





New Method for the Application of Voxels in Product Design for Multi-Material 3D-Printing

Stefan Junk¹  and Henning Einloth² 

¹Offenburg University of Applied Sciences, Germany, stefan.junk@hs-offenburg.de

²Offenburg University of Applied Sciences, Germany, heinloth@stud.hs-offenburg.de

Corresponding author: Stefan Junk, stefan.junk@hs-offenburg.de

Abstract. Additive manufacturing (AM) and in particular the application of 3D multi material printing offers completely new production technologies thanks to the degree of freedom in design and the simultaneous processing of several materials in one component. Today's CAD systems for product development are volume-based and therefore cannot adequately implement the multi-material approach. Voxel-based CAD systems offer the advantage that a component can be divided into many voxels and different materials and functions can be assigned to these voxels.

In this contribution two voxel-based CAD systems will be analyzed in order to simplify the AM on voxel level with different materials. Thus, a number of suitable criteria for evaluating voxel-based CAD systems are being developed and applied. The results of a technical-economic comparison show the differences between the voxel-based systems and disclose their disadvantages compared to conventional CAD systems. In order to overcome these disadvantages, a new method is therefore presented as an approach that enables the voxelization of a component in a simple way based on a conventional CAD model. The process chain of this new method is demonstrated using a typical component from product design. The results of this implementation of the new method are illustrated and analyzed.

Keywords: Additive manufacturing, CAD, Voxel, multi-material 3D-printing, product design, voxelization.

DOI: <https://doi.org/10.14733/cadaps.2021.624-633>

1 INTRODUCTION

In conventional manufacturing, components are manufactured by removing material from a blank (subtractive manufacturing) or by reshaping a blank (formative manufacturing). Accordingly, CAD systems are used in product development, in which the components are also understood as solid bodies made of one material. In addition to conventional manufacturing, additive manufacturing has become increasingly important in recent years. The essential feature is that the components are created by applying layers of material [3].

In the meantime, new additive processes, such as e.g. 3D multi-material printing on the market. This method allows, for example, different colors to be used by combinations of differently colored filaments. In demanding applications, however, different materials can be applied in pure form or as a mixture - also called "digital material". Theoretically, the product designer can now use any material anywhere on a component. This type of manufacturing can no longer be represented with a CAD system that uses only a simple solid body made from only one material. It is therefore necessary to use new CAD systems in which a component consists of a large number of small elements. These small elements, also called voxels, can then be made with different materials depending on their function.

In order to be able to offer the product designer the possibility of 3D printing using voxels, a new method is being developed starting from the component design, through the print preparation up to the 3D printing. During the method, there will always be a visible 3D model of the component to make it easier for the product designer to design the component and manipulate the voxels. The presentation of the method chain and the more detailed description of the components should provide an overall overview of the method developed for user-friendly 3D multi-material printing using voxel instead of solid bodies.

2 LITERATURE REVIEW

The first approaches to the development of voxels were made in 1993 by Kaufmann et al. These showed the possibilities of voxelizing images using grids [10]. Chandru et al. transferred these findings to additive manufacturing because they recognized the connection between layered structure and voxel-based representation of components [1]. Current research by Faiegghi et al. shows the great importance of voxel-CAD for 3D printing [3]. Zhou and Zheng also show the use of voxels for special features, such as the minimum wall thickness and the use of multi-material 3D printing [14]. To show a current example of the potential of digital materials, Swetly et al. tested the impact strength of a digital material compared to a material that consists of only one component. The digital material was composed of a hard, brittle material and an elastomeric material in a checkerboard pattern and generatively manufactured using the PolyJet process [13]. The results clearly show that for all edge lengths tested, the samples from the mixed material have a significantly higher impact resistance than the samples from one material. Zhu et al. see the material selection, the material distribution and the arrangement of the materials within the component as a great challenge. Further research work had to be carried out here in order to be able to precisely predict and define the achievable material properties [15].

Modeling with voxels is also used, for example, in the development of 4D printed components. An example of this is a body network. If this is made of smart materials, it can assemble itself under the influence of an external stimulus and without any additional aids [11]. According to Sossou et al. modeling with voxels is suitable for designing smart materials. The voxels are used in software to design the smart materials virtually and to expose them to certain stimuli. An example is a valve that is placed in water and opens and closes based on the temperature of the water. If the temperature rises, the components contract and close the valve. If the stimulus is removed, the initial state is restored and the valve opens again [12]. Hiller and Lipson describe the modeling of any complex component using voxels as a tool with great potential. The authors see the printing of compact, integrated network chips in just one production step as a possible field of application for voxel modeling in connection with 3D multi-material printing and the resulting digital materials. The voxels to be used are insulating, conductive or other electrical components [5].

3 TECHNICAL-ECONOMIC EVALUATION OF VOXEL-BASED-CAD-SYSTEMS

In order to assess their performance, two voxel-based CAD systems are evaluated against technical and economic criteria. In addition, a conventional, volume-based CAD system is included to provide a comparison between volume-based and voxel-based CAD systems. First of all, the

chosen approach of the technical-economic comparison is described. Subsequently, the technical and economic value of the CAD systems is determined. At the end of the section, the results are plotted in a diagram [6].

3.1 Method of Technical and Economic Evaluation

The technical and economic evaluation is carried out in accordance with the guideline VDI 2225. First, the technical and economic value of the CAD systems to be compared is determined separately from each other, which is described in more detail below [2]. For the calculation of the technical value, evaluation criteria are defined in the first step, which are subsequently weighted. The weighting of the criteria takes place in the range between 0 and 1, whereby the sum of all weights is 1. The CAD systems are then analyzed against the defined criteria and evaluated with points from 1 to 10. The evaluations are first multiplied with the weighting factor. Subsequently, these results are added together and the overall result is divided by the maximum number of points (in this case 10). It is important to set a scale of values, otherwise the weighting is not meaningful. The resulting value is compared with the ideal solution in order to obtain a technical comparison value. The ideal solution results from the respective weight of a criterion multiplied by the maximum score. The different evaluation criteria, the weighting and the rating of each criteria can be found in the table 1.

The selection of the evaluation criteria is based on the findings and functions obtained during the study of the two voxel-based CAD systems „MagicaVoxel“ and „Qubicle“ [7]. The design of components plays a central role in the following technical comparison, which is why the criteria were mainly selected on the basis of this and are weighted accordingly. The comparison also includes „CATIA V5“ to represent the conventional CAD systems that work with volume-based modelling. The scale for scoring the criteria is in the range of 0 to 10 points. A 10-point rating means that the criterion has been fully met or implemented excellently. A 0-point rating, on the other hand, means an extremely poor implementation of the criterion in question. The following criteria are used for the technical evaluation:

Graphical user interface (GUI): The user interfaces of the voxel-based CAD systems are basically very similar. Both CAD systems convince with clarity and the sensible arrangement of the different registers. Because in „Qubicle“ symbols, such as a cylinder or a box, represent the corresponding tool, the user finds the desired function even faster than in MagicaVoxel. CATIA V5 also impresses with a clear user interface. Symbols or icons are also used to represent the functions, which makes the user interface clear.

Operation: The operation of the voxel-based CAD systems deviates from each other, but in principle the design functions work similarly. The user creates the base of a solid, which is then extruded. After working longer with both CAD systems, it becomes apparent that the operation of „MagicaVoxel“ is more dynamic and agile than the operation of „Qubicle“. Furthermore, „MagicaVoxel“ performs the operations to create bodies in much smaller increments and separates them from each other. „CATIA V5“ is extremely user-friendly, as sketches can be dimensioned directly by keyboard input and then extruded or otherwise processed. Creating bodies of a certain size is much easier and much faster in „CATIA V5“.

Design Features: „Qubicle“ offers significantly more design features than „MagicaVoxel“. In „Qubicle“, geometries such as cones or pyramids can be created using particular tools in one step, which is not possible in „MagicaVoxel“. The voxel colouring functions are also more versatile and user-friendly than in „MagicaVoxel“. „Qubicle“ has made design easier in certain features (e.g. chamfer using the tool for cones) thanks to the greater variety of functions. The „CATIA V5“ volume-based CAD system integrates a wide range of shapes and design functions.

Implementation of the design functions: The implementation of the design functions is better and simpler in „MagicaVoxel“ than in „Qubicle“. A suitable example of this is the production of a cylinder. In „Qubicle“, the corner point of the base of the desired body has to be searched for, which causes additional computational effort and thus makes the design much longer. In

„MagicaVoxel“, the designer only has to create a circle as the base, starting from the center of the circle and dragging it with the mouse. In a second step, the base is then extruded. This procedure saves effort in calculating and searching the coordinates of the starting point and illustrates the design. In „CATIA V5“, on the other hand, only sketches are created in a selected layer, which are then dimensioned and extruded. Using the appropriate tool performs the desired function. Also, in this criterion, „CATIA V5“ is clearly superior to the voxel-based CAD systems.

Approximation: The maximum installation space in „MagicaVoxel“ is (126 x 126 x 126) voxels. The developer-recommended size of a „Qubicle“ matrix is a maximum of (128 x 128 x 128) voxels with a maximum actual size of (1024 x 1024 x 512) voxels. However, the performance of „Qubicle“ decreases considerably by creating very large matrices. The component approach in „CATIA V5“ is almost perfect. The CAD system represents all bodies geometrically correct, since it does not use voxels to represent the components.

Export functions: The most important export functions in terms of additive manufacturing of the components both offer voxel-based CAD systems. Most important for this work is the slice function of both programs, which exports the layers of the component in the form of images. In „MagicaVoxel“, however, these are exported to each other in a single PNG file, which is very confusing. „Qubicle“ creates a separate PNG file for each layer, which is much clearer and more useful. „CATIA V5“ offers numerous export options, such as the STL format.

The ratings and results of the technical evaluation are shown in Table 1. The strengths and weaknesses of the two systems in the different criteria becomes clear. The results show that „Qubicle“ has a slightly higher technical value than „MagicaVoxel“, even though the conventional CAD-System „CATIA V5“ performs significantly better than the two voxel-based CAD systems. It can therefore be deduced from the comparison that the use of volume-based CAD systems for the design of components is much more appropriate for technical applications.

CAD-System		<i>Magica Voxel</i>	<i>Qubicle</i>	<i>CATIA V5</i>
Criteria	Weighting factor	Rating		
GUI	0.1	8	9	9
Operation	0.15	5	3	10
Design features:	0.25	3	6	10
Implementation of the design functions	0.25	5	3	9
Approximation	0.15	5	8	10
Export functions	0.05	8	10	10
Training materials	0.05	7	10	10
Technical value		0,51	0,58	0,97

Table 1: Technical value of CAD systems.

3.2 Economic Value

For the calculation of the economic value, the required design times for the sample component of the CAD systems seem to be a suitable basis for comparison. As a starting point for the allowable costs from which the ideal costs are calculated, the times for design from volume-based CAD systems, such as „CATIA V5“ (or cost-free alternatives, e.g. „Onshape“ and „Fusion 360“), are used [8]. Thus, times for design for the sample part are determined in „MagicaVoxel“, „Qubicle“ and „CATIA V5“, which represent the actual cost. From the ratio of these times for design, the economic valences of the systems are calculated.

The initial costs for Qubicle are marginal and should therefore not be included in the economic value. For the reasons mentioned above, only the times for design are considered. Also, the cost of conventional CAD systems are neglected because there are cost-free alternatives to CATIA V5. The specimen "wheel" was designed as fast as possible in each CAD system and the required time was measured. Table 2 shows the times for design in the respective CAD systems. In addition, the economic values of the CAD systems are shown in Table 2, which were determined using the method of VDI guideline 2225. The ideal cost target was defined by default as 70% of the best result, in this case „CATIA V5“ [2].

CAD-System/Criteria	<i>MagicaVoxel</i>	<i>Qubicle</i>	<i>CATIA V5</i>
Time for design	8,26 min	8,79 min	3,35 min
Economic value	0,28	0,27	0,70

Table 2: Time for design and economic value.

3.3 Results of the Technical-economic Evaluation

The values of the technical-economic evaluation show that the two examined voxel CAD systems perform quite similarly. Remarkably insufficient is the long design time of the voxel-based CAD systems compared to the times for design in conventional, volume-based CAD systems such as CATIA V5. If design time is multiplied by a cost rate per hour and thus evaluated in monetary terms, the use of voxel-based CAD systems to construct components is significantly less cost-effective than using conventional CAD systems.

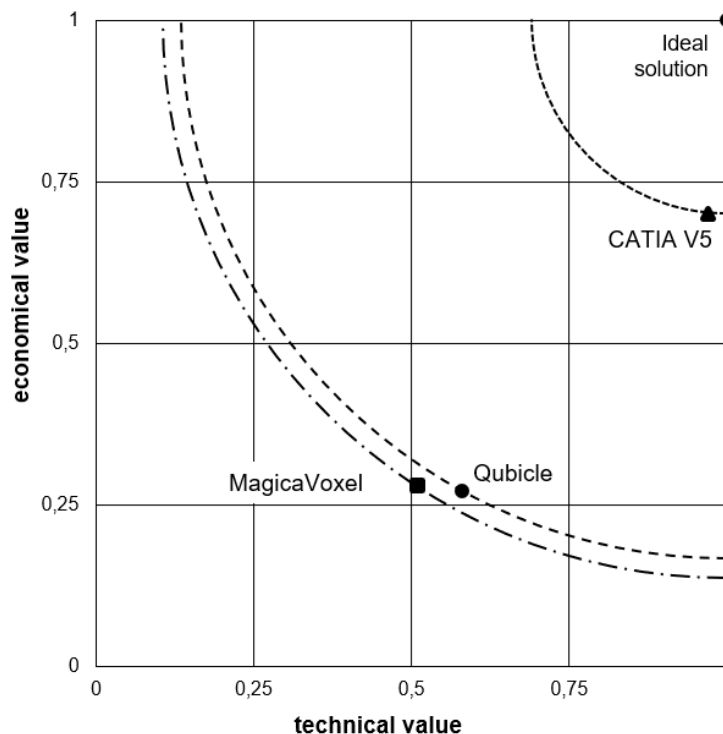


Figure 1. Evaluation of technical and economic value.

The results of the technical-economic comparison are summarized in Figure 1, in the form of a diagram. It follows that „Qubicle“ is to be preferred after the technical-economic comparison of the two voxel-based CAD systems, since it shows the smallest distance to the ideal solution. The decisive difference comes from the technical evaluation, since the two voxel-based systems are almost equally in the economic evaluation. „CATIA V5“ as a representative of the volume-based CAD systems is much closer to the ideal point. This clearly shows that from a technical and economic point of view it is better to use a volume-based CAD system for the design of components.

4 METHOD FOR THE APPLICATION OF VOXELS IN PRODUCT DESIGN

In order to overcome the disadvantages of using voxel-based CAD systems in product design, a new method was developed. The process chain for this new method of user-friendly 3D printing using voxel can be seen in Figure 2. The software used and the file formats for the interfaces are also illustrated. Based on the CAD model of an example component, which was designed using a conventional CAD system, this model is first divided into individual voxels. Then the voxels are manipulated and this modified model is prepared for the additive manufacturing (sliced in layers). Finally, the manufacturing takes place using a material jetting process (Poly-Jet-Modelling, PJM).

In the first step, the 3D model of the component is designed using a volume-based CAD system such as „CATIA V5“. The results in section 3 show that volume-based CAD systems are more suitable for the design of components than voxel-based CAD systems. For this reason, the component should be designed in a volume-based CAD system. When the 3D model of the component has been completed, the STL file of the component is exported from the volume-based CAD system and then imported into the software „Voxelizer“. This website offers the possibility of importing STL files and exporting them into specific formats that depict the component using voxels. At the same time, the resolution of the components can be determined. In general, this should be chosen as high as possible for reasons of accuracy and to avoid loss of information about the contours of the component. In order to be able to export the component to the software „Qubicle“, the QB file format must be created. This method represents the second step, which saves the user the high design effort in voxel-based CAD systems.

The voxel-based CAD system „Qubicle“ is then opened and the QB file of the component just created is imported and opened. Since the component now consists of voxels, each voxel or entire voxel areas can be edited in „Qubicle“. Editing means the coloring of the voxel, since the selected color later corresponds to a material assigned to the color. The user must therefore already consider which materials he intends to use in which component areas in order to define the desired component properties at these areas. The voxel-based CAD systems are ideal for processing the component at the voxel level, since they offer an easy-to-use, clear and user-friendly interface for processing the voxel. In addition, the user always has a complete 3D model of the component on the screen.

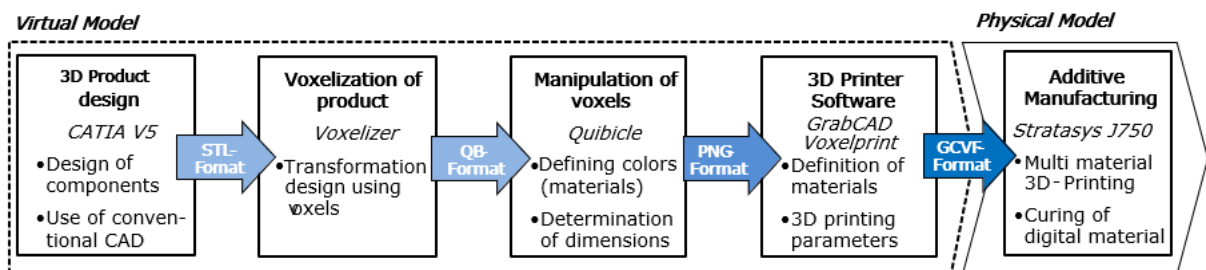


Figure 2: Process chain for user-friendly 3D printing using voxels.

As soon as the processing of the voxel is completed, the component must be dimensioned for the subsequent 3D printing. It is crucial to choose the correct size, since the size of the matrix in "Qubicle", in which the component is represented, determines the format of the later PNG files. To get the height of the matrix, a calculation is performed, how many PNG files or slices are needed for later printing. The component height in mm is divided by the layer thickness of the printer of 0.027 mm.

Since "Qubicle" creates a PNG file for each layer for each voxel in the vertical Z direction, the number of voxels in the Z direction has to be determined. "Qubicle's" scaling function is very useful in this method because each layer and the voxels it contains are ultimately only multiplied by the entered factor. Thus, there is no loss of information about the voxels of the different levels of the component when scaling the component height. However, you can only scale with integers in "Qubicle". As a result, due to rounding errors, it is usually not possible to fully adhere to the real component dimensions.

When dimensioning the width and length of the component, it must be considered that the later resolution of the J750 when printing is 600 dots per inch (DPI) in the X direction and 300 DPI in the Y direction. When exporting the layers, "Qubicle" allows the user to define how many pixels are to be used to represent a voxel. For example, if a PNG file has the dimensions (600 x 300) pixels, the printed layer would have the dimensions (25.4 mm x 25.4 mm) with a layer thickness of 0.027 mm. Taking this into account, the component dimensions must be converted from mm to pixels and the component must be scaled accordingly in the X and Y directions. Here too, only whole numbers can be used to scale the width and length of the component in "Qubicle".

After the dimensioning of the component has been completed, it can be exported using the "Qubicle" slice export function in the form of PNG files. The PNG files are numbered in ascending order and saved in a target folder. It is also possible to choose how many pixels are used to represent a voxel. This can also be helpful when scaling the component.

When this process is completed, the PNG files created by "Qubicle" are loaded into "GrabCAD Voxel Print" from Stratasys. This is an extension of the standard software. Finally, the necessary settings for generating the printable file must be made within this software. This includes assigning the printer's materials to the colors recognized by software in the PNG files. If this has been successfully completed, the component can be printed.

5 EXAMPLE OF USE FOR THE NEW METHOD

The developed method is demonstrated in this section using a practical example. One wheel serves as a sample component for the application of the new method. The method aims to offer the product designer the possibility of manipulating the voxels of a component. The focus is therefore not on the achieved or achievable component properties as a consequence of the manipulation of the voxel. The goal is to achieve user-friendly 3D printing using voxels. The first step is the design of the 3D model of the component using a conventional, volume-based CAD system. Figure 3a shows the finished 3D model of the wheel in conventional CAD-System „CATIA V5“.

In the second step, the browser is opened and the "Voxelizer" website is opened. The website can display STL or OBJ files using voxels and export them in different formats. The generated STL file from „CATIA V5“ is imported and the target format QB is selected for use in "Qubicle" (see Figure 3b). In order to get the closest possible approximation, the dimensioning and therefore the resolution must be determined at this point, since only integer multiples can later be used to scale the component in "Qubicle". The wheel in this example has a total diameter of 35 mm. The resolution is set to 103 voxels. The particular feature should also be activated to fill the interior of the component. Thereafter, the scaling of the component in "Qubicle" will be adjusted in order to ultimately achieve the correct dimensions again. The next step is to import the file into "Qubicle" as illustrated in Figure 3c. The dimension of the matrix in "Qubicle" corresponds to the dimensions defined in "Voxelizer". Thus, the voxels of the component can be manipulated and edited according to certain target variables using the functions of "Qubicle".

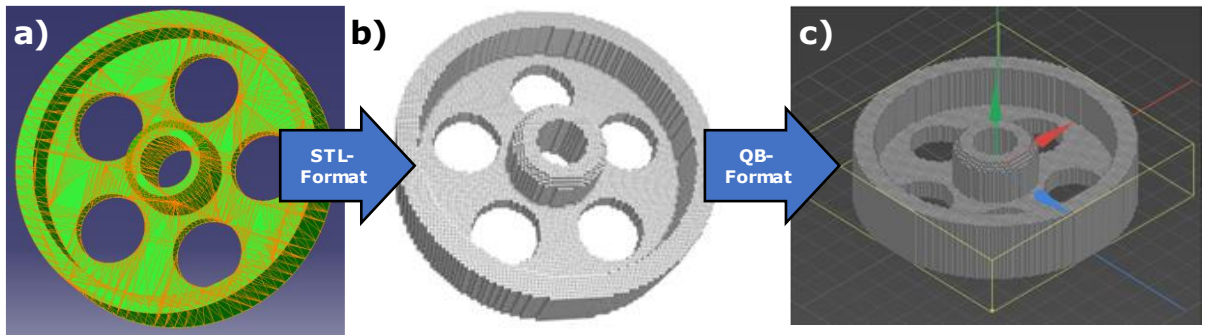


Figure 3: a) CAD-Modell of the component using conventional CAD-System, b) Transformation of CAD-Model to Voxels using "Voxelizer", c) Voxel-CAD-Model imported into "Qubicle".

The user always has access to the complete 3D model of the component. This is descriptive and extremely helpful during the processing of the component. Figure 4a shows a finished example of the JetMobil wheel, in which three different colors are used. Various color patterns have also been incorporated to illustrate that each voxel of the component can be manipulated. In the next step, certain printing materials and thus functions can be assigned to these colors of the voxels.

Once the processing is complete, the correct dimensioning of the component follows in order to correspond to the specified dimensions of the technical drawing. The component is then sliced into 296 PNG files using "Qubicle's" slice export function. The basis for using the voxel printing software "GrabCAD Voxel Print" (GPVP) is created by generating the PNG files for displaying the layers of the component. The print preparation software must now be opened to check the color setting. The desired materials are then assigned to the recognized pixel colors. As demonstrated in Figure 4b, the component is then loaded into the installation space of the 3D printer and the geometry is checked. Finally, 3D printing is started and the component is generatively manufactured using PJM and a 3D multi material printer Stratasys J750 (see Figure 4c).

Small deviations of approx. 0.15 to 0.4 mm in comparison of the 3D printed component to the technical drawing can be measured. The deviations are caused by the rounding due to voxelization and scaling during the previous process steps. In the PJM process, there is a deviation in the geometry accuracy of a few hundredths of a millimeter [9]. The deviations due to voxelization of the component are therefore much higher than expected due to the printing process. Since a very fine tessellation (2120 triangles) was chosen for the transfer of the CAD data in STL format (see Fig. 3a), the error due to tessellation cannot cause the deviation [6].

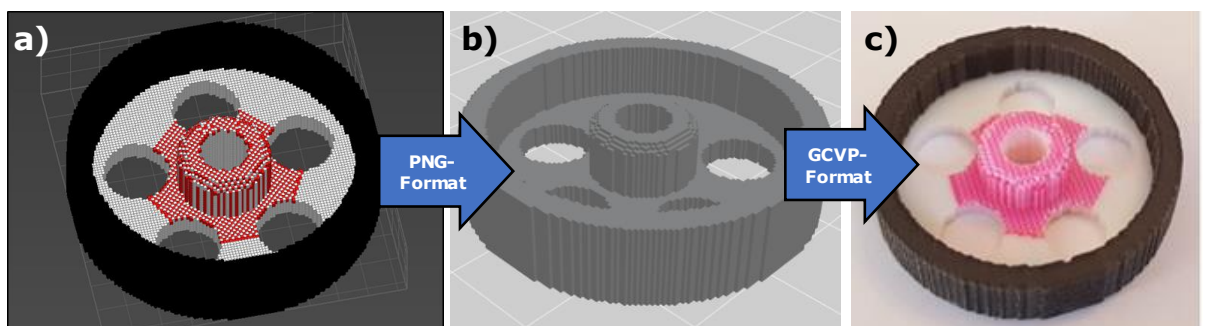


Figure 4: a) Manipulation of voxels using Software "Qubicle", b) Print preparation using "Grab-CAD Voxelprint" Software c) 3D multi material printing of the wheel.

6 CONCLUSIONS

In the context of this contribution, it was initially possible to show that a product design is possible with the help of voxels, but that this is at a disadvantage compared to conventional CAD. If the effort to design the component is considered, the product designer bypasses by using in this newly developed method the complex and time-consuming product design in a voxel-based CAD system. Instead, a volume-based CAD system is used, which considerably simplifies and shortens the product development process.

The simple and user-friendly manipulation of the voxel gives the user complete control over the design and distribution of the materials on the component. For the subsequent dimensioning of the component, a one-off calculation must be carried out for the corresponding component. The scaling of the component does not lead to any loss of information about the contained voxels.

After the developed method has been implemented, it becomes evident that the specified dimensions of the component can only be approximated. The deviation is based on the necessary rounding of the calculated numbers for scaling the component, since only whole numbers can be used for scaling. Depending on the application, these deviations may still be acceptable. When assembling components, however, these deviations can lead to considerable difficulties. Therefore, it should be determined in the following tests how the assembly can be simplified, e.g. by additive manufacturing of several parts of one product together in one batch.

In summary, it can be stated that with the presented new method, the complex process of 3D multi-material printing using voxels can be realized with reasonable effort and sufficient accuracy. Possible applications for this new approach are the targeted modification of voxels in a component. In the future it will be possible to display special color gradients and textures. A further application can also be the targeted mixing of materials in order to achieve certain material properties. By varying the voxels, the properties could also be strengthened locally or in a certain direction.

ACKNOWLEDGEMENTS

The authors would like to thank Stratasys EMEA Regional Office in Rheinmuenster/Germany for their generous support through the training and provision of GrabCAD Voxel Print and the 3D multi-material printing of sample parts.

Stefan Junk, <https://orcid.org/0000-0001-6183-7080>

Henning Einloth, <https://orcid.org/0000-0002-5546-238X>

REFERENCES:

- [1] Chandru, V.; Manohar, S.; Prakash, C. E.: Voxel-based modeling for layered manufacturing, IEEE Computer Graphics and Applications, 15, 1995, 42–47. <https://doi.org/10.1109/38.469516>
- [2] Ehrlenspiel, K.; Kiewert, A.; Lindemann, U.: Cost-Efficient Design, Springer Berlin, 2007. <https://doi.org/10.1007/978-3-540-34648-7>
- [3] Faieghi, M.; Tutunea-Fatan, O.R.; Eagleson, R.: Fast and cross-vendor OpenCL-based implementation for voxelization of triangular mesh models, Computer-Aided Design & Applications, 15, 2018, 852–862. <https://doi.org/10.1080/16864360.2018.1486961>
- [4] Gibson, I.; Rosen, D.; Stucker, B.: Additive Manufacturing Technologies, Springer New York, NY, 2015. <https://doi.org/10.1007/978-1-4939-2113-3>
- [5] Hiller, J.; Lipson, H.: Tunable digital material properties for 3D voxel printers, Rapid Prototyping Journal, 16, 2010, 241–247. <https://doi.org/10.1108/13552540910943441>

- [6] Hällgren, S.; Pejryd, L.; Ekengren, J.: 3D Data Export for Additive Manufacturing - Improving Geometric Accuracy, *Procedia CIRP* (Elsevier), 2016, Volume 50, 518–523. <https://doi.org/10.1016/j.procir.2016.05.046>
- [7] Junk S.; Einloth H.: Untersuchung zum Einsatz von Voxel-CAD-Systemen beim 3D-Multimaterialdruck, *Conference Proceedings, Additive Manufacturing, German Materials Society (DGM)*, 2020.
- [8] Junk, S.; Kuen, C.: Review of Open Source and Freeware CAD Systems for Use with 3D-Printing, *Procedia CIRP* (Elsevier), Volume 50, 2016, 430–435. <https://doi.org/10.1016/j.procir.2016.04.174>
- [9] Junk, S.; Eble, N.: Influence of Post-Processing on the Component Quality in 3D-Multi-Material- Printing, *DDMC, Fraunhofer Direct Digital Manufacturing Conference*, 2018, 135–140, *Fraunhofer-Verlag, Stuttgart*, 2018.
- [10] Kaufman, A.; Cohen, D.; Yagel, R.: Volume graphics, *Computer*, 26 (7), 1993, 26, 51–64. <https://doi.org/10.1109/MC.1993.274942>
- [11] Pei E, Loh GH. Technological considerations for 4D printing: an overview. *Progress in Additive Manufacturing*, 3(1-2), 2018, 95–107. <https://doi.org/10.1007/s40964-018-0047-1>
- [12] Sossou, G.; Demoly, F.; Montavon, G.; Gomes, S.: Design for 4D printing: rapidly exploring the design space around smart materials, 70, *Procedia CIRP*, 2018, 120–125. <https://doi.org/10.1016/j.procir.2018.02.032>
- [13] Swetly, T.; Stampfl, J.; Kempf, G.; Hucke, R.-M.; Willing, M.; Warkentin, M.: Bioinspired engineering polymers by voxel-based 3D-printing, *BioNanoMaterials*, 17(3-4), 2016, 145–157. <https://doi.org/10.1515/bnm-2015-0021>
- [14] Zhou, M.; Zheng, G.: Geometry Attributes Computation of 3D Model for Additive Manufacturing, 17, *Computer-Aided Design and Applications*, 2019, 138–146. <https://doi.org/10.14733/cadaps.2020.138-146>
- [15] Zhu, B.; Skouras, M.; Chen, D.; Matusik, W.: Two-Scale Topology Optimization with Microstructures, *ACM Transactions on Graphics*, 36(5), 2017, 164:16. <https://doi.org/10.1145/3072959.3095815>