

THE EFFECTIVENESS OF MULTI-CRITERIA OPTIMIZATION IN RAPID PROTOTYPING

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This paper presents the strategy for multi-criteria optimization of a prototype. There are taken into account two different optimization criteria. An original computer program was made to make possible the graphic display of regions on the 3D model surface, which exceed a limit for surface roughness, initial established. The computer program allows the automate calculation of optimal position for prototype manufacturing on a Rapid Prototyping system platform, according to manufacturing time and surface quality optimization criteria. The determination of Pareto-optimal diagram is presented. There are shown, in a graphic way, the optimal solutions which belong to Pareto-optimal set. The numerical and experimental results are analyzed on a practical example.

Key words: multi-criteria optimization, pareto-optimal set, Rapid Prototyping, strategic manufacturing.

1. INTRODUCTION

For actual technologies, the open market requirements imposes the handling of multiple aspects. Thus, each manufacturing technology must offer optimal answers not only from economical viewpoint (i.e. productivity, cost) but also from qualitative, esthetic, ecological viewpoints etc. The manufacturers have to know that specific set of technological parameters so that the product is optimal from several viewpoints. Experience has shown that those technological parameters for optimal product manufacturing from a particular point of view, offers a poor solution in terms of another optimization criterion. When a problem is solved monocriterial, usually, there is a complete incompatibility between optimal solutions of the optimization problems. Today it is known that such an outcome is not satisfactory. An optimal solution for all optimization criteria taken simultaneously is an ideal solution, which usually has no correspondence in practice. But, we can search a solution which satisfy simultaneously all criteria as much as possible. Such solution might be found within the Pareto-optimal set of solutions for multi-criteria optimization problem.

2. PREVIOUS WORK

The optimization of Rapid Prototyping (RP) technology has a long history. The researchers conclusion can be pursued along several major directions such as: slicing algorithms, process parameters, modeling and simulation, part orientation, packing problem, optimal selection of RP technology, multi-material fabrication, multi-criteria optimization etc.

To slice a geometric 3D model, two methods can be highlighted. The accustomed technique is to make slices into a 3D geometric model in stl format. The advantage of slicing the stl file is that the problem is reduced to finding plane-intersections. Another technique is based on a direct slicing of a CAD 3D model formats [9]. A direct slicing method avoids some approximation which exists in stl format and can provide a more exact path by slicing a constructive solid geometry representation of a part. However, it should be noted that a very high accuracy, which exceeds the precision of the RP manufacturing system is not justified, as long as the manufacturing system cannot perform it, and the data processing time increases unacceptably long.

Ahn et al, investigates the relationship between the main process factors and roughness distribution to make possible the modeling of the step effect, as a result from stacking layers [1]. Based on such investigation an optimum part orientation for fabrication is chosen. The optimization of the fabrication direction is the way to reduce the post-processing operation time, due to the step effect and burrs from the support structure [12]. Among the criteria taken into account by Hur et al, can be mentioned: minimum part height and the minimum value of the part dimensions ratio, which is the part length considered into the direction of powder disposal on the platform must not overstep the part width[10].

To estimate the surface roughness according to the surface slope, layer thickness, rounded edges, different means are proposed by Luis Perez et al., in[14]. In [2] the aim of their research is the optimal part orientation that minimizes the manufacturing cost. There are proposed different techniques to calculate the manufacturing cost on FDM and SLA systems.

Regarding the process parameters some researchers commonly used a statistical analysis of the rapid prototyping processes. Their main goal is finding out the combination of parameters leading to the best accuracy of the manufactured parts [6]. Consequently, it is possible to increase the accuracy of parts by setting the process parameters to specific values. For instance Lee et al, make use of Taguchi method, as a powerful tool to design optimization for quality, to find the optimal process parameters for Fused Deposition Modeling [13]. To estimate the build-time, Choi and Samavedam, developed a mathematical model for selective laser sintering process [7]. This model has been integrated into a virtual reality system. In the paper of Zhang et al., a simulated annealing algorithm was applied to find the optimal batch configuration layout for the minimum cost of production for solid ground curing processes [19]. Three kinds of objectives has been taken into account: fitting models into the specified container, avoiding any overlap between models and achieving high packing density, in other words, achieving the minimum overall height. A comprehensive analysis of some important build parameters which affect the quality and accuracy of the final stereolithography parts, such as the layer thickness, resultant over cure, hatch space, blade gap, and part location can be found in [20]. This research suggests the best setting of these control factors for different 20 individual features.

A research direction with important results for the manufacturing cost and time calculation, refers to adaptive slicing method as a function of shape and slope surface [4].

Other researches are oriented on the automation of optimal part orientation on the RP system platform, depending on several criteria. Concerning the automation of the part orientation on the machine platform, in [5], there are calculated some weights for each optimization criterion. These weights are in fact degrees of importance in order to make a better selection, according to a specific criterion, of the RP process. To find a suitable part orientation Pandley et al, try to set up in which way the manufacturing time is affected by the support structure, dimensional accuracy, surface quality and manufacturing cost [16].

The improvement of the physical and mechanical properties of a prototype might be realized by simultaneous use of some different materials. So, Dutta and Shpitalni, investigate several works and evaluate their results according to traditional methods [8]. While the dimensional accuracy and surface finish are so important in RP manufacturing, Ippolito et al, propose a new technique of checking the machine quality of a RP workpiece according to the ANSI-ISO standards [11]. To optimize the work space of RP machines, Nyaluke et al, suggest an algorithm that fills the work space with parts by partitioning the work volume into layers, and then filling these layers one after another [15]. In [18] the effect of build orientation on cylindrical error is analyzed by three methods: first by a simple analytic method, second by simulating the manufactured surface using a CAD file of the part and third by using an STL file. The authors find out a relationship between cylindrical error and part orientation in a RM process. In [17] there are used three methods based on a simple analytic model, a CAD model and a 3D model in stl format respectively, for studying the variation of cylindrical error. Based on this study, the optimal part orientation is deduced. Unfortunately, this research is limited to cylindrical surfaces and analyzes the form errors only.

Almost majority of mentioned investigations deals with monocriterial optimization of the RP processes, as a main feature. As a consequence, the optimal solution suits a single optimization criterion. When a research takes into consideration the process of optimization according to different optimization criteria, each criterion has its own result. Nevertheless, there are studies which specify for instance part orientation according to some criteria simultaneously. Often, the part orientation choice is made when

criteria such as: surface quality, manufacturing time/cost, influence of supports removal at surface quality, dimensional accuracy are satisfied. What is still necessary in the research field is a method to decide on the optimal solution, when there are involved different optimization criteria simultaneously.

This is why, this paper tries to find an answer to the question: how useful are the solutions in the Pareto-optimal set, from practical viewpoint?

The paper is organized on five paragraphs. After a short remark about the importance of the multicriterial optimization, the second paragraph shows the researchers main interest in RP optimization. The third paragraph examines the optimal position of a 3D model on the RP system platform, taking into account two different optimization criteria. In the fourth paragraph an experimental research on Sinterstation 2000 selective laser sintering system is presented. The conclusion of the research is presented in the fifth paragraph, and the paper ends with the list of bibliographic references.

3. THE OPTIMIZATION OF WORKING POSITION

For this study a frame glasses was chosen as a model, in order to produce a silicone rubber mold (see Fig.1). For this model, the manufacturing time and surface quality were chosen as optimization criteria. Very important to know in advance is the optimal position of the 3D model on the RP system platform, in order to obtain best surface quality and minimum manufacturing time. To acquire this objective, a computer program to represent the 3D model in stl format, has been made. This program is able to represent, with a contrast color, all facets of the model which have an inclination angle within some limits established in advance. The surface roughness directly depends on the step effect [5], and the step effect is a function of facet inclination angle. By this program, we can display before manufacturing, those areas on the prototype surface, which will exceed a value of the step effect established in advance. In Fig. 2 we can see the dark* colored areas which has a value of the step effect higher than the initial established threshold value.

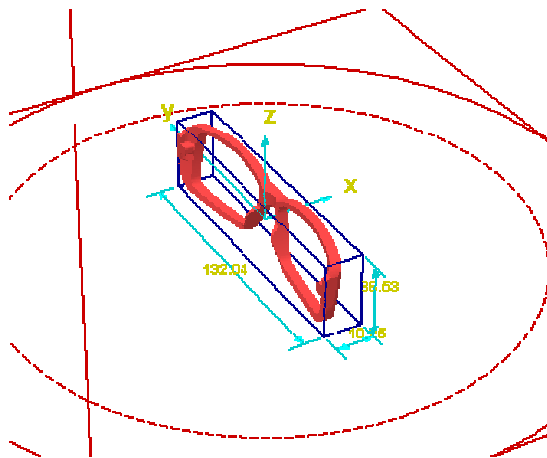


Fig. 1 – The 3D model of the glasses frame.

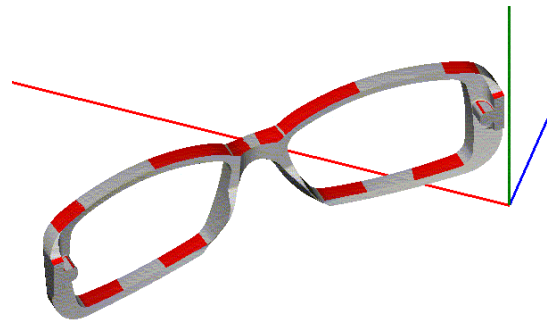


Fig. 2 – The 3D model surface displays the regions which exceed a limit of the step effect.

The position of the 3D model on the RP system platform can be automatically determined by the computer program, so that the number of dark colored facets is minimum. In the same time, the total area (in mm²) of facets that exceed the initial established threshold value for step effect can be calculated. Also, the program allows the human operator intervention every time it becomes necessary.

3.1. Optimal position of the 3D model

Optimal position of the 3D model on the RP system platform has been established by taking into account two optimization criteria: surface quality and manufacturing time.

* For the on-line version of the paper, dark colored regions are represented in red color.

3.1.1. Surface quality criterion

It is known from experiments that for a surface inclination angle in the interval $[\theta_1, \theta_2] = [5^\circ, 30^\circ]$, the step effect will generate a surface roughness R_a about $10 \div 20 \mu\text{m}$ (Ahn et al., 2007). For this research, we admit for surface roughness a limit value $R_a = 10 \mu\text{m}$. Figure 3 shows the variation of facets number whose inclination angle is in the interval $[\theta_1, \theta_2]$, when the model rotates incrementally around Ox and Oy axes. According to the initial position of the 3D model, as it was designed (Fig.1), a computer program was made, so that we can see and automatically count the number of facets whose inclination angle are in the interval $[\theta_1, \theta_2]$. Using this program, the position of the model with minimum number of facets inclined with an angle in the interval $[\theta_1, \theta_2]$ was calculated (Fig. 4). This position of the model on the RP system platform according to the initial position, can be acquired by a rotation of the model with $\alpha_x = 45^\circ$, $\alpha_y = 90^\circ$.

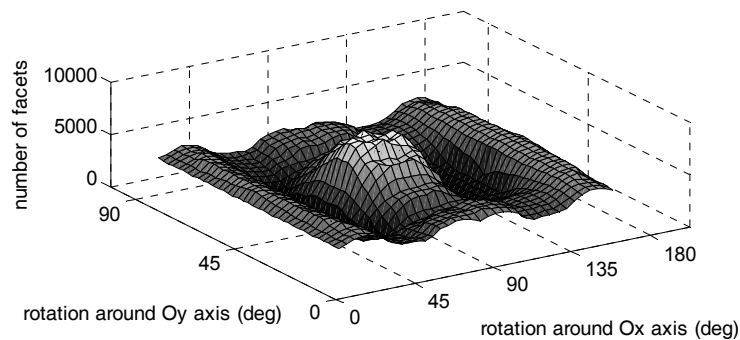


Fig. 3 – The variation of facets number whose inclination angle is in the interval $[\theta_1, \theta_2]$, during rotation around Ox and Oy axes.



Fig. 4 – Optimal position of the model, corresponding to surface quality criterion;
a) the front side of the model; b) the back side of the model.

In Fig. 4 we can remark the existence of very small dark colored areas, which cover less than 5% from total area of the 3D model. Even more, these areas where the step effect overstep an initial established threshold value, are placed on the backside of the glass frame (Fig. 4b), so that the aesthetic criterion of the surface is not affected.

3.1.2. Manufacturing time criterion

The manufacturing time on a selective laser sintering system was also calculated for different orientation of the 3D model, during its incremental rotation around Ox and Oy axis. For this purpose, a mathematical model for manufacturing time has been used [3].

Figure 5 illustrates the variation of the manufacturing time with incremental rotation of the 3D model around axes Ox and Oy. Figure 6 shows the 3D model in its optimal position in terms of manufacturing time criterion. This position corresponds to a rotation with $\alpha_x = 0^\circ$, $90^\circ = \alpha_y$, from the initial position.

Along the vertical axis, the prototype elevation is minimal. Instead, stand slightly higher value of the dark zone area. From here it can be easily deduced that, when we have a minimum value of the manufacturing time, the surface quality criteria is highly depreciated.

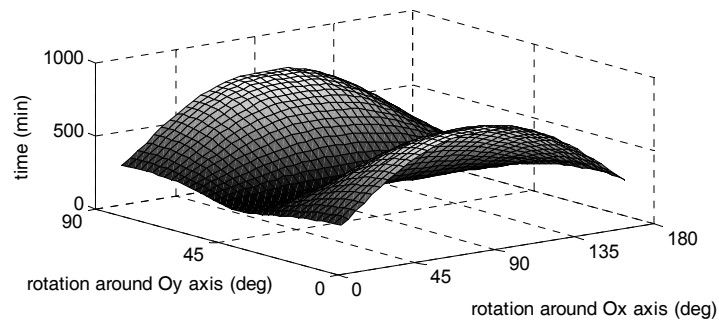


Fig. 5 – The variation of the manufacturing time during 3D model rotation around Ox and Oy axes.



Fig. 6 – Optimal position of the 3D model, corresponding to the minimum value of the manufacturing time criterion.

3.1. The determination of Pareto-optimal diagram

During the incremental rotation of the 3D model around Ox and Oy axes in the horizontal plan, to each specific position of it corresponds a specific value for manufacturing time and area which overstep the initial established threshold of surface roughness. If we consider a diagram which has the manufacturing time on the horizontal axis and the area which overstep the initial established threshold of surface roughness on the vertical axis, then for each specific position of the 3D model on the RP system platform, during rotation, will correspond a specific point in this diagram. Figure 7 shows the entire set of points, which correspond to each specific position of the 3D model on the RP system platform, during rotation around each horizontal axis, from 0° to 180° only, due to the symmetry, with 5° as increment.

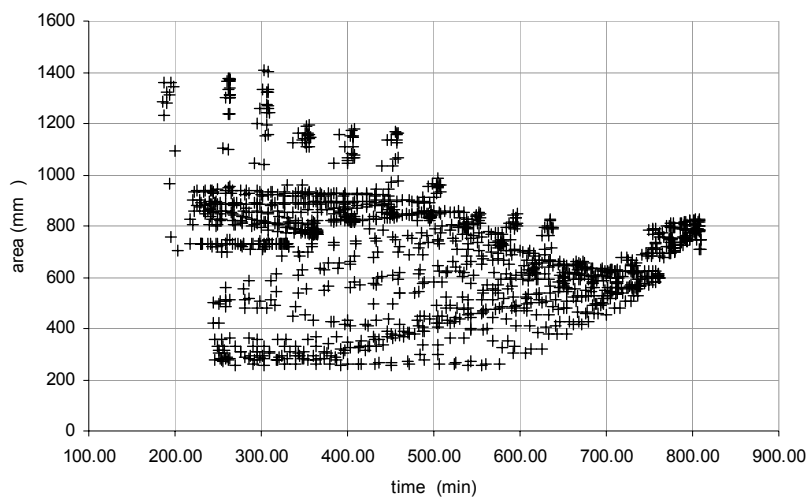


Fig. 7 – Time-area diagram for all possible positions to build the model.

If we represent on the vertical axes the number of facets whose inclination angle overstep the same limit of step effect, then we obtain the diagram in Fig. 8.

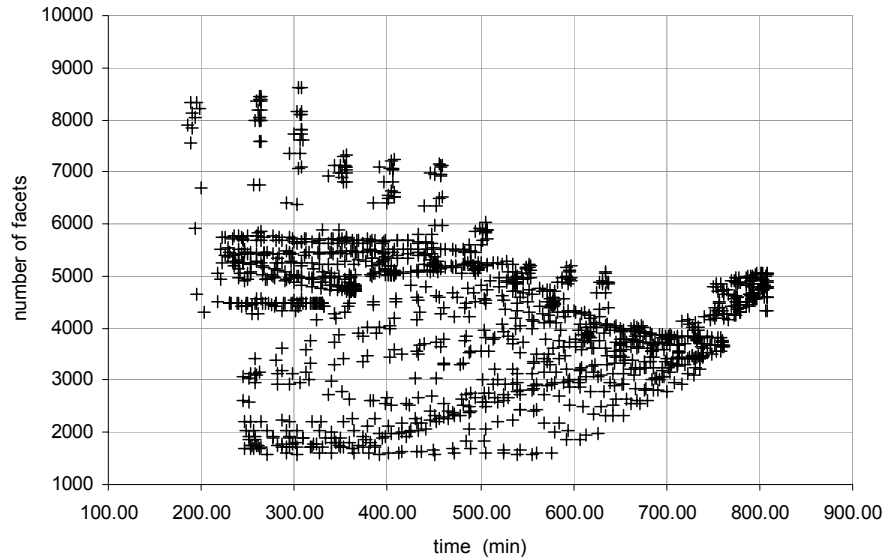


Fig. 8 – Time-facets number diagram for all possible positions to build the model.

It can be easily remarked a similarity between Figs. 7 and 8. This is due to the high faceting resolution of the 3D model in stl format. As the faceting resolution increases, the difference between both diagrams decreases. In these diagrams, a particular interest shows the points which belong to the Pareto-optimal set. These points are the solutions of the multicriterial optimization problem. These points are represented in the diagram in Fig. 9.

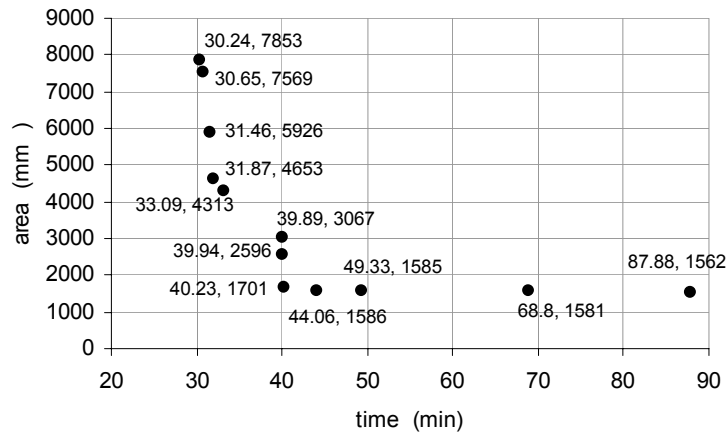


Fig. 9 – The set of Pareto-optimal solutions.

In this figure, the point of coordinates (87.88, 1562) is an optimal point, in which the position of the model on the RP system platform depends on a single criterion, which is *surface quality*. According to the position in which the 3D model was designed, the above optimal position can be acquired by rotation with $\alpha_x = 45^\circ$, $\alpha_y = 90^\circ$ (Fig. 4). If the optimal position of the model is determined only as a function of *manufacturing time* criterion, then optimal solution is represented by the point of coordinates (30.24, 7853). This optimal solution can be obtained by model rotation with angles $\alpha_x = 0^\circ$, $\alpha_y = 90^\circ$ (Fig. 6). If we select any of the above solution, one criterion will be accomplished, while the other will be deteriorated. Figs. 10, 11 and 12 show the position of the 3D model corresponding to three different points along the Pareto-optimal set. For the position of the model shown in Fig. 10, corresponds a manufacturing time of 31.46 min and a value of the surface area which overstep the established threshold of 5 926 mm². These values of the optimization criteria correspond to a rotation of the model with $\alpha_x = 15^\circ$, $\alpha_y = 90^\circ$, according to the position of the 3D model from Fig. 1.



Fig. 10 – Representation of a Pareto-optimal point (time = 31.46 min; colored area = 5 926 mm²).



Fig. 11 – Representation of a Pareto-optimal point (time = 39.89min; colored area = 3 067 mm²).



Fig. 12 – Representation of a Pareto-optimal point (time = 44.06 min; colored area = 1 586 mm²).

For the next considered point from Pareto-optimal set which is (39.89, 3067), it can be observed that, as a result of model rotation with $\alpha_x = 20^\circ$, $\alpha_y = 90^\circ$, the area which overstep the established threshold is decreasing (i.e. the *surface quality* criterion is improved). Instead, the high of the model on the RP system platform (Fig. 11) is increasing (i.e. the *manufacturing time* criterion is deteriorated). In Fig. 12, both tendencies are accentuated, which means that we see an improvement of *surface quality* criterion, while the *manufacturing time* criterion is more deteriorated.

4. EXPERIMENTAL RESULTS

The experiments were made on Sinterstation 2000 from 3D System. The prototypes were made by Duraform PA6 polyamide. The glass frame was made in two different positions. Firstly, the glass frame was made in the optimal position corresponding to the *surface quality* criterion (Fig. 13a). Secondly, the glass frame was made in the optimal position corresponding to the *manufacturing time* criterion (Fig. 13b). In both situations, the measurements were made with a portable surface roughness tester Mitutoyo SJ301.

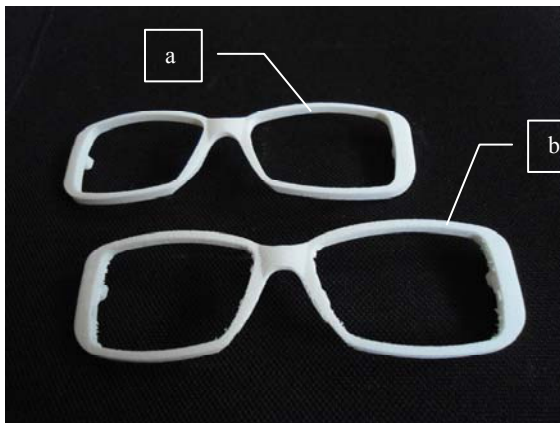


Fig. 13 – The glass frame made by Duraform PA6, using as optimization criteria: a) best surface roughness; b) minimum manufacturing time.



Fig. 14 – The step effect as a result of layered manufacturing.

According to the *surface quality* criterion, the computer program calculates the position of the 3D model on the RP system platform, so that the value of the region which overstep the threshold value of 10 μm on the model surface, is minimum (Fig. 4). The measurements of the surface roughness in different regions of the prototype in Fig. 13a, show a roughness R_a in the interval $(14.09 \div 15.47) \mu\text{m}$. The variation of the surface roughness is done by step effect on part surface, as you can see in Fig. 14, and also by the grain size of the material powder and porosity of the part surface after sintering. According to the *manufacturing time* criterion, the computer program calculates the optimal position of the 3D model on the RP system platform, so that the manufacturing time is minimum. It must be noted that the program takes into account the time necessary for layer processing, which depends on layer number, all the rest being practically independent and neglected in our calculation. The measurements of the surface roughness in different regions of the prototype in Fig. 13b, show a roughness R_a in the interval $(19.27 \div 21.21) \mu\text{m}$.

5. CONCLUSION

The extreme points of Pareto-optimal set represent the optimal solutions of optimization problem for each criterion independently taken. All other intermediary points are optimal solutions which take into account both criteria simultaneously. The influence of each optimization criterion within the Pareto-optimal set is variable and the selection of a specific point as optimal solution depends on each specific problem.

For *manufacturing time* criterion, it can be easily select the position of the 3D model on the RP system platform, so that the value of this criterion is minimum. On Sinterstation 2000 system, the manufacturing time is determined by the layers number. So, we have to find that position of the 3D model which has the lowest height.

For the *surface quality* criterion, due to quite complex shape of the 3D model, is virtually impossible to find o specific position of the model, so that the area on the model surface which overstep the initial established threshold value for step effect is zero. This is why, for this criterion, a position of the model on The RP system platform is determined so that the dark colored area is minimum. From this perspective, the optimal solution offered consist of a very small region on the glass frame, whose roughness overstep the threshold of 10 μm , having $14.09 \div 15.47 \mu\text{m}$. For the case of this glass frame, the aesthetic role is essential, and the size and position of this region is very important. In our case, fortunately, the region with higher roughness is symmetrically situated on the backside of the 3D model (Fig. 4). The disadvantage of this optimal solution is represented by the manufacturing time three times higher than in the case of optimal solution for *manufacturing time* criterion.

If we want to reduce the manufacturing time, we have to chose between the solutions offered by Pareto-optimal points. Examples of such solutions are illustrated in Figs. 10, 11 and 12.

What is unwanted in case of such solutions is the fact that the deterioration of the surface quality does not limit to the increasing of the region which overstep the established threshold for step effect, but also the location of this region on the model surface is unwanted.

So, in all three position of the model illustrated by Figs. 10, 11 and 12, the region whose roughness overstep the established threshold of 10 μm is located on the front side of the 3D model and not on the backside, as in Fig. 4. This aspect is in disagreement with the aesthetic principles, being known that all details on the prototype will be identical copied on the rubber mold and from the mold to all molded parts.

When we chose a Pareto-optimal solution, we have to compare the cost of additional postprocessing according to the cost of processing on the RP system, to be able to evaluate the supplementary finishing of the surface area which overstep the threshold limit of 10 μm , initial established for surface quality criterion. If the cost of this supplementary postprocessing overstep the economy obtained due to a lower manufacturing time, then the choice for a solution from the Pareto-optimal set is not the best option.

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