evaluation method

For the evaluation of candidate solutions, the method of a weighted objective function is proposed, a technique commonly used for multi-criteria decision making problems. In the system developed, the objective function *OF* (*i*, *j*) value for orientation *i* and layer thickness *j* incorporates the relative rating of three criteria—build time (*BT*), surface roughness index (*SR*) and layering error (*PE*)—multiplied by the corresponding criteria weighting factor/coefficient (w_1, w_2 and w_3), which are (judiciously) defined by the operator according to their relative importance and fabrication requirements. The objective function to be *minimised* reads:

$$OF(i,\ j) = w_1 BT(i,\ j) + w_2 SR(i,\ j) + w_3 PE(i,\ j) \tag{1}$$

The build time is defined as the time required by the stereolithography system in order to build a part in a specified orientation and with a specified layer thickness. It is proposed as one of the three basic criteria because it is directly related to the building cost. The latter is the main part of the total fabrication cost, due to the high (hourly) operational and maintenance cost of the stereolithography system. Furthermore, the build time is the cost-associated factor that is mostly affected by parameter selection, since resin cost (the second most important factor in terms of cost) depends primarily on the volume of the part and is, therefore, similar for all candidate solutions. Surface roughness, on the other hand, is a fabrication quality criterion that can be directly associated with post-processing (finishing) time and is especially important in cases where the fabrication of casting patterns or tools is involved. Process error is the third criterion incorporated in the objective function as a measure of the expected errors caused by the stereolithography process itself, like stairstepping error or/and overcure. Build time and surface roughness are estimated according to experimentally derived formulae, while process error is computed analytically based on the STL representation of the part in a given orientation and for a given layer thickness.

Prior to the objective function evaluation, the operator may define constraints or maximum limits for any of the three criteria, so that possibly "infeasible" solutions are excluded. After having checked the feasibility of candidate solutions, the respective objective function values are computed. Since the units and the order of magnitude of the values of the three criteria differ considerably, and in order to avoid situations where a particular criterion over-influences the objective function, the objective function value is computed employing appropriately normalised variables for each one of the three criteria. The normalisation procedure adopted in this work relates the "score" of the solution (with respect to a particular criterion) in terms of the best and worst possible solutions. Thus the normalised $BT_n(i, j)$ criterion, for instance, reads:

$$BT_n(i,\ j) = \frac{BT(i,\ j) - BT_{\min}}{BT_{\max} - BT_{\min}} \tag{2}$$

where $BT_{\min}$ is the minimum and $BT_{\max}$ is the maximum build time, estimated for all candidate solutions. Likewise, the normalised $SR_n(i, j)$ and $PE_n(i, j)$ criteria variables are introduced in the objective function.

Following the evaluation of candidate solutions, the support tool developed classifies each one of the different orientation–layer thickness pairs according to the objective function value. For every candidate solution, the actual values of build time, surface roughness and process error, as well as the respective building cost and supported area, are presented to the operator for criterion-specific evaluation. Quantitative data permit objective comparison of candidate solutions, but are not very useful in assessing qualitative factors, such as finishing difficulty or critical features accuracy. These aspects are assessed through the examination of 3D VRML virtual models of the selected solutions, in which average roughness and stairstepping for every part surface are presented employing colour codification schemes. It should be noted that VRML is a popular standard for the representation of 3D objects on the Internet and the Web; therefore, any VRML model can be examined thoroughly in any Internet browser equipped with the appropriate free-of-charge plug-ins, (say, the "Cosmo Player"). Detailed analysis of the criteria/objective function calculation procedures, as well representative test cases, are presented in the following sections.

3.2.1 Build time and cost estimation

The total fabrication cost of a stereolithography part is the sum of the costs associated with the three phases of the process, namely, pre-fabrication cost (*PreCost*), build cost (*BCost*) and post-fabrication cost (*PostCost*). It reads:

$$FabricationCost = PreCost + BCost + PostCost \tag{3}$$

The pre- and post-fabrication cost can be estimated as the product of the time required for the completion of the associated tasks (*PreTime* and *PostTime*, respectively) multiplied by the associated hourly costs C_{pre} and C_{post}, respectively:

$$PreCost = PreTimeC_{pre} \tag{4}$$

$$PostCost = PostTimeC_{post} \tag{5}$$

The build cost is the sum of the operational cost, which is the product of build time (*BTime*), multiplied by the machine hourly operational cost (C_{m}) plus the resin cost, calculated using the volume of the part (V_{part}) and the supports (V_{sup}), the density of the resin (ρ_{r}) and the resin cost (C_{r}):

$$BCost = BTimeC_m + \left(V_{part} + V_{\mathrm{sup}}\right)\rho_r C_r \tag{6}$$

A comparison of the above three costs shows that the build cost, in most cases, is the highest, due to the relatively longer time required, to the increased hourly costs involved and to the high resin prices. On the other hand, the pre-processing cost is quite low because neither the respective hourly cost (cost associated with the required computer hardware and software) is especially high, nor is the required time for the completion of the various tasks usually very long (rarely exceeds one hour). The post-processing hourly cost is also quite low (neither expensive tools nor a lot of labour is involved). The post-processing cost is relatively low even if finishing requires a few hours to be completed.

In order to accurately estimate the building cost of a given candidate orientation–layer thickness pair, an accurate estimation of the build time and the volume of the part and supports is required. Part and support volume figures can be fairly easily and quite accurately derived from the STL representation of the part. On the other hand, build time estimation is a more complex problem.

The build time of a part is actually the time required for the addition of all layers. The addition of a single layer is performed in two steps; the recoating step, during which uncured resin is spread on the previously solidified layer, and the scanning step, during which the laser beam scans the appropriate area solidifying the uncured resin layer. Thus, the time required for the creation of a single, say the *i*th, layer *Tlayer*(*i*) is evaluated as the sum of the recoating and the scanning times:

$$TLayer(i) = TRecoat(i) + TScan(i) \tag{7}$$

Both the recoating time (*TRecoat*) and the scanning time (*TScan*) can also be analysed as smaller periods of time. For any layer, *TRecoat* can be calculated as the sum of the time required for the lowering of the platform (*TPlatform*), the time required for the recoater movement (*TRecoater*) and the pre- and post-scan resting or delay periods (*TPRe*, *TPOst*, respectively). Thus, for the *i*th layer:

$$\begin{aligned} TRecoat(i) = {} & TPlatform(i) + TRecoater(i) + TPRe(i) \\ & + TPOst(i) \end{aligned} \tag{8}$$

The recoater and platform time are expressed as:

$$TRecoater(i) = \frac{Rd}{Rv(i)} \tag{9}$$

and:

$$TPlatform(i) = \frac{Lth(i)}{Pv} \tag{10}$$

where *Rd* denotes the (constant) distance covered by the recoater, *Lth* is the layer thickness and $R\nu$ and $P\nu$ denote the recoater and platform velocities, respectively. For every value of layer thickness, an optimum set of recoating parameters is defined through diagnostic testing [31]. Since *Lth* is constant, it is quite obvious that the total recoating time estimation is relatively straightforward, provided that the number of layers is known.

The main difficulty in the estimation of build time resides in the estimation of the individual layers' scanning time. The scanning time (*TScan*) is the sum of the times required for the completion of layer contouring (*TContour*) and hatching (*THatch*), which can, theoretically, be computed as:

$$TScan(i) = THatch(i) + TContour(i) = \frac{Hl(i)}{Hv(i)} + \frac{Cl(i)}{Cv(i)} \tag{11}$$

where *Hl* and *Cl* denote the total length of all vectors drawn during hatching and contouring (hatching and contouring length), respectively, and *Cv* and *Hv* are the respective scanning velocities.

The extensive experimental investigation, which has been carried out for the stereolithography system that is in operation at the University of Piraeus (EOS, Stereos Desktop S), indicated that, instead of using the theoretical expression for *THatch*, the following expression should be employed:

$$\begin{aligned} THatch(i) = {} & \frac{Hl(i)}{Hv(i)} + 0.0005 No.Vectors \\ & + \frac{Hl(i)}{54Hv(i) + 6114} - 0.206 \end{aligned} \tag{12}$$

Equation 12 accounts for the observed delays which are partially directly related to the number of hatching vectors (*No.Vectors*), as well as the hatching length and velocity. Detailed presentation of the experimental investigation and the associated results can be found in [37, 38].

It is evident that the accuracy of the build time estimation depends not only on the validity of the equations employed, but also on the accuracy of the estimations of all relevant parameters, i.e. *Hv*, *Cv*, *Hl*, *Cl* and *No.Vectors*. Our investigation [37] showed that the scanning velocities estimation can be quite accurate, to within ±5%, provided that the system laser power is monitored and "continuously" updated within the scanning velocities calculating formulae. The estimation of properties related to the layer geometry (*Hl*, *Cl* and *No.Vectors*) requires an accurate representation of the layer geometry. Such information is incorporated in slice models (in SLI or CLI format) of the part which contains the actual geometrical data that drive the stereolithography system during part building. However, slice models are constructed after the orientation and layer thickness are selected; thus, they are not available in the parameter selection phase. To overcome this problem in our methodology, we employ the expressions proposed by Tata and Flynn [39], which estimate total contouring and hatching length for all *n* layers of a part based on geometric data obtained from the STL model. Assuming that a constant layer thickness *Lth* is employed, these expressions read:

$$TotalHatchingLength \equiv \sum_{i=1}^{n} Hl(i) = \frac{V}{Lth \cdot hs} \tag{13}$$

$$TotalContouringLength \equiv \sum_{i=1}^{n} Cl(i) = \frac{VA}{Lth} \tag{14}$$

where *V* is the volume of the STL model and *VA* is the vertical area. *VA* represents the area sum of all of the triangles of the tessellated model of the part, projected on a vertical (normal to the machine's platform) plane. Strictly, Eqs. 13 and 14 are valid only if the whole volume of the part is fully cured, i.e. no semi-hollow building styles, such as Skin&Core or Quickcast, are adopted.

The present authors carried out build time estimations for a variety of "real-world" build jobs using both CLI and STL data, employing the above given Eqs. 7–14. The comparison between the estimated and the actual build time recorded showed that STL-based estimations are accurate to within 5% on average, while CLI-based are accurate to within 2% [38]. As far as the software support tool developed in this work is concerned, STL-based estimations are at an acceptable level of accuracy, indicating that the corresponding methodology can be safely employed as a build time estimator in the parameters selection phase.

3.2.2 Surface roughness estimation

Surface roughness is one of the major issues concerning the quality and accuracy of parts fabricated with stereolithography. Especially in the case of casting models for secondary processes (e.g. vacuum casting), low surface roughness is of great importance, as it affects not only the appearance and functionality of the part but also the life of the associated moulds and tools; hence, the cost of the reproduction process.

The major cause of excessive surface roughness of stereolithography parts is stairstepping, which is observed in all non-horizontal/-vertical surfaces of a part with respect to the build orientation [40]. The intensity of stairstepping of a planar surface depends on the layer thickness employed and the angle of the surface with respect to the build axis. Another factor that may affect the roughness of down-facing surfaces, regardless of their orientation, is whether they are in contact with supports (after the fabrication support remains).

The correction of excessive surface roughness of stereolithography parts, or "finishing" as it is usually referred to, is usually performed via manual polishing using power tools and sandpaper (depending on the size, complexity and level of detail of the part) or via coating with compatible materials. In most cases, finishing is a very time-consuming and skill-intensive task that only experienced technicians can achieve smooth surfaces without damaging or impairing the accuracy of the part [41]. Overall estimation of a part's surface roughness is, therefore, useful not only as a measure of build quality and accuracy, but also as a measure of the required finishing time and effort.

In order to construct accurate analytical surface roughness prediction models for the stereolithography system under consideration in this work, a set of three specifically designed test parts, each one for a different value of layer thickness, were built and measured. The geometry of the parts is similar to that of the corresponding test parts used in other researchers' studies [39, 40] and they are comprised mainly of planar surfaces of gradually increasing slope (Fig. 3) between 0° (up-facing horizontal plane) and 180° (down-facing horizontal plane). The supports of the parts were removed through careful washing in acetone.

The three test parts were measured using an inductive digital roughness gauge with a resolution of 0.01 μm. The average roughness R_α was chosen as the representative measure of surface roughness. For each planar surface, three measurements of R_α were taken, from which, a mean value for the surface roughness was calculated. Average roughness measurements of the test parts, as well as corresponding results of the study of Reeves and Cobb [40] for a test part fabricated with the SL-250 ACES (0.15 mm) build style are presented in Fig. 4.

Regression analysis to the obtained measurements has been employed to define the following set of new analytical relations, which express the surface roughness of a planar surface as a function of its slope (*s*) and the layer thickness:

$$\begin{aligned} R_\alpha(0.20,\ s) = {} & -2\times10^{-10}s^6 + 1\times10^{-7}s^5 - 2\times10^{-5}s^4 \\ & +0.002s^3 - 0.1226s^2 + 3.5109s - 1.359 \end{aligned} \tag{15}$$

$$\begin{aligned} R_\alpha(0.15,\ s) = {} & -2\times10^{-10}s^6 + 9\times10^{-8}s^5 - 2\times10^{-5}s^4 \\ & +0.002s^3 - 0.1072s^2 + 2.6154s - 1.161 \end{aligned} \tag{16}$$

$$\begin{aligned} R_\alpha(0.10,\ s) = {} & -1\times10^{-10}s^6 + 6\times10^{-8}s^5 - 1\times10^{-5}s^4 \\ & +0.001s^3 - 0.0501s^2 + 1.3187s + 0.117 \end{aligned} \tag{17}$$

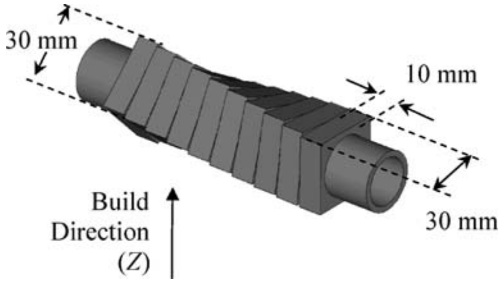
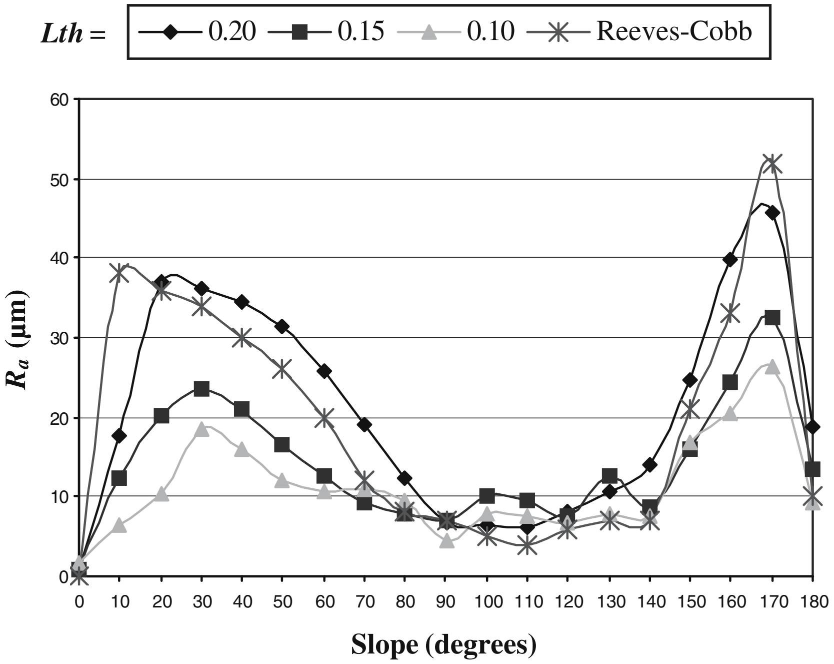


Fig. 3 3D model of the roughness measurement test part

Fig. 4 Average surface roughness with respect to the slope of each planar surface (in °) for different layer thicknesses



The above relations in Eqs. 15–17 are actually used in the present software support tool in order to estimate the expected roughness of each facet of the STL-tessellated model of the part to be fabricated. Detailed presentation of the analytical expressions for roughness prediction as well analysis and discussion of the results can be found in [42].

3.2.3 Accuracy estimation

Dimensional accuracy of the stereolithography part compared to the original CAD model is of prime importance (as with any other manufacturing process). The overall accuracy of stereolithography has been investigated in previous studies [43]. Cheng et al. [18] identify the following possible sources of dimensional inaccuracies:

- STL tessellation errors
- Slicing-induced errors
- Resin shrinkage
- "Closed volumes" (or "trapped volumes") effect
- Stairstepping
- Overcure of bottom layers

STL tessellation is the first possible cause of errors, since STL representation is, by definition, an approximation of the original 3D model geometry. Nowadays, however, STL approximation is by far more accurate than in the past, since modern computer hardware and software are capable of handling the vast amount of triangular facets required for the "smooth" and sufficiently accurate approximation of non-planar surfaces. Slicing-induced errors, on the other hand, are observed in cases where the chosen value of layer thickness is not an integer dividend of a certain dimension of the part. The control of slicing-induced errors, therefore, cannot be achieved prior to slicing and are not taken into account by the system. A complementary aiding module is currently under development that could help the stereolithography operator evaluate the accuracy of particular critical dimensions of the part.

Resin shrinkage and the "closed volumes" effect are related to the stereolithography resin properties. Resin shrinkage is a natural result of the solidification process and may not only lead to dimensional errors, but also to deformations of the geometry of the part, like "cantilever distortion," a distortion caused by forces exercised to bottom layers by the layers immediately above them. The "trapped volume" effect is related to the surface tension and is more evident in older types of high-viscosity resins. Both problems are, to a great extent, reduced in modern stereolithography systems as a result of the continuing improvement in stereolithography resins technology and the use of more efficient compensation mechanisms/

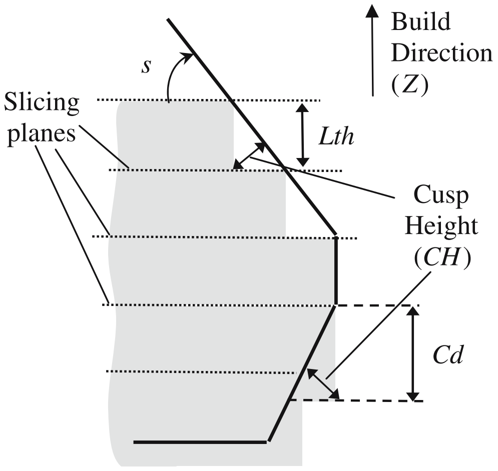


Fig. 5 Schematic representation of stairstepping errors and the associated build parameters

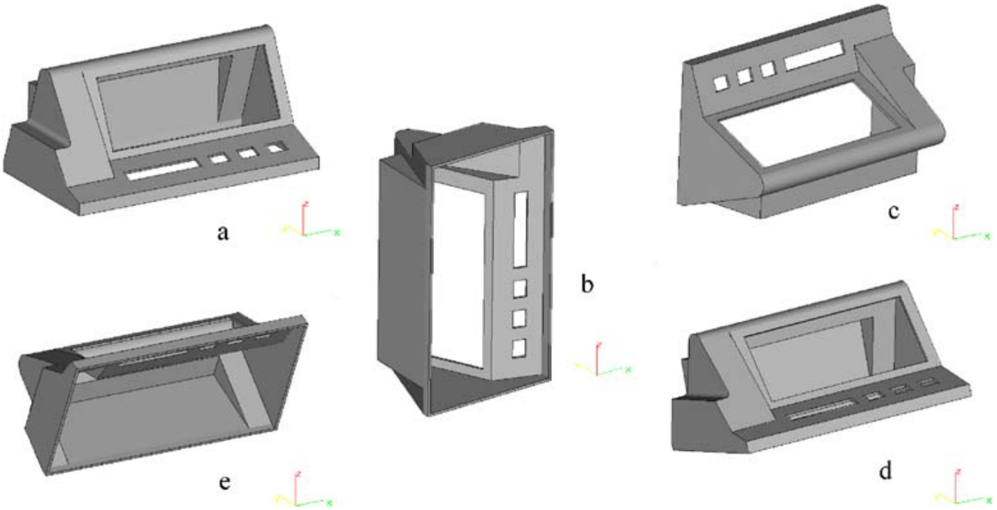


Fig. 6 Candidate orientations for Part “A”

strategies (i.e. better hatching styles and recoating mechanisms, accurate diagnostic tests for the calculation of shrinkage compensation, employment of sufficiently strong support structures in bottom layers etc.).

Stairstepping and overcure are two types of error related to the layer-wise nature of the stereolithography process and are both directly dependent on the layer thickness value. As noted earlier, the stairstepping of an inclined surface depends also on its slope with respect to the build axis. Compared to the original part geometry, stairstepping may lead either to excessive resin solidification or volume loss, known as positive or negative stairstepping error, respectively, as illustrated in Fig. 5.

In order to achieve sufficient mechanical strength and uniformity, the layers are, in most cases, solidified to a depth higher than their nominal thickness. The difference between curing depth (*Cd*) and layer thickness is defined as overcure. In this work, the inaccuracies induced by stairstepping and overcure are only taken into consideration. As a quantitative measure of the perceived layer-induced inaccuracies, the concept of build-process error is proposed. Build-process error is not an actual physical measure but, rather, a measure of the expected errors due to stairstepping and overcure and it has been employed in previous studies [14, 15]. In our methodology, build-process error (*PE*) is expressed as:

$$PE = \sum_{i=1}^{n} \frac{CH(i) \cdot A(i)}{V} \tag{18}$$

where n is the number of facets of the STL-tessellated model, V is the volume of the STL model and $A(i)$ and $CH(i)$ are the area and cusp height, respectively, of facet i. The CH of a facet depends on its slope (s), the value of layer thickness (Lth) for up-facing inclined facets and the value

Table 1 Evaluation results of the candidate solutions for the fabrication of Part “A” according to the candidate orientations presented in Fig. 6 and assuming different objective function weighting schemes

I (1-0-0)		II (0.8-0.1-0.1)		III (0.6-0.2-0.2)		IV (0.4-0.3-0.3)		V (0.2-0.4-0.4)		VI (0-1-0)		VII (0-0-1)	
a-0.20	0.000	**a-0.20**	0.126	**a-0.15**	0.213	**a-0.10**	0.233	**b-0.10**	0.200	**b-0.10**	0.000	**b-0.10**	0.000
d-0.20	0.025	**a-0.15**	0.152	**a-0.10**	0.248	**b-0.20**	0.271	**a-0.10**	0.217	**b-0.15**	0.115	**b-0.15**	0.156
e-0.20	0.050	**d-0.20**	0.164	**a-0.20**	0.251	**a-0.15**	0.273	**b-0.15**	0.223	**a-0.10**	0.172	**b-0.20**	0.192
c-0.20	0.070	**d-0.15**	0.190	**d-0.15**	0.256	**d-0.10**	0.289	**b-0.20**	0.241	**b-0.20**	0.231	**a-0.10**	0.230
a-0.15	0.091	**c-0.20**	0.219	**b-0.20**	0.300	**b-0.15**	0.310	**d-0.10**	0.275	**d-0.10**	0.246	**c-0.10**	0.271
d-0.15	0.124	**e-0.20**	0.240	**d-0.10**	0.303	**d-0.15**	0.322	**a-0.15**	0.334	**a-0.15**	0.355	**d-0.10**	0.277
e-0.15	0.158	**e-0.15**	0.253	**d-0.20**	0.303	**c-0.10**	0.362	**c-0.10**	0.342	**c-0.10**	0.374	**c-0.15**	0.413
c-0.15	0.186	**c-0.15**	0.254	**c-0.15**	0.322	**a-0.20**	0.377	**d-0.15**	0.388	**e-0.10**	0.431	**e-0.10**	0.431
a-0.10	0.280	**a-0.10**	0.264	**e-0.15**	0.349	**c-0.15**	0.390	**e-0.10**	0.421	**d-0.15**	0.458	**a-0.15**	0.434
d-0.10	0.331	**d-0.10**	0.317	**c-0.20**	0.368	**b-0.10**	0.400	**c-0.15**	0.457	**a-0.20**	0.538	**d-0.15**	0.450
b-0.20	0.360	**b-0.20**	0.330	**c-0.10**	0.382	**e-0.10**	0.411	**a-0.20**	0.503	**c-0.15**	0.637	**e-0.15**	0.554
e-0.10	0.381	**e-0.10**	0.391	**b-0.15**	0.397	**d-0.20**	0.443	**e-0.15**	0.539	**d-0.20**	0.670	**a-0.20**	0.718
c-0.10	0.422	**c-0.10**	0.402	**e-0.10**	0.401	**e-0.15**	0.444	**d-0.20**	0.582	**e-0.15**	0.715	**c-0.20**	0.731
b-0.15	0.572	**b-0.15**	0.485	**e-0.20**	0.430	**c-0.20**	0.517	**c-0.20**	0.666	**c-0.20**	0.899	**d-0.20**	0.771
b-0.10	1.000	**b-0.10**	0.800	**b-0.10**	0.600	**e-0.20**	0.620	**e-0.20**	0.810	**e-0.20**	1.000	**e-0.20**	1.000

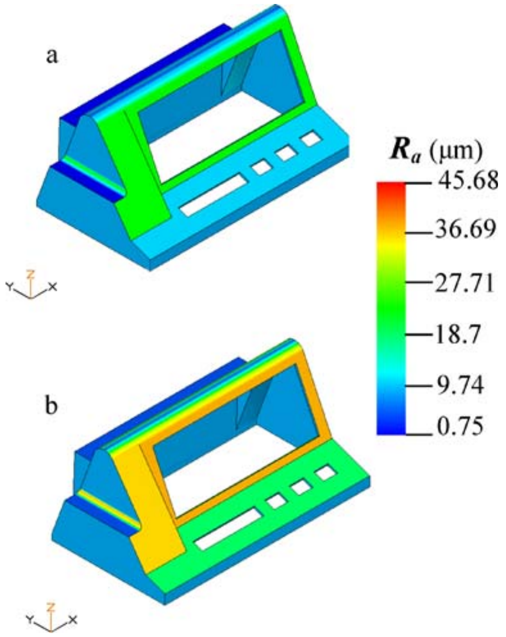


Fig. 7a, b VRML roughness models for Part "A" for candidate solutions: **a** (a-0.10) and **b** (a-0.20)

of curing depth (*Cd*) for down-facing inclined facets (Fig. 5). It reads:

$$CH = 0,\ s = 0^\circ \text{ or } s = 180^\circ\ (\textit{horizontal facets}) \tag{19}$$

$$CH = Lth\cos(s),\ 0^\circ < s \leq 90^\circ\ (\textit{up} - \textit{facing inclined or vertical facets}) \tag{20}$$

$$CH = Cd\cos(180 - s),\ 90^\circ < s < 180^\circ\ (\textit{down} - \textit{facing inclined or vertical facets}) \tag{21}$$

4 Example case studies

The decision support tool developed in this work has been programmed in the C language based on the software code of "AdMesh 0.95," a software utility developed for the verification, correction and manipulation of STL files [44]. In order to illustrate better some of the functional and operational characteristics of the system, as well as of the underlying concepts, two case studies are presented. In these case studies, the support system is utilised in order to evaluate candidate orientations–layer thickness pairs given different fabrication requirements and criteria priorities, as expressed by the associated weighting factors of the objective function.

4.1 Part "A"

In the first example, the case of Part "A" is examined. This is the top-half frame of a digital table alarm clock. Part "A" geometry is relatively simple, consisting mainly of cylindrical and planar surfaces forming a relatively small number of morphological features (screen position, button holes, base etc.). Based on the optimum orientation of the basic features, five candidate orientations were selected (Fig. 6). The first orientation in STL format is the actual input to the support system. The alternative orientations considered are defined by applying the initial orientation to the appropriate rotation with respect to the coordinate system axes shown in Fig. 6a.

In each of the candidate orientations, the three values of layer thickness (0.10 mm, 0.15 mm and 0.20 mm) are assigned consecutively, forming the candidate solutions, i.e. the orientation–layer thickness pairs. For each of these candidate solutions, the associated values of build time, surface roughness, process error, building cost and supported area are computed. According to the values of the first three criteria, their maximum and minimum values

Fig. 8 Candidate orientations for Part "B," illustrated in the form of VRML stairstepping models

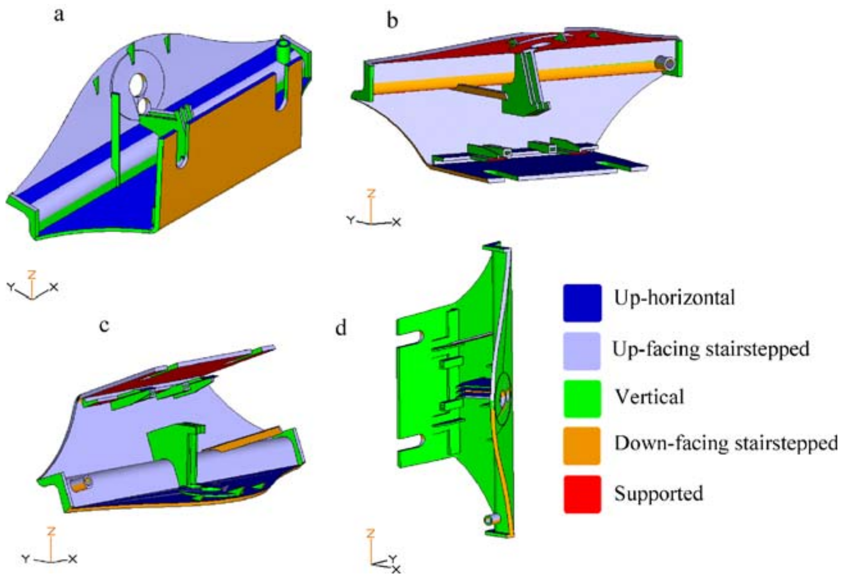


Table 2 Evaluation results of the candidate solutions for the fabrication of Part “B” according to the candidate orientations presented in Fig. 8 and assuming different objective function weighting schemes

I (1-0-0)		II (0.8-0.1-0.1)		III (0.6-0.2-0.2)		IV (0.4-0.3-0.3)		V (0.2-0.4-0.4)		VI (0-1-0)		VII (0-0-1)	
a-0.20	0.000	**a-0.20**	0.111	**a-0.15**	0.185	**a-0.10**	0.198	**d-0.20**	0.195	**d-0.10**	0.000	**d-0.10**	0.000
c-0.20	0.049	**a-0.15**	0.120	**a-0.10**	0.190	**d-0.20**	0.249	**d-0.10**	0.200	**d-0.15**	0.051	**a-0.10**	0.130
b-0.20	0.055	**a-0.10**	0.182	**a-0.20**	0.223	**a-0.15**	0.250	**d-0.15**	0.201	**d-0.20**	0.103	**d-0.15**	0.147
a-0.15	0.055	**b-0.20**	0.187	**b-0.15**	0.268	**b-0.10**	0.300	**a-0.10**	0.207	**a-0.10**	0.300	**d-0.20**	0.177
c-0.15	0.121	**b-0.15**	0.199	**b-0.10**	0.295	**d-0.15**	0.302	**b-0.10**	0.305	**b-0.10**	0.410	**b-0.10**	0.211
b-0.15	0.129	**c-0.15**	0.225	**d-0.20**	0.304	**a-0.20**	0.334	**a-0.15**	0.315	**a-0.15**	0.470	**a-0.15**	0.290
a-0.10	0.174	**c-0.20**	0.239	**b-0.20**	0.319	**b-0.15**	0.338	**c-0.10**	0.400	**c-0.10**	0.502	**b-0.15**	0.333
c-0.10	0.272	**b-0.10**	0.290	**c-0.15**	0.330	**c-0.10**	0.368	**b-0.15**	0.408	**b-0.15**	0.622	**c-0.10**	0.360
b-0.10	0.285	**c-0.10**	0.304	**c-0.10**	0.336	**d-0.10**	0.400	**a-0.20**	0.446	**a-0.20**	0.640	**a-0.20**	0.475
d-0.20	0.414	**d-0.20**	0.359	**d-0.15**	0.404	**c-0.15**	0.434	**c-0.15**	0.538	**c-0.15**	0.751	**c-0.15**	0.534
d-0.15	0.607	**d-0.15**	0.505	**c-0.20**	0.429	**b-0.20**	0.451	**b-0.20**	0.584	**b-0.20**	0.835	**b-0.20**	0.597
d-0.10	1.000	**d-0.10**	0.800	**d-0.10**	0.600	**c-0.20**	0.620	**c-0.20**	0.810	**c-0.20**	1.000	**c-0.20**	1.000

and the weights for each criterion defined by the operator are partial and the overall score for each solution is extracted. The overall scores of the candidate solutions for seven different weighting schemes of the objective function are presented in Table 1. In the first row of the table, the weighting factors of the three criteria, namely, build time, surface roughness and process error, are shown in this order.

According to the results of the evaluation, it can be seen that, if the build time is given absolute priority (column I), the maximum layer thickness should be selected, i.e. candidate solutions that exhibit relatively lower objective function values. The orientation does not seem to be quite as critical, probably because most of the candidate orientations have comparable height, hence, requiring approximately the same number of layers. The pair (a-0.20) proves to be the best. It is also the best in the case where the build time is assigned a relatively high weight compared to the two quality-driven criteria (column II), but it is interesting to note that (d-0.20) is also a high-score solution.

On the other hand, if the surface roughness or process error are considered as the main criteria (columns V-VII), orientation (b), solutions with the minimum or middle layer thickness seem to be the most appropriate choices, a reasonable result since, in orientation (b), the total stairstepped area is minimum. Finally, in the relatively balanced weighting schemes (columns III and IV), orientation (a) with the minimum or middle layer thickness seem to be the most favourable solutions offering a good compromise between cost and quality. In this case, and in order to compare and fully evaluate one or more solutions, the operator may choose to export the associated VRML roughness models, in which the surface roughness information is graphically illustrated. Two examples of VRML roughness models for solutions (a-0.10) and (a-0.20) are illustrated in Fig. 7. The colour of every triangle comprising the roughness model is assigned according to its estimated average roughness and a predefined colour codification scheme.

4.2 Part “B”

Part “B” is a 3D model of a “real” electrical appliance plastic component comprising of a higher number of geometrical features. In Fig 8, the four candidate orientations are illustrated in the form of a VRML stairstepping model. Instead of roughness, coloured VRML models are, in this case, employed for the illustration of information that help the stereolithography apparatus operator to identify the surfaces of the part, for instance, that come into contact with supports or exhibit negative/positive stairstepping or no stairstepping at all (horizontal and vertical surfaces). This kind of information can be quite

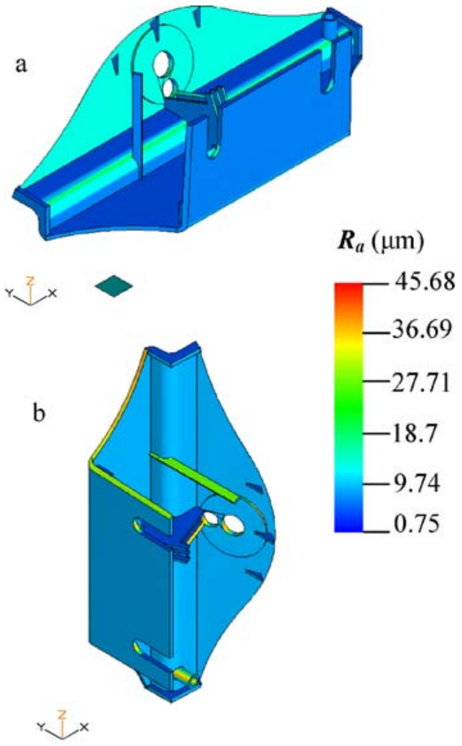


Fig. 9a, b VRML roughness models of Part “B” for candidate solutions: **a** (a-0.10) and **b** (d-0.10) useful for defining the type of finishing to be performed at any surface (e.g. polishing for down-facing stairstepping or coating for up-facing), as well as for identifying problematic areas and assessing the level of difficulty.

Evaluation results of the twelve candidate solutions (four orientations with three layer thicknesses each) classified per weighting scenario are presented in Table 2. The evaluation results show that, employing the highest layer thickness in the (b) or (c) orientations are the best choices if the build time is the only criterion (column I). If all criteria are considered, but the build time is still relatively more important (column II), the solutions based on orientation (a) present the highest evaluation score.

On the other hand, assigning relatively higher weights on the roughness and accuracy factors implicitly “favours” orientation (b) with minimum and middle layer thickness. However, even if roughness is the only criterion, (a-0.10) could still be selected, since its score with respect to roughness is very good, an observation that is clearly illustrated in Fig. 9, in which the VRML roughness models of solutions (d-0.10) and (a-0.10) are presented.

5 Concluding remarks

In the present paper, a software support tool that may serve as an aiding tool for the stereolithography operator in the build parameter selection phase is presented. The decision support tool evaluates a set of candidate parameter configurations, defined by the build orientation and the value of the layer thickness, and classifies them according to their overall performance rating. For the evaluation and rating of the candidate solutions, a weighted multi-criteria objective function is employed. As criteria for the construction of the objective function, the estimated build time, surface roughness and process error are proposed. The criteria relative weights are “judiciously” specified by the operator to account for variations in fabrication requirements and priorities among different build jobs. The build time and surface roughness estimation are based on experimentally derived analytical equations, while the process error is computed based on the STL representation of the part. Alternatively, the operator may evaluate the surface roughness and stairstepping distribution on the part surfaces for a given parameter configuration via examination of the corresponding VRML models. The information and models extracted by the support tool can also be useful in other pre-fabrication tasks, such as pricing, quote offering, job scheduling and finishing time estimation. It should be emphasised that the overall methodology presented in this work is applicable, subject to appropriate minor modifications and adaptations, to other layer manufacturing (LM) technologies.

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