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Automated determination of the optimal manufacturing direction of polymer composite shell structures

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Abstract. There is a promising potential in polymer composites in the automotive industry; therefore, design methods aimed at cost and weight efficiency have become increasingly important. The tool cost is a considerable amount of the total cost, which is affected by the direction of the manufacturing planes. In this paper, a method is introduced to automatically determine the optimal manufacturing direction of an arbitrary shell structure. The method is implemented in Python environment. A meshed surface model is read as input, and the geometrical complexity factors are calculated from all directions in the space in a discretized way. A new 3D branch diagram is shown with which the calculated values can be visualized and evaluated. After that, an undercut factor is introduced and calculated, and it is demonstrated that the minimum of the product of these measures can give the optimal manufacturing direction in a fully automatized way. The paper presents a study about a train seat to show the industrial applicability of the method by evaluating the effect of the manufacturing directions and geometrical complexities at different partitioning of the composite shell on material cost.

1. Introduction

Polymer composite parts have become increasingly important in the automotive industry due to the regulations of emission reductions and to make vehicles more energy-efficient [1]. The large production volume of this industrial sector drives the conduction of extensive research of cost-effective manufacturing technologies [2]. The manufacturing systems, in general, have undergone significant development in the last decades [3]. Focusing on the automotive industry and the cost-effectiveness, Khan and Mehmood [4] accomplished a comprehensive review of composite manufacturing technology. The authors confirmed that the traditional technology in this sector is resin transfer molding (RTM). Still, they showed two success stories to prove the potential of the vacuum-assisted resin infusion (VARI). Here, it is worth mentioning that the RTM technology is developed nowadays by using composite matrix materials other than epoxy, like polyurethanes [5] or thermoplastic matrix with in-situ polymerization [6].

By the spread of composite materials, not only the manufacturing technologies have been developed, but new design methods have emerged like design-to-cost (DtC) [7], design for manufacturing (DfM) [8], or even recycling by design [9]. DtC and DfM methods are based on using cost estimation techniques. Cost-estimation has three main approaches: analogous, parametric, and bottom-up [10]. The analogous method is based on the data of similar projects from the past and includes expert judgment,

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and the parametric method defines mathematical relationships between cost and past events and trends. Both methods can be used, e.g., in the aerospace industry where enough data is available from the past. In the automotive industry, the bottom-up method can be helpful to examine the work at the most granular level of detail. Kaufmann et al. [11] enhanced this method with a combined cost and weight optimization and showed that if the total lifecycle cost is taken into account, the weight and its magnitude of penalty strongly affect the results. The authors later developed their method to target the best draping strategy of a composite part [12]. On the principle of the bottom-up approach, Bacharoudis et al. [13] developed a process- and feature-based cost modeling method in Matlab/Simulink that can be used on complex composite assemblies, while Irisarri et al. [14] developed a new method called Quilted Stratum Design (QSD) and implemented it in a software tool which became a commercial software product with the aim of the partitioning of the structure into small numbers of constant stiffness areas which can serve as a trade-off between manufacturing complexity and mechanical performance.

Martensson et al. [15], by also using a bottom-up cost estimation approach, showed that larger and more complex composite parts might become more cost-effective when divided into several sub-parts and then joined together. The authors showed that the assembly cost has a shallow effect on total cost, and the partitioning of the part can lower the complexity and thus reduce scrap volume and tooling cost. The tooling cost they proportionated with a geometrical complexity factor. This method was later enhanced by combining the partitioning with multi-material diversity [16]. Besides, an analysis routine was also introduced [17] to investigate the partitioning of a part from the perspective of costs and mechanical performance. These methods calculate the complexity of the parts by knowing the manufacturing direction in advance because the partitioning has to be made manually. To automatize the partitioning in an optimization framework, the optimal manufacturing direction of an arbitrary shell structure has to be determined automatically.

We aim to develop a method that can automatically determine the optimal manufacturing direction of a composite shell structure. This would allow to automatically calculate the complexity factor of an arbitrary shell structure. That would mean a further step to have a fully automated optimization framework with the aim of cost- and weight-efficient partitioning.

2. Method

To determine different geometrical properties and then manufacturing characteristics of composite shell structures, we developed a software application in Python environment. Python is an open-source programming language that is very powerful and has an application programming interface (API) for every finite element software. This is beneficial because, in the conceptual design phase, not only the manufacturing properties but also the stiffness and strength of a composite structure are to be evaluated, and the most effective tool of that is the finite element analysis.

Based on this, it is appropriate to work with a geometry discretized by a finite element mesh throughout the whole process. In the case of composite structures, this means a finite element mesh of layered shell elements that handles the geometry as a surface model. In addition, if a mesh can be used as input, a 3D-scanned surface model in STL-format can also be used.

As we investigated composite structures produced with resin transfer molding (RTM) manufacturing technology, we used the complexity-factor C as the main measure, quantifying the geometry's deviation from a flat plate [15]. The complexity factor is described with formula (1) and shown in Figure 1.

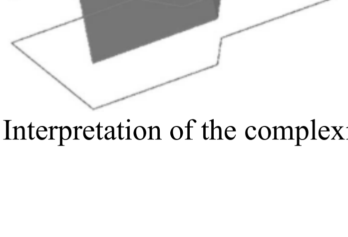


Figure 1. Interpretation of the complexity-factor.

$$C = \frac{A_{total}}{A_{proj}}, \tag{1}$$

where *A_total* is the total area of the component, i.e., the sum of the areas of each element that make up the geometric model; *A_proj* is the area of the perpendicular projection of the geometry in the manufacturing direction. It is clear from the definition that C ≥ 1 and equality are obtained for *A_total* = *A_proj*, which means producing a completely flat part. The lower the value of C is, the less the shape of the part deviates from a flat plate, the less complex and expensive the tool required for production is, and the less production waste will be produced [15]. Since C depends on the projection (i.e., manufacturing) direction, it is worth plotting its value as a function of the possible three-dimensional directions. Since the value of C is invariant for translation and mirroring in a plane perpendicular to the view, all possible values of C can be obtained if we investigate it in a spherical coordinate system in the range of $\{(r,\theta,\varphi)|r = 1 \wedge \theta \in [0,2\pi) \wedge \varphi \in [0,\pi/2]\}$. This range includes the vectors of a unit radius hemisphere in the +z half-space which is shown in Figure 2.

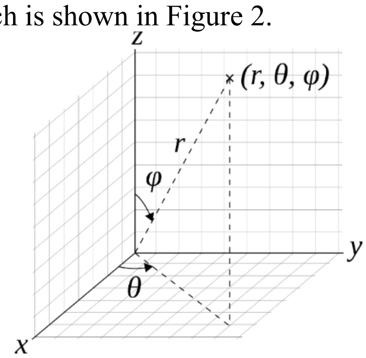
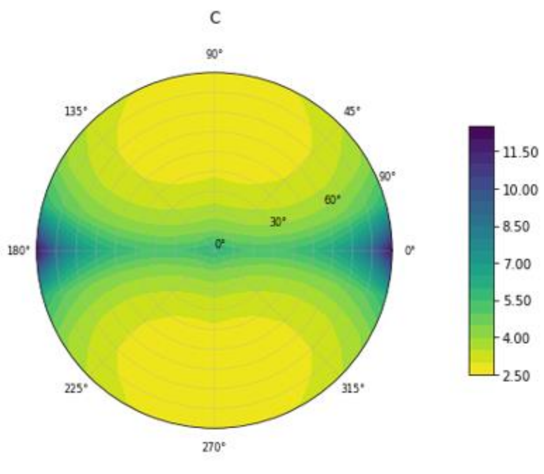
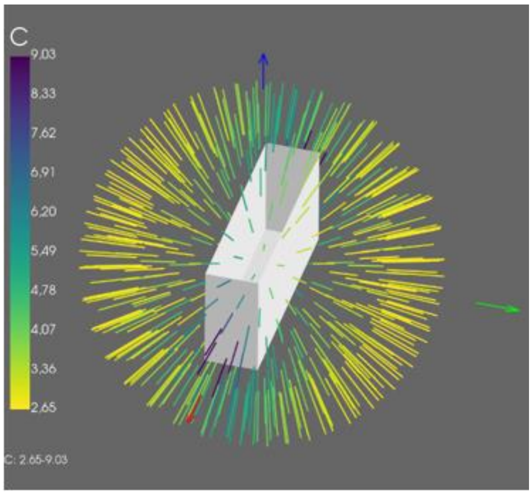


Figure 2. The spherical coordinate system used for selecting directions.

The assignment (θ, φ) → C can thus be represented in plane on a polar graph, and the values of C belonging to different theoretical production directions can be displayed in a spatial diagram. These are shown in Figure 3, where we plotted the complexity factor C of a five-sided rectangular shell from different directions in space. In the figure on the right, each radius indicates different projection directions, and their color indicates the C value calculated from that direction.



(**a**)



(**b**)

Figure 3. Polar graph (a) and branch-diagram (b) of complexity factor C.

The general trends are more observable in the polar diagram, while in the branch diagram, the spatial directions are more illustrative. The branch diagram shows that – according to engineering considerations – C is maximal when the projection direction is perpendicular to the side with the smallest area. But it does not take its minimum value in the real manufacturing direction: it would be parallel to the z-axis in this case, which corresponds to point (0,0) in the polar graph. In addition, the minimum and maximum C values can be in a significant range for such a simple part, so it is necessary to consider the only C value that belongs to the manufacturing direction as a measure of the complexity of the part.

Examining the C value alone does not provide a method for selecting the direction of production but considers it to be predetermined. The direction of manufacturing has a significant effect on the projected surface and thus on the value of the complexity factor C: different views give a completely different C value, but the aim would be to assign a single C value to the part that characterizes its complexity and can be used in cost estimation methods.

During the traditional development process, the manufacturing direction is determined by an expert technologist. To define it automatically, we supplemented the complexity factor with another essential quantity: the undercut factor.

In the case of the production of composite shell structures, it is essential to consider whether their geometry includes undercuts: a geometry with undercuts makes the production of the part significantly more difficult or impossible in the given production technology. That is why it is worth considering whether the geometry has undercuts from that direction when examining the production directions. It is advisable to investigate this to the extent that it indicates not only the existence of the undercut but also its degree. With such a measure, the assignment of the view to the undercut factor can be made continuous, which can be helpful, especially for optimum search.

To quantify the undercut according to the above criteria, we introduced a value, denoted by U, which is the quotient of the projected area (*A_proj*, "shadow") and the projected surface of the part surface (*A˜_proj*, "multiple shadows"). This can be illustrated by applying N projection beam perpendicular to the projection plane in the direction of the part, each of which intersects the surface model at a total K point. This is shown in Figure 4.

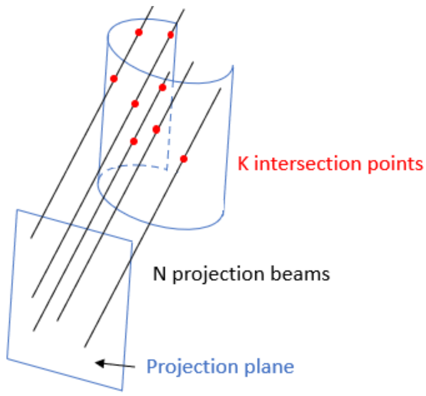


Figure 4. Determining the undercut of a part.

The quotient of the two values for a sufficiently large N gives a good approximation of the value of U (2):

$$U = \frac{\tilde{A}_{proj}}{A_{proj}} \approx \frac{K}{N} = \frac{number\ of\ intersections}{number\ of\ projection\ beams} \tag{2}$$

Similar to C, for any geometry U ≥ 1. The value of U for a given view of some simple geometries is illustrated in Figure 5.

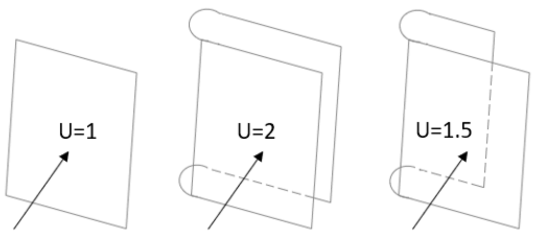


Figure 5. Illustration of the undercut-factor on three simple geometries.

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Equality occurs from a given direction in the case of an entirely undercut part, in which case each projection beam intersects the geometry exactly once. $U > 1$, if there is an undercut in the geometry from the examined view; $U = 2$, if it is undercut from a given direction with respect to the entire projection of the part, and so on, in the case of multiple total undercuts, $U > 2$ may be obtained. A further similarity with the complexity factor C is that smaller values are also preferred here.

But the value of U can give surprising results as Figure 6 shows: for this kind of U-shaped part, a low U-value belongs to a direction that has no undercut but is still not suitable for manufacturing since we see the inner and outer surfaces of the part from the same viewpoint; thus, e.g., a press would not be lockable. Such a direction is indicated with a red arrow in Figure 7 (a), and on the right-hand side (b), the part is seen from this view. The inner surface is shown with grey; the outer surface is shown with yellow. Based on this, we quantified whether both sides of the part are visible from the manufacturing view. The definition of the outer and inner surfaces is simple in the case of a properly prepared surface model since the surface normal vectors assigned to the elements obviously give the orientation of the entire surface.

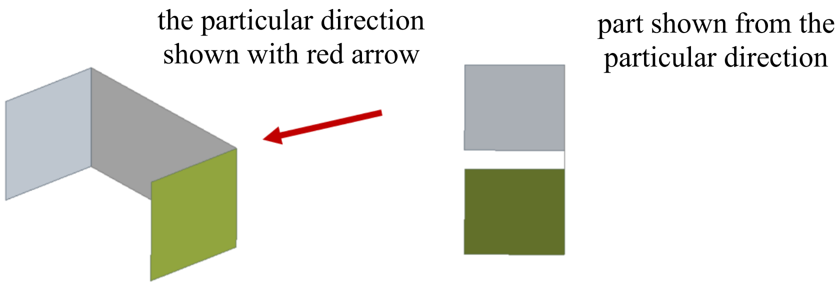

Figure 6. Example for a particular case with a misleading evaluation of the value U.

By using the information of surface normal, we extended the definition of U with a sign: we don't simply take the number of intersections K into account, but separate K+ intersections, where the direction of the projection beam and the intersected surface normal is the same, and K-, where they are opposites. This way, a measure of U_{eqv} can be defined (3).

$$U_{eqv} = \frac{K^{+} - K^{-}}{N} \tag{3}$$

$U_{eqv} = U$ if $K+ \cdot K- = 0$, i.e., only one side of the surface is visible from the examined view.

This can be used to define a value of U_s, which can also be considered as an extension of U (4):

$$U_s = U + (U - |U_{eqv}|) \tag{4}$$

As the definition shows $U_s = U$ if only the outer or only the inner of the surface is seen from a given viewpoint, and $U_s > U$ if the outer and the inner of the surface are both seen from a particular viewpoint. Thus, this measure can be used to quantify the undercut and the orientation of a surface with a single measure. Furthermore, the nature of U_s stays the way that the lower values are preferred for manufacturing reasons. Thus, we have defined two measures above, which make it possible to quantify manufacturing-relevant properties of a component represented by a surface model from certain directions. However, it is also necessary to automatically select one of the possible directions corresponding to the manufacturing direction. By knowing such a direction, the value C will already be considered characteristic of the part.

Our proposed way to choose the manufacturing direction is to select the direction corresponding to the best value of the measures defined so far. But as shown above (e.g., see Figure 3), the minimum C often does not belong to a valid manufacturing direction, so this method is not appropriate. On the other hand, minimum U_s is neither enough alone, because if it is applied to the simple geometry shown in Figure 3, for example, it will not give a good result. This is because the value of C has a local maximum in the directions perpendicular to the sides, since there is a smaller projected area than from the oblique directions. Based on the above, we proposed the method to examine what directions we can find in the case of minimizing the product $C \cdot U_s$: since neither too large C nor too large U_s is suitable for manufacturing. Still, one can see that neither is suitable separately.

3. Case study

We performed a case study on the composite shell of a train seat. This is a glass fiber reinforced, polyester resin composite produced with RTM technology. We investigated the effect of the manufacturing direction on the material costs with two different partitioning variants shown in Figure 7.

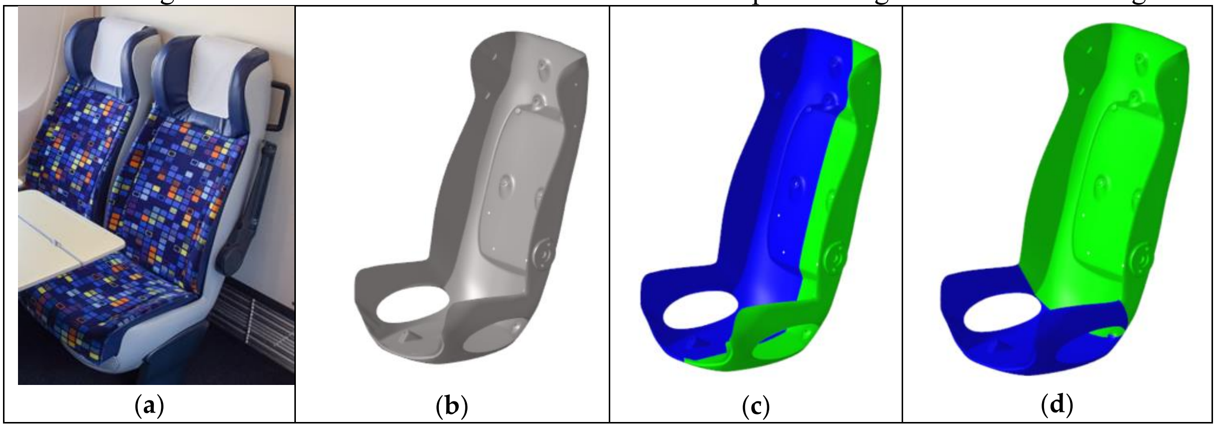

Figure 7. The investigated train-seat a) end-product b) shell geometry as one part c) partitioning ver 1 d) partitioning ver 2.

We assessed the shell as a single part and with two different partitioning variants as well. We calculated the C values for each part from the optimal direction of the original shell and from the optimal direction of the smaller parts themselves as well. With the calculated C values, we estimated the material costs. The input parameters of cost estimation are summarized in Table 1. Specific costs and scrap levels come from industrial experience; weight portions of fiber and resin are calculated with the densities of glass and resin, the volumetric fiber content of 40%, and a total weight of the complete shell of 12 kg.

Table 1. Input parameters of material cost estimation.

Abbreviation	Interpretation	Value	Unit
C_{fiber}	Specific cost of fiber	8	EUR/kg
C_{resin}	Specific cost of resin	3	EUR/kg
w_{fiber}	fiber weight of the complete shell	7.2	kg
w_{resin}	resin weight of the complete shell	4.8	kg
$s_{init\_scrap\_fiber}$	initial scrap level of fiber	0.15	1
$s_{init\_scrap\_resin}$	initial scrap level of resin	0.02	1

With the bottom-up cost estimation we used, the total cost includes investment, tool, material, and running costs [15]. In this case study, the seats were produced in a working composite plant with RTM machines and operational staff, so we investigated only the material cost estimated with formula (5), where C_{mat} is the total material cost of 1 piece of product.

$$C_{mat} = C_{fiber} w_{fiber} \left(1 + s_{scrap_{fiber}}\right) + C_{resin} w_{resin} \left(1 + s_{scrap_{resin}}\right) \tag{5}$$

The scrap levels of fiber and resin are calculated as the product of the initial scrap level and the calculated complexity factors. And note that the assembly cost's effect is negligible [15].

4. Results and Discussion

With the proposed method we calculated the complexity and the undercut factors on the train seat, and with the minimum search, we determined the optimal manufacturing direction of the shell structure. The

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3D branch diagrams are shown in Figure 8 with the optimal direction highlighted with a purple arrow. For an illustrative visualization, the parts contain only the beams for which the U value falls in the lowest 20 percent.

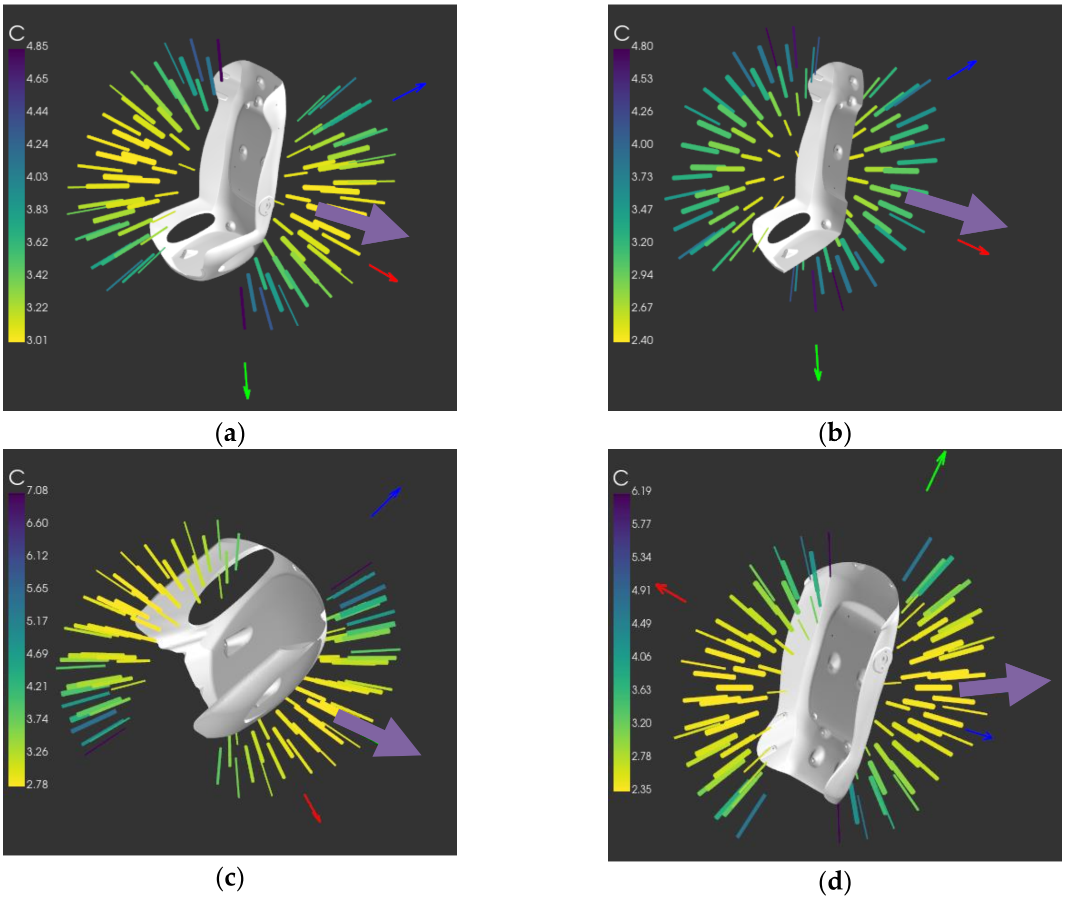

Figure 8. Complexity factors and optimal manufacturing directions (a) train seat as a single part (b) partitioning ver 1, right side (c) partitioning ver 2, seat bottom (d) partitioning ver 2, backrest.

As for the 1st partitioning variant, only one side is shown in Figure 8 (b) since the structure is symmetrical. The purple arrows indicate the optimal manufacturing direction obtained. According to engineering judgment, the results are reasonable. But to have a quantitative comparison, Table 2 summarizes the complexity factors and material costs, that are calculated in two different ways.

Table 2. Complexity factors and material costs.

		C [-]	**C_{mat} [€]**	**C [-]**	**C_{mat} [€]**
		optimal direction of the seat as single part		**optimal direction of the subpart itself**	
Seat – as single part		3.02	98.9	n/a	n/a
Seat – partitioning ver 1	left-side	3.19	100.5	2.87	97.6
	right side	3.19		2.87	
Seat – partitioning ver 2	backrest	2.56	101.4	2.36	94.6
	seat bottom	4.39		2.78	

On the one hand, from the optimal direction of the seat as a single part, this means that even if the seat is divided into partitions, the manufacturing direction of each part remains the same direction as the

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seat had as a single part. On the other hand, as the seat is divided into partitions, each part has its own optimal direction. After partitioning the structure, the values show that we must consider the parts' optimal manufacturing directions; the complexity values are naturally always smaller from these directions. The results also show that partitioning a complex part gives subparts with smaller complexity, which is beneficial in manufacturing.

According to these complexity factors, the material costs were also calculated. It can be clearly seen that the partitioning would mean, in this case, 1.3-4.3% saving when comparing material costs 97.6 € and 94.6 € to the original 98.9 €. But on the other side, taking the optimal manufacturing directions of the subparts into account would mean a 2.8-6.7% saving compared to the case when the manufacturing direction of the subparts remains the same as the undivided seat. With an annual production volume of 20 000 parts, these saving would mean a significant difference in manufacturing costs.

5. Conclusions

This paper aimed to introduce the method we developed to determine the optimal manufacturing direction of composite shell structures. We implemented the method in Python software environment that reads in a discretized surface model as input then calculates geometrical complexity factors and undercut factors from any direction in space. The new undercut factors we introduced characterize the surface in terms of undercuts. One can also evaluate the values visually since the software illustrates them with a 3D branch diagram. We showed a case study to demonstrate that by minimizing the product of these two factors, the optimal manufacturing direction can be determined automatically. By applying a bottom-up cost estimation approach, we pointed out how the manufacturing direction affects the material cost. In the case study of a train seat, we proved that partitioning the shell structure and determining the optimal manufacturing directions separately for each part can save more than 6% in the material cost. Based on this, the method can be a very efficient tool in the hands of composite technologists.

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