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Computer integration for geometry generation for product optimization with Additive Manufacturing

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Abstract

Designing parts for additive manufacturing (AM) offers a broad range of geometrical and functional potentials. On the one hand the manufacturing technology offers the possibility of manufacturing highly complex freeform shapes, often referred to as bionic shapes. By use of these, perfect force fluxes without stress risings due to imperfect notches are realizable, getting the most value of used material. On the other hand these complex structures require a reliable geometry representation in compatible CAD-files. Conventional CAD systems were developed to generate geometries that are manufacturable with conventional machining. These are not capable of representing the high complex designs for AM. Especially for geometries generated by CAE like from topology optimization the conventional CAD systems fail to take advantage of the combination of CAE and AM.

This paper explains why there is a lack of compatibility of well-known CAD systems with the potentials of AM. Therefore the AM-side of the problem is described by showing some potentials of AM and the need of high complex structures for this manufacturing technology. For the other side of the problem conventional methodologies for geometry representation of CAD systems are described and their limitations with regard to AM are worked out. Finally a voxel based geometry representation is presented as a solution for computer aided geometry generation of high complex AM–structures.

Introduction

Nowadays additive manufacturing (AM) has evolved to a reasonable direct manufacturing technology for actual components, made of a variety of materials. Parts are created by material addition layer by layer combining two dimensional layers (2D) made from small volume elements (1D) to three-dimensional shapes (3D). Therefore the manufacturing is conducted tool less, as the material is deposited, molten and solidified in place without a shape-giving tool like a cutter or a mold. Thereby AM can be differentiated from conventional manufacturing technologies by two core characteristics: the “1D–2D–3D-principle” and tool less manufacturing, taking into account that “1D” represents small volume elements – voxels – what is very important for the later described geometry representation methodology. [RK16; RK15]

The layer wise and tool less manufacturing enables a broad range of geometrical and functional potentials between which the potential “complexity for free” temporary had become something like a mantra for selling AM as a promising technology [HHD05]. Beside this a lot of other potentials as monolithic design and function integration or flexible semi-automatic production of slightly different designs in one manufacturing shot are named. [GRS10; RK16]

No matter whether these potentials are way more easy to realize with AM instead of conventional manufacturing many of them have been discussed years ago [EKH+07]. Crucial for a successful

manufacturing of parts and especially for exploiting the potentials of AM is a well-designed digital representation of the latter part. Not merely for "complexity for free" but rather most of the AM-potentials and particularly for computer generated lightweight components, very complex geometries arise. Conventional CAD-tools are often doomed to fail for these complex geometries as their basis was developed many years ago for replacing 2D-drawing and the clear aim of generating geometries possible to be made with conventional machining.
Thus there is a need for new digital geometry representation methodologies in CAD tools, especially developed for high complex freeform designs as a vital link of computer aided geometry generation and additive manufacturing. Therefore in the following an explanation and comparison of requirements coming from AM and capabilities of CAD tools will be given to work out a new voxel-based principle to enhance the overall process.

Existing CAD representation schemes

In over 50 years development of CAD-systems many different methodologies for geometry representation were invented. All of them are following the same aims of describing and capturing geometrical objects and their attributes with a strong focus on geometry visualization. Therefore suitable data structures have to be used and for a long time complex geometries had to be approximated by more simple ones [Sha01]. Following [Sha01] there are three general rules mandatory for each engineering language in terms of solid modeling to guarantee and maintain their integrity:

- "Any constructed representation should be valid in the sense that it should correspond to some real physical object;
- Any constructed representation should represent unambiguously the corresponding physical object;
- The representation should support (at least in principle) any and all geometric queries that may be asked of the corresponding physical object."

Thus, there is something like a common sense in feasibility, usefulness and correctness postulated. Validity, correctness and correspondence to a physical object is one of the major challenges in terms of high complex geometry representation and the direct evolution from digital to physical product subsistence. The most direct conversion from digital to physical is boon and bane in the same time, as there are barely fallback levels to overcome failures in the digital geometric data. When thinking about efficient generation of geometric data for AM this has to be kept in mind especially in contrast to design for conventional machining like milling where little freeform surfaces but mostly flat or concentric surfaces for turning are cut. In a mathematical understanding there is the difference of not-, simple- or double curved elements. For conventional manufacturing the double curved elements are seldom seen as this is way more complex to produce than not-, or simple curved elements, while for AM the additional effort is circumstantial. [Ada15]
Methodologies for solid modeling can be classified via the representation scheme and the modeling processes. Thereby the representation scheme is the technology that is actually representing the geometry and enables the user to see a geometry on screen. In comparison the modeling processes describe the way the geometry is generated by means of defining the location and relationship of each point and edge that will be used in the representation.
In the beginning of computer aided design as digital support for engineers, only simple 2D-drawings as direct substitution for hand drawings were available. Based on these very simple digitalization of manual work, over the years many different approaches for representing geometric objects have been invented. The great number of different schemes can be categorized in three categories as shown in Figure 1: direct, indirect and parametric representation schemes. [Fra09]

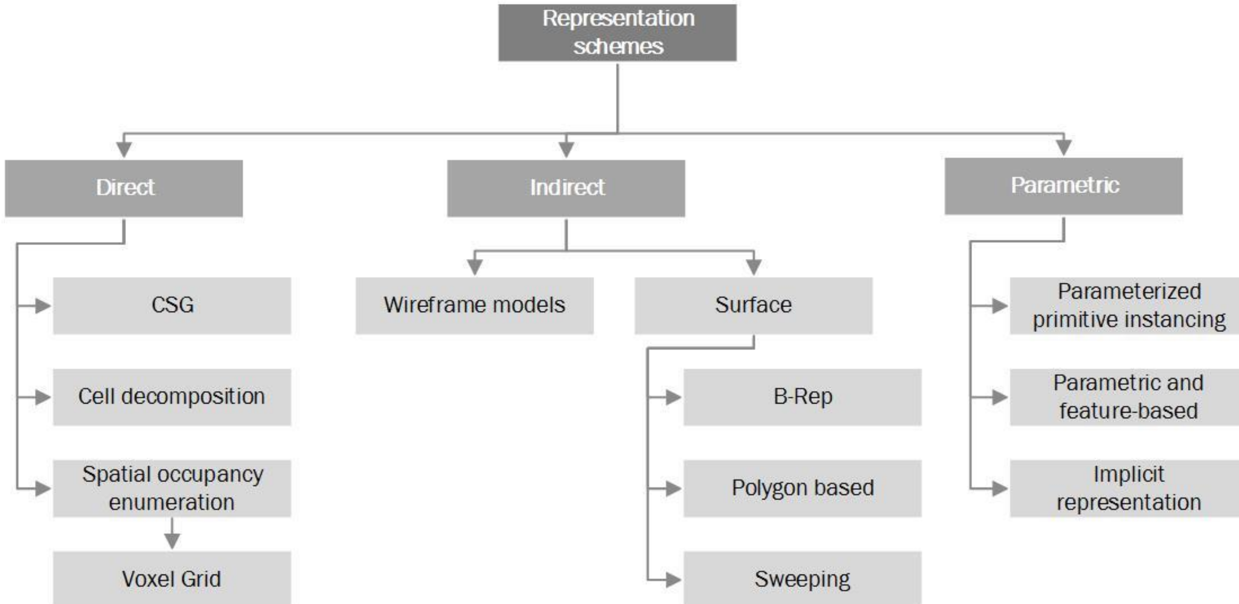

Figure 1: Representation Schemes in solid modeling

The category of **direct representation schemes** is specifically marked by representing a solid volume by direct representation with volumetric elements. Thus single mistakes like missing small elements do not destroy the overall geometry. For indirect schemes like a polygon mesh the absence of one single element ruins the closed surface so that no entire volume is surrounded and the solid cannot be detected. Furthermore, with regard to the geometry generation for additive manufacturing, direct representation schemes based on norm cells or voxel grids enable simple local editing like smoothing when single elements are added or removed. [RK15] On the contrary for other schemes like CSG (Constructive Solid Geometry) or norm cells with low resolution it is difficult to represent complex freeform shaped surfaces. Voxel based schemes like spatial occupancy enumeration are used for example in computer tomography scans (CT) to save the scanned information for each volume element. Those scans enable the representation of very high complex geometries but require very big storage systems.

One of the first invented representation schemes in CAD systems is based on simple primitives used with Boolean operations for addition and subtraction to create more complex geometries. Figure 2 gives an example for such a complex geometry generated by the combination of very simple volumes and one cutting plane. This technology is called **Constructive Solid Geometry** (CSG) and until today is one of the most underlying and used principles. Studies show that a lot of parts are representable only with these features. All of these are easily manufacturable conventionally with respect to undercuts or the like. A survey from the evolving time of CAD has shown that "63% of all the parts could be handled with a CSG system based on only orthogonal block and cylinder primitives. A larger class of primitives provided a natural description of over 90% of the parts. This indicated that CSG is therefore a good fit for a CAD system in that sort of environment because most mechanical parts seemed to be relatively simple." [SRE76; Ago05]

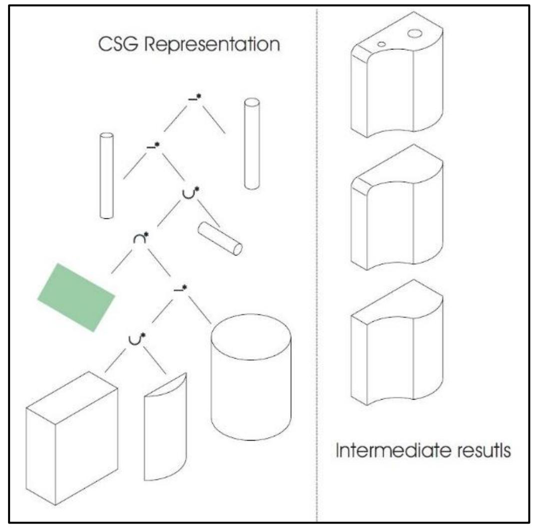

Figure 2: Constructive Solid Geometry [Sha01]

Another representation scheme is the **Cell Decomposition Representation**. This is what is mostly used for finite element modeling as the geometry is decomposed into plenty small elements like triangles in two-dimensional cases or tetrahedra for three-dimensional models [Ago05]. Thus the cell decomposition is a versatile principle as the use of triangles is possible as well for indirect representation schemes (B-REP) if a volume is represented only via a closed surface. In this case the tetrahedra are small volumetric elements whose combination results in a direct volumetric geometry representation.

Near to the cell decomposition the **Spatial Occupancy Enumeration** represents a geometry with small uniformly sized cells. In this case the volume is represented by small squares in 2D (pixel) or small volume elements in 3D (voxels). These voxels are ordered in a fixed grid and all of them that are inside the volume are marked as volume elements whose coordinates are explicit. As already written bevor, the main problem of this representation is the big amount of data that has to be stored. Thereby this scheme was not used much for CAD systems. Though today the computing power and memory have increased that much that this scheme gets more and more important. [Ago05] Due to its capabilities and the voxel-based approach that is near to a special interpretation of the AM technology this scheme is very usable in the context of geometry generation for AM [RK15; RLJ+17]. Thereby later on this scheme will be discussed again in detail.

The next category is the indirect representation schemes. The main characteristic feature in this case is, that the geometry is not represented by any volume but more by the edges or the surfaces one can see from the outside and the volume is not explicitly represented.

In the beginning of the development of three-dimensional CAD systems the **Wireframe Representations** have been the most usable way of representing a geometry because it is easy and fast to compute and display. Thereby the vertices of a geometry are stored in a database and then connected with edges. These edges can be displayed and thereby a wireframe of the model is shown. Unfortunately for these representations it is hard to decide which edges are in the front or behind the rest of the model and one cannot get cutting view. On the other hand for complex geometries it is very fast to display and one can see through the part to identify inner structures. Today most CAD systems still enable such a view. [Ago05]

In the group of surface based indirect schemes the main important one is the **Boundary Representation** (B-REP) scheme. In this scheme the geometry is represented only via its surfaces. If the surface of a geometry is fully closed, the inner volume can be interpreted as a solid. The overall surface of the geometry can be interpreted as a relationship between objects and certain graphs. Hereby the surface consists of *n* faces which are based on n edges that are always connecting 2 vertices. Inside the graph the vertices can be used by arbitrary edges that can be used for arbitrary, but reasonably two surfaces. [Ago05]

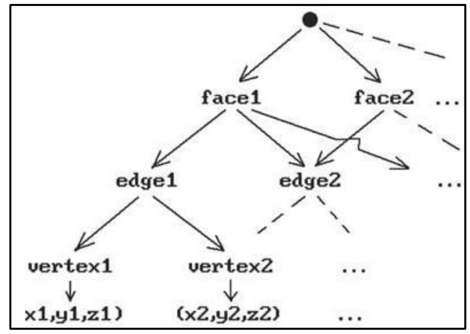

Figure 3: A boundary representation Graph [Ago05]

B-REP as well as CSG is one of the basic representation schemes that have been used from the early beginnings of CAD system development. B-REP thereby is capable of being combined with many other schemes. Figure 1 names the **Polygon** and the **Sweeping Representation** as explicit schemes, but can be interpreted as or at least easily translated in a B-REP as well. Sweeping is a scheme where a set of lines is “swept” along another line and thereby encloses a volume. Thus this representation corresponds naturally to the way many mechanical parts are manufactured like sheet metal systems, turning or milling [Ago05].

Polygon meshes again are well-known from FEM analysis as mentioned for the Cell Decomposition already. Thereby the Surface of a three-dimensional geometry is divided in small finite elements, mainly triangles or squares. The difference is that the two-dimensional surface can be of any high complex freeform shape but has to enclose a volume so that the inner area can be interpreted as a solid. The decomposition of the boundary representation with triangles to enclose a solid volume is as well what is known from the .stl data format that is used as a de facto standard for additive manufacturing. Here one of the main problems of indirect representations can appear. If one of the great number of triangles, easily up to a million for big complex structures, is flipped around to indicate the wrong side as inner volume or is missing at all, the inner volume is not fully enclosed and cannot be interpreted as solid. This fault cannot appear for direct representation schemes.

The last category of representation schemes is the parametric category. Mainly the parameterized primitive instancing, the parametric and feature-based modeling and the implicit representation can be named here. [Fra09] As the category name already is indicating, the main characteristic is the strong influence of parameters. Because of the inferior importance for the topic discussed in this paper these are only explained in short.

Parameterized Primitive Instancing is the representation scheme used for part libraries as for screws. Thereby certain primitives are fully described with parameterized measurements that are often depended from each other. All single objects are generic primitives which are members of a family of objects, distinguishable from the others by a few parameters. Thus the user can easily change one of the parameters and thereby call another family member. The main drawback of this technique is that not all new geometries can be designed as the family already defines the possible variants. Furthermore the definition of these families is very complex and thus only feasible if a broad usage, as for bolts, is expected. [Ago05]

Parametric and Feature Based modeling is what we mostly see in CAD systems and is based on the use of parametric shapes associated with attributes like length, width, radii etc. This modeling is often used in combination with CSG representations but with the difference, that there is a clear focus on the parametrization of the used primitives. Thereby a linkage of the model with databases as for variant management is possible.

The last representation scheme is the **implicit representation**. Hereby the geometry is defined implicitly to consist of all points that satisfy a specified condition. This condition can be a mathematical function and each point describable from this function is a part of the geometry. Thereby complex geometries can be designed with only a small mathematical description. [PAS+95]

Existing modeling techniques

As we now have seen several possibilities to store digital geometries we need to discuss modeling techniques to design these geometries. Some of the modeling techniques can be used for different representations as well as some representations can be filled with different modeling techniques, while for some there are clear relationships. Figure 4 gives an overview of different modeling techniques, clustered in polygon based, curve based and digital sculpting techniques.
In general the choice of the right modeling techniques is dependent on the intention what to do and the used representation scheme. Thereby the **polygon based modeling** techniques are nothing for manual geometry generation. As a complex geometry consists of a plethora of polygons these need to be generated automatically. A definition of each of the vertices and the conducting combination to polygons would be very time consuming and only seems to be feasible for very easy geometries. Thus the polygon based geometries always are generated on basis of other geometry definitions. One possibility therefore is on basis of a **point cloud**. This cloud can be the result of a 3D-Scan of an existing geometry like from 3D-cameras or tactile measurement arms. Also a definition via mathematical defined points with curves and an appropriate division could be feasible. Another possibility for modeling a polygon based geometry is on a **surface mesh** on basis of an already existing surface made with any other modeling technique. A common approach for smoothing geometries gained from any voxel based scanning methodology like CT-scanning is the **Marching Cube Algorithm** which divides the voxel grid and approximates the stair-stepped geometries to much more smooth geometries on polygon basis.

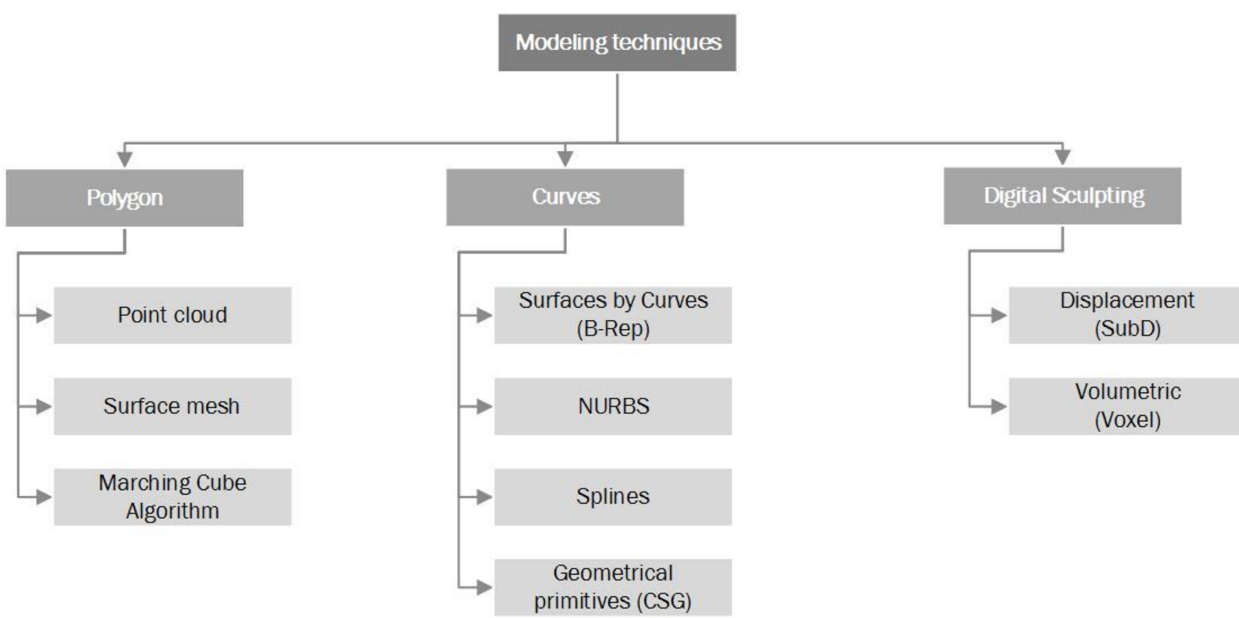

Figure 4: Modeling Techniques overview

Polygon meshes are widely spread in digital geometry representation. The big advantages of a very simple geometry definition and simple data formats in combination with very fast rendering, saving and loading have brought polygons to a standard in graphics processing and 3D-printing. Furthermore most FEA tools make use of polygons for surface meshing. Apart from that of course there are some drawbacks like as already mentioned an active design by defining the coordinates of each vertex is nearly impossible. In addition it is impossible to represent curved surfaces really accurate. There is always a triangulation error so that a circle never is perfect round but consists of many straight lines with little angle difference. Thus a high resolution for smooth surfaces lead to a high amount of data. At least it is possible to create meaningless geometries as if a surface is interrupted no solid can be interpreted. In case of 3D printing there have been quite good tools developed to identify those mistakes and correct them automatically. Nevertheless one have to keep in mind that in the end each geometry seen on screen is rendered on basis of polygons and then converted in to 2D-pixels!

The second modeling technique branch are the curve based modelings. There is quite a different to the polygon based models though both techniques can be used for the surface based representation schemes like B-Rep, Polygon and Sweeping. The main difference is that any curved things via polygon based modeling are mapped discontinuously while the curve modeling is capable of representing complex geometries continuously.

The simplest one to understand is the direct linkage of modeling technique to representation scheme for the **geometrical primitives** and CSG, as each of the simple primitives is set up with mathematically clear defined formulas like a circle, cylinder etc. Only the combination generates more complex structures. Though this is hardly capable of representing real freeform elements like bionic looking structures, as these designs are not based on the simple geometric primitives. Nevertheless a careful use of only proper defined primitives like of the so called r-set guarantees a correct model without geometrical mistakes. [Ago05]

Most CAD-Designs start with sketching some 2D representations and then doing some extrusions, sweeping or the like. This is a reasonable extension of 2D design and often is near to conventional manufacturing like milling, turning or extrusion. Over the years these techniques have been implemented very well so that they work well without errors and are easily to combine with other techniques.

But if a complex smooth surface shall be designed feasible of taking advantage of the AM-potentials these simple CAD features come to their end. For very smooth surfaces shapes need to be designed by the use of mathematically describable continuously differentiable curves like **Splines**. Splines in general are two- or three-dimensional lines drawn on a plane or in space whose curvature might change as often as necessary. By combination of many of these mesh can be drawn in space to represent a **surface by curves.** If we assume only four splines defining each edge of a squared surface this conforms perfectly to the definition of one surface of a Boundary Representation scheme (B-Rep) where only some further surfaces are needed to enclose a volume and form a solid.

Later-on **basissplines** (B-Splines) and **non-uniform rational b-spline** (NURBS) were developed to define complex shaped surfaces with curvatures in more than one direction. These surfaces are described mathematically precise and thereby capable of representing complex technical geometries. The generation of these surfaces is easy to manage for geometry systems where the designer can keep track of each surface and the connection to the adjacent surfaces.

Figure 5 shows an example for a part where a manual creation of numerous NURBS for representing a complex topology optimization structure has failed. The combination of over 300 single, handmade NURBS surfaces resulted in a vast number of failures not only can be seen in unconnected surfaces but also in missing G² continuity and thereby smoothness. For G² continuous surfaces the second derivation of the surfaces curvature needs to be continuous. Furthermore NURBS should be capable of enabling perfect smooth junctions of struts and surfaces as fatigue notch factors can be reduced drastically with the right notch geometry [DRK15]. Take advantage of this possibility is not easy and nearly impossible for the shown overall geometry complexity.

Figure 5: Example for bad geometry retransition by manual NURBS creation [RK15]

The manual generation of freeform surfaces by use of several splines combined to a surface by something like a mesh is possible. The complex surface transitions in areas of strut-combinations however is manually not possible as a bunch of several surfaces is needed to represent the complexity in those areas. Thereby for curve based modeling with NURBS for setting up a B-Rep model similar to polygons automatic algorithms are needed to support the user. [RK15]

Summarizing curve based modeling in general is capable of designing high complex geometries and represent them reliable in the digital world. Nevertheless complex combinations with struts are hardly made manually and the process is error-prone. Perfect notch factors as well as G² continuity is hard to realize. Furthermore the designer needs to know how the structure shall look like and it easily can get very complex to adjust single elements after being designed.

The third branch are quite new modeling techniques: **digital sculpting** which is especially capable to overcome the hurdles of freeform design, developing new ideas during design process and making small changes on freeform elements after they have been initially designed. These techniques are taking advantage of many already mentioned principles but are combining them in a new way to enable to work with the material like in real-life with clay.

The **displacement** principle, better known as **subdivision** (Sub-D), sets up surfaces on basis of a cube whose eight corner points as well as the twelve edges are used as control points and the surface in between is gravitated towards these. Thereby the simplest geometry with a low but equal weighting on each point and edge is a perfect sphere. With maximum weight on each point and edge, the surface is that much pulled to these control elements, that a cube is represented. The underlying principle does not focus on a manual design of new products but more is a method of representing a smooth surface by decompositioning it with polygons step by step as shown in Figure 6. This underlying algorithm was mainly developed by Edwin Catmull and Jim Clark, resulting in the "Catmull-Clark subdivision surface".

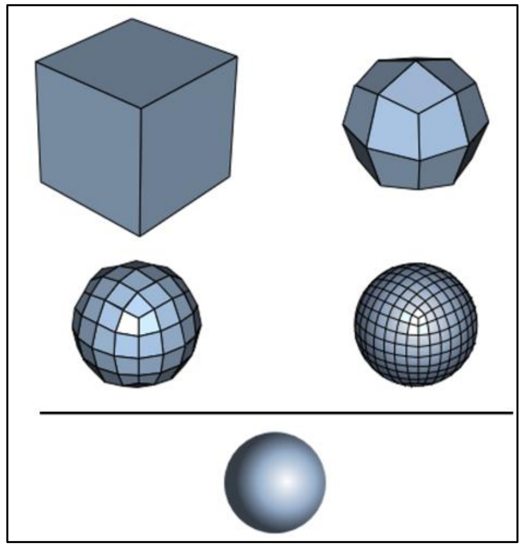

Figure 6: Subdivision of a cube [Rom-ol]

The great advantage of subdivision surfaces for modelling are high complex, but faultless, smooth surfaces. Each generated surface is G^2 continuous what seems to be perfect for both stress equality and fluid dynamics in channels.
The systematic refinement of the single decompositions enables the design of big, smooth elements as well as highly complex and very detailed elements in one shot. Furthermore even very complex subdivision surfaces do not require a high amount of storage because only the control points are saved. Even the export in conventional CAD systems is very easy as a conversion into standard NURBS surfaces is no problem.
The other main representative for digital sculpting is the **voxel based** approach. For this approach the geometry is set up by a vast number of small voxels in a clear structured voxel grid. Thereby it is easily possible to add and remove elements and thereby design a geometry as in real-life with clay. Advanced software tools allow the user even to interact via a haptic interface to really model the part as in real-life with well-known clay-modeling tools. One of these tools is Geomagic Freeform©. Here either an already existing geometry can be transferred into a voxel based model and adapted or the user can start with a block and design a new part. The transformation of a voxel based model in a standard CAD geometry requires some work but is possible. One often used approach is the already mentioned "marching cube algorithm" that works very well on the clear defined regular voxel grid. Additionally quad meshes are easy to generate and retranslate to NURBS.
The main disadvantage of both technologies is the lack of a parametric description of geometries. Whilst in general this is technically possible, nowadays it is barely used. This might be a reason why these technologies are mainly found in arts. In engineering areas for the design of technical products it can be less found, except for special usage like texturing of surfaces, what is often made by voxel technology. The handling of these technologies is unfamiliar for most engineers and especially for Sub-D barely comparable with any other method. Furthermore for simple, perhaps easy parametric describable, geometries the needed storage is comparably high but changes for high complex geometries.

What is a complex structure (...good for)?

When talking about complex structures realized with AM two questions arise: what characterizes a complex structure and what is the benefit of such structures? Generally a complex

system is defined as a system in which many different parts interact with each other composed from the Latin words “com” (together) and “plex” (woven). Thereby a complex structured geometry consist of many different structure elements which interact with each other. This is not an all-new thing for additive manufacturing, as on the one hand entire products, like the assembled car or plane, have been developed since years. On the other hand single parts of these assemblies have been optimized for its purpose as well. Thereby one single part can consist of several “features” in a CAD system combining volume elements with holes, radii, ribs and chamfers.
AM is now a key enabler to increase this complexity as every single geometry element of a part can be adjusted to interact optimal with the others. Transferred into a geometry this implies that surfaces are not forced to be flat or curved in explicit radii with defined ends but can freely merge very smooth into each other with several overlying curvatures and without discontinuities. These surface combination areas can be optimized for optimal force flux without stress risings due to notch effects and thereby follow renowned bionic principles [MB03; Mat06]. Especially for geometries that are not handmade but designed with the aid of advanced computer algorithms like topology optimization where a vast number of single elements like big and small struts, stiffening shear plates, interfaces, holes and sponge or bone-like areas are combined to one complex system, a vast number of joining and dividing surfaces have to be designed.
That comes to the conclusion that for a pretty good design in terms of lightweight design for optimal material usage, each of these surfaces and combinations need their curvature to be at least described by a third grade function and continuous in the second derivation as long as it is no interface region to adjacent parts. This implies that two curved surfaces are not only connected by a tangential combination but with the same tangent plane and same normal curvature in a common point resulting in perfect smooth transitions. This is called curvature – or third-level parametric continuity (G^2). [Har03; Ago05]
With conventional CAD systems such shapes are barely generable by hand in a high number per part. The representation of such surfaces is done by NURBS that need many control points. Automatic functions are needed, as described later on.

Motivation

None of the beforehand described methodologies is capable of representing the desired complexity and functionality of geometries alone. Furthermore the use of computer integration for semi-automatic geometry generation as on basis of topology optimization results require advanced methodologies of geometry generation, representation and modification.
Some of the existing methodologies are made for arts or for gaming and capable of representing complex geometries but fail for the use in actual mechanical components as mentioned before. Most components are only small pieces in bigger assemblies and thereby need some clear defined interfaces for mounting, connection and force transmission. Figure 7 shows a simple lever for such a combination of parametric elements (brown) and freeform optimized geometries around (grey). When designing a new product with freeform surfaces it is necessary to design these elements as parametric defined features like for drill holes or bearing seats. A logic connection needs to be established and possible to be represented and changed in both parts. Conventional CAD methodologies are powerful in modeling such exact defined parametric and easy conventionally manufacturable geometries but have a lack in the representation of high complex freeform surfaces. A new process, maybe including new data formats for 3D files need to be established.

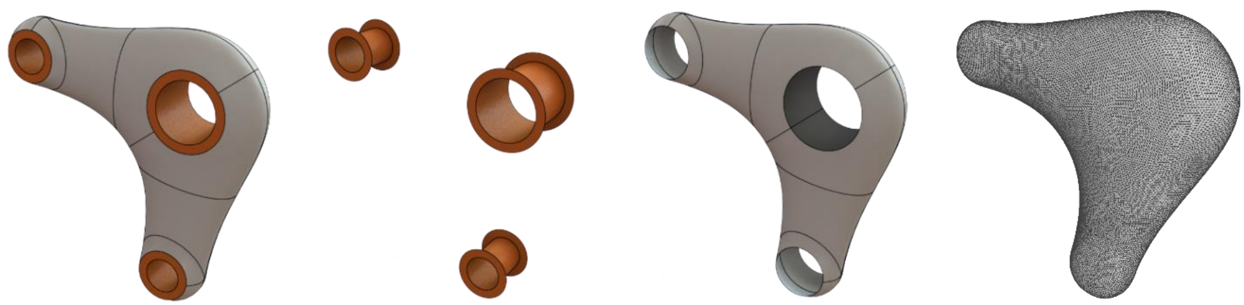

Figure 7: Example for simple lever as a combination of freeform and parametric features and representation via quad mesh

Thus a CAD file containing a geometry taking advantage of the AM potentials has following requirements:

- automatic geometry generation and optimization
- shaping of highly complex structures
- consideration of AM-restrictions
- compatibility with parametric features
- fit for the future: multi-material production information content
- easy variability, adaptability and customizability

These requirements will be described and assessed for their usability in the following chapter. Furthermore already solution approaches will be shown.

Methodology for computer integration in geometry generation

The development of a lean method of designing CAD geometries taking full advantage of the potentials of additive manufacturing thereby can be broken down to finding solutions for the six requirements defined above.
First point thereby is the **automatic geometry generation and optimization**. In this case we shorten up the different possibilities of inventing geometries and focus on FE-based technologies like topology and shape optimization and their subsequent steps. Other advanced methodologies

could be a definition based on mathematical functions definition. As these technologies are very well for generating complex arts, it gets hard to define actual mechanical components only with these technologies.

For topology optimization a finite element (FE) model is set up including all boundary conditions and outside influences like occurring loads, constraints, heat transfer or the like. These are acting upon a virtual volume called design space in where material is allowed but might be reduced if not needed for withstanding the loads while keeping in mind boundaries like maximum displacement, Eigen frequencies or maximum weight. Thus structural parts can be optimized regarding their structural integrity or material consumption. As the standard procedure works on standard finite element models the results are barely directly usable. While for conventional manufacturing the results needed to be redesigned and adapted to the manufacturing technique anyway, no one has been bothered about imperfect optimization results. Nowadays, AM enables the manufacturing of arbitrary complex shapes so that one can imagine that it is desirable to generate results in a quality sufficient for sending directly into manufacturing. Of course one should never trust the optimization results without sufficient validation and for high value parts it might be reasonable to adapt the results. For simple parts though, a mainly automatic process could reduce environmental impact by material usage reduction while only low effort is acceptable. A feasible approach based on the use of a voxel based software already was shown in 2015 by [RK15]. There the Topology Optimization results are smoothed and adapted after the optimization process to gain smooth and manufacturable designs by converting the results into a voxel representation. Afterwards it is transferred back to a CAD representation by generating NURBS patches on the surface, supposedly by use of the marching cube algorithm and quad meshing as already mentioned above.

Second requirement is the **shaping of high complex structures**. On the one hand this aims at the general generation and imagination of complex structures as only these are really economical feasible of being manufactured additively towards other technologies. Additive manufacturing of simple structures mainly is not feasible as traditional techniques are more reliable and less expensive than AM and should be used for geometries they are capable of producing. One example for AM-specific structures could be the use of lattice structures for inner geometries or making use of the freeform capabilities by creating perfect smooth radii and reduce the notch factors in parts. Both might as well be possible to generate with topology optimization, despite nowadays there is only questionable possibilities of integrating simulation of lattice structures in topology optimization. Thus on the other hand these complex structures do not only have to exist, they even have to be manageable by Simulation, CAD and slicing systems. Again the lattice structures are easy to manufacture and there are high benefits of these structures but is hard to be designed them as the high amount of surfaces to be constructed and displayed on screen is too much for most computer systems. So there is a need of a file system that is capable of replacing these geometries internally in a more manageable thing or better a representation scheme that is capable in general. Again a voxels representation might be a solution, as for a given resolution there is nearly no difference on how complex the represented structure is. Nevertheless a very high resolution leads to a big amount of data that might cause other problems that might even be worse. A more detailed discussion on the question of voxel capabilities towards need for storage will be shown in the following.

In a third point the geometries have to **consider AM-restrictions**. AM often is said to be capable of producing any shape easily. In some points this is, especially for metal AM, not correct. As for other manufacturing technologies there are a lot of design rules that have to be considered for a successful print job. This starts with the need of support structures to channel off the heat from the melt pool to the build platform below and to keep the parts in place during build job. But furthermore the size of a cross section per layer is limited, as the higher the cross section the higher the internal stresses that might lead to a distortion of the part. [Ada15] These are just two very rough rules of a big bunch of them. So for a worthy CAD file a design check is mandatory to ensure printability. Thus a check of cross section area size, wall thickness and the like has be done before. If this should be integrated in the topology optimization this might come to a big effort of checking the part during each optimization iteration. As well in this case a voxel grid might enforce the optimization process as it is way more easy to determine cross sections and wall thickness inside a structured voxel grid than on basis of spline-based or triangulated geometries as for those a lot of computation per layer is needed. The voxel grid directly can answer with the number of voxel per layer.

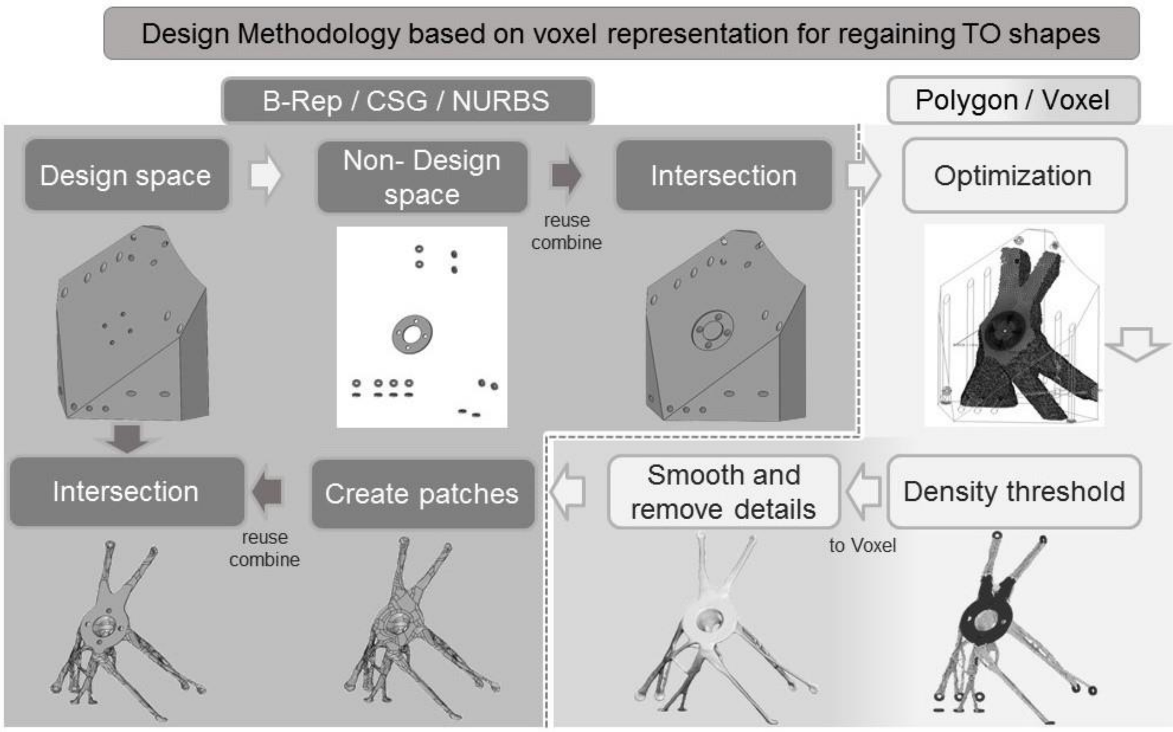

Figure 8: Design Methodology based on voxel representation for regaining [RK15]

When considering a voxel based geometry the next point of **multi-material production information content** is very easy to cover, as well. Thinking about AM as a voxel based manufacturing technology theoretically it is possible to print each voxel with a different material, perfectly adapted to the local requirements. At the current state multi-material printing, especially for metals, is only in research and not usable for real part manufacturing. Though, some ceramic processes are already capable of using different ceramics in one process. A voxel based representation scheme easily would be able to include the material properties per volume unit.

As there are a lot of potentials and reasons for using a voxel based representation scheme for CAD files taking advantage of all AM potentials, there are still several drawbacks as already mentioned before both from a programming view which will be discussed later on as well as from a logical view. A real worthy CAD file still needs **compatibility with parametric elements** to be digitally connectable with other parts as in assemblies and for lean CAD-CAM coupling for the mechanical post processing. As neither polygon models as .stl files nor voxel based models are capable of this, there seems to be a need for a combined representation scheme which will still include standard CAD representations as for example CSG or B-REPs with NURBS. Even more a conversion from voxels to NURBS seems to be mandatory as parts developed and ready for print need to be usable in standard CAD system by standard trained, conventionally very experienced engineers.

Assessment of a voxel based approach

Thinking about a voxel based approach for making CAD files feasible to produce high value AM parts taking advantage of the full potentials of AM seems to reasonable. However there are some reasons beside the parametric features, why this kind of geometry representation scheme for engineering has not become a standard by now. For explanation of the hurdles and possible solutions, in the following a detailed view on the voxel based representation scheme with focus on memory usage, representable complexity and modelling techniques will be given.

First, as already mentioned above, the memory usage for geometries represented by voxels raises very fast and seems to be not feasible representing a big, complex geometry. If complex freeform geometries shall be represented smoothly by voxels, a very high resolution is needed to overcome stair stepping effects. This is the same as for two dimensional computer graphics represented by pixels. Furthermore using a voxel grid there is a need for having a storage place for each voxel inside the grids space. Thereby the number of voxels easily can raise to very high amounts. A comparison of the two main considerable representation schemes in terms of additive manufacturing and complex designs is given in Figure 9.

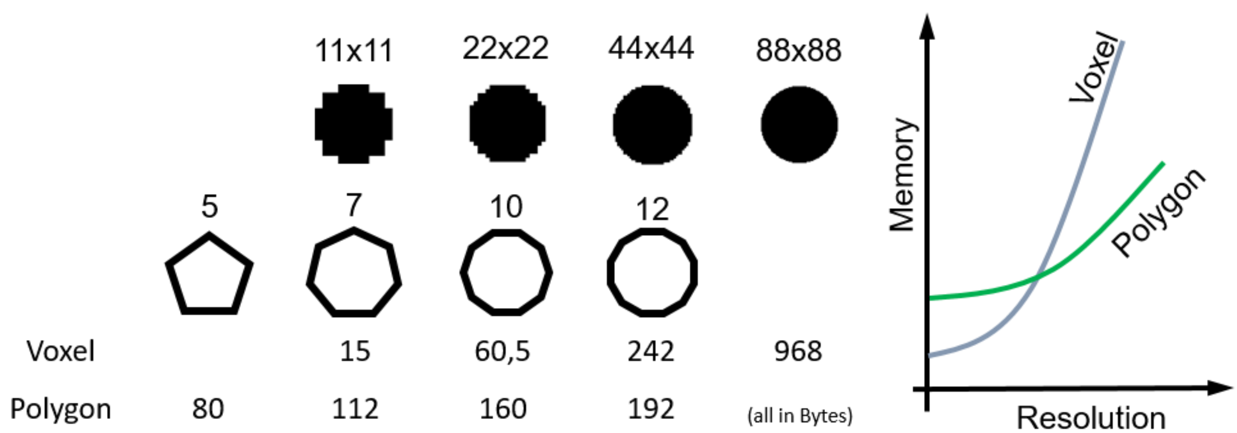

Figure 9: Comparison of memory consumption for a simple geometry in voxel and polygon representation scheme

There a simple circular geometry is shown represented by pixels and lines as two-dimensional equivalent of voxel and polygons. One can see, that there is a big difference in the actual shape regarding different resolutions with a very bad representation for low resolutions. Nevertheless, as the graphs are well indicating, the voxel representation starts with only small amount of memory for low resolutions but then is raising very fast. On the other hand, for low resolutions the polygons are needing much more memory but then is raising slower than for voxels. As indicated by the different color of the representations this is, among others, due to the fact that the voxel need to store each single point, while the polygons are only representing the boundary. This equals the categorization of the representation schemes as above where the voxel are called direct representation in comparison to indirect representation via polygons.

Though, looking at the memory consumption when keeping into account the complexity of the geometry, there is a big advantage of voxel representation identifiable. Figure 10 shows three different geometries: a simple circle, slightly complex shape and a high complex bone structure represented in voxel, polygon and NURBS.

The following comparison of memory consumption for voxel and polygon than shows the big advantage of voxels for high complex geometries. As each voxel inside the grid needs to be stored, there is no difference in memory consumption immaterial how complex the geometry represented is while for polygons the memory consumption raises continuously with increasing complexity.

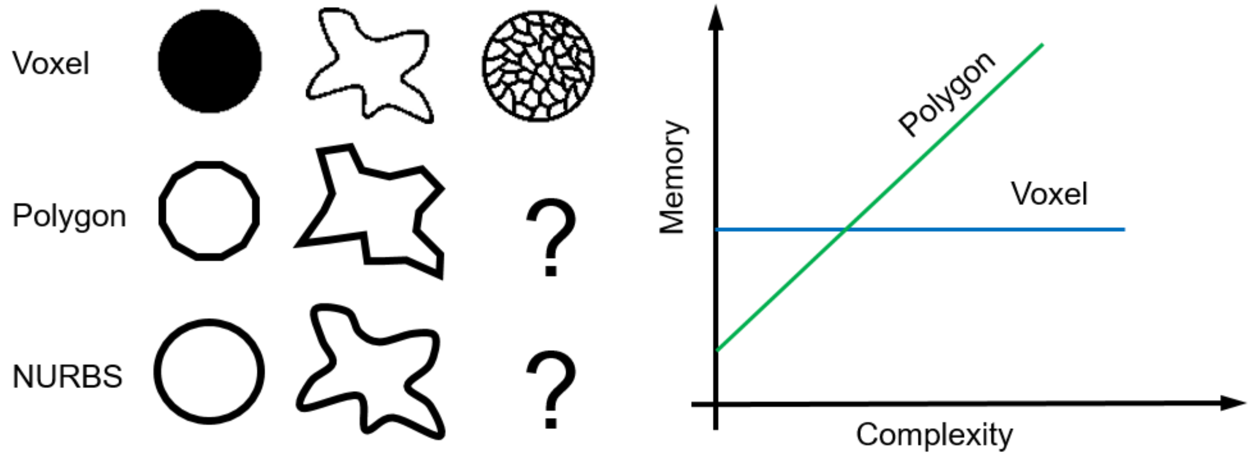

Figure 10: Comparison of memory consumption for different complex geometries in voxel, polygon and NURBS

Thus one can see that indeed the starting memory amount is quite high in the beginning but is equaled for more complex geometries. Furthermore the extremely simple logic behind the voxel grid allows a lot of compression. An impressive study on compression of voxel based geometry representation was done in [VMG16]. By use of very advanced compression algorithms including an octree approach it is possible to store an entire aircraft in only a small amount of memory.
Considering the size of a standard metal AM machine like the SLM 280^{HL} with 280*280*360mm³ and a layer height and thereby resolution of 50µm, a great number of voxels are needed to represent the overall build chamber on layer resolution. Though, these are still less than from the examples in [VMG16] where need less than 100 MB of storage. Thus it seems feasible to store a full build chamber on a resolution higher than printable in a reasonable file size. If this is really working during geometry generation and adaptation has to be proved by further work.
The next point is that voxel based representations furthermore are easily capable of enabling geometry manipulation even in high resolutions. For example generating an offset of a geometry is shown in a comparison towards a surface based representation like .stl in Figure 11. One can easily see, that at the bottom of the groove an intersection of polygons or self-intersection of the surface is expectable that needs to be filtered out by additional algorithms to generate a valid geometry. In comparison to that for a voxel representation the offset generation algorithm is developed very easy and a self-intersection is not existent, as already existing voxel just are existing and there will invalid geometry be generated that needs to be cleaned up. The same benefit can be transferred to other geometry adaption algorithm as Boolean or slicing operations as well.

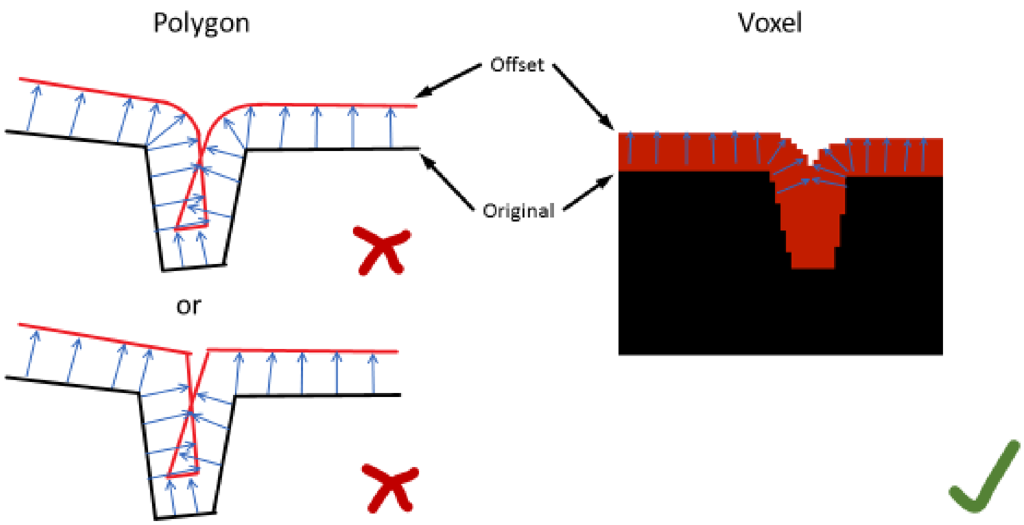

Figure 11: Comparison of generating an offset with polygon and voxel based representation

Generating offset geometries is a very strong method for the retransition of topology optimization results. An example is shown in Figure 12 where different steps are compared to retranslate a very simple topology result into a smooth geometry. It can easily be seen that first creating a positive offset that is than smoothed and in a third step taken back with a negative offset generates a very good surface. In this case, there has no manual work has been done. After the rough optimization taking three minutes, the voxel offset and smoothing tooks only one minute. Thereby one can see how fast this voxel based method is. Furthermore for very high complex parts like the upright, manual effort except in detailed areas would not be feasible and thus an automatic approach is needed.

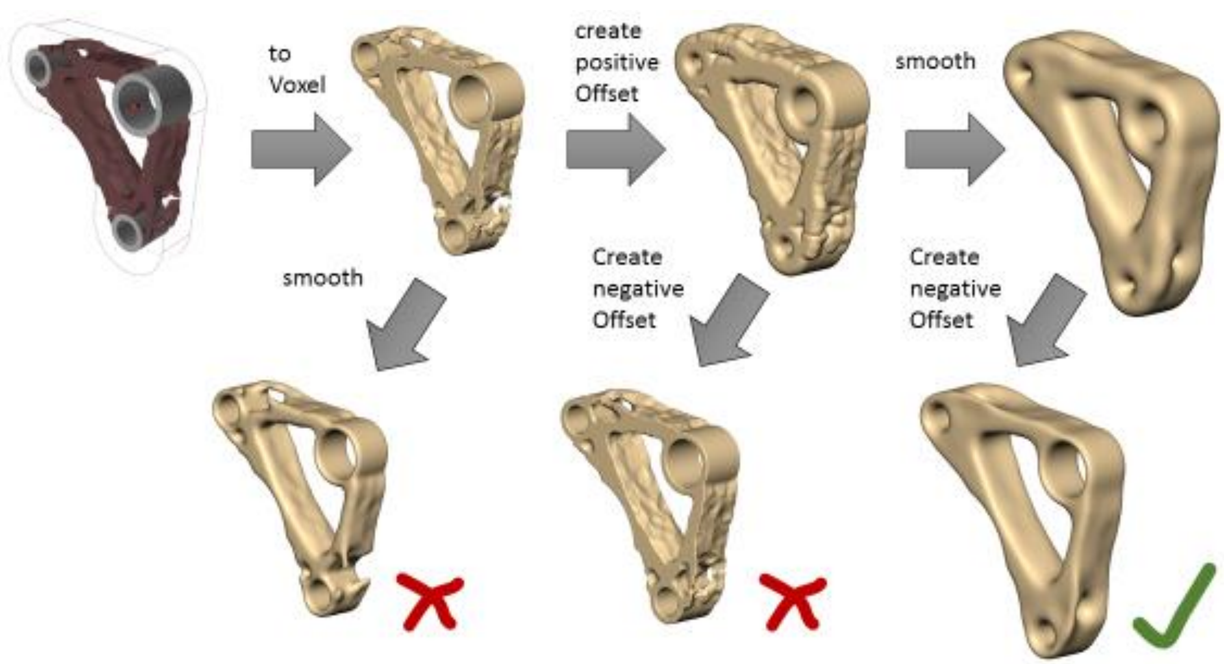

Figure 12: Using offset geometries to generate valid smooth geometry retransitions of topology optimization results

The last task is to guarantee an easy and fast conversion from existing NURBS data out of existing CAD assemblies into a voxel based generation and for the conversion back again to keep standard systems still compatible.
Therefore Figure 13 shows how this process can be done nowadays with a polygon based interim stage. As can be seen, the continuous edge from beginning is triangulated by polygons in red. As well it has to mentioned that the beforehand existing additional information regarding the circular bore hole is no longer existing. On basis of the polygons it is easily to set up voxels, or in this two dimensional figure, the pixels.
After assuming any changes in the geometry there is the back transition by use of a marching cube algorithm triangulating the pixel / voxel back to a polygon based representation. Using further algorithms for auto surfacing, these polygons can be transferred back to the NURBS again. Unfortunately in this process the information on the circular bore hole is still lost. Thus a good surfacing algorithm needs to store the information of the bore hole and include this information when retransferring.

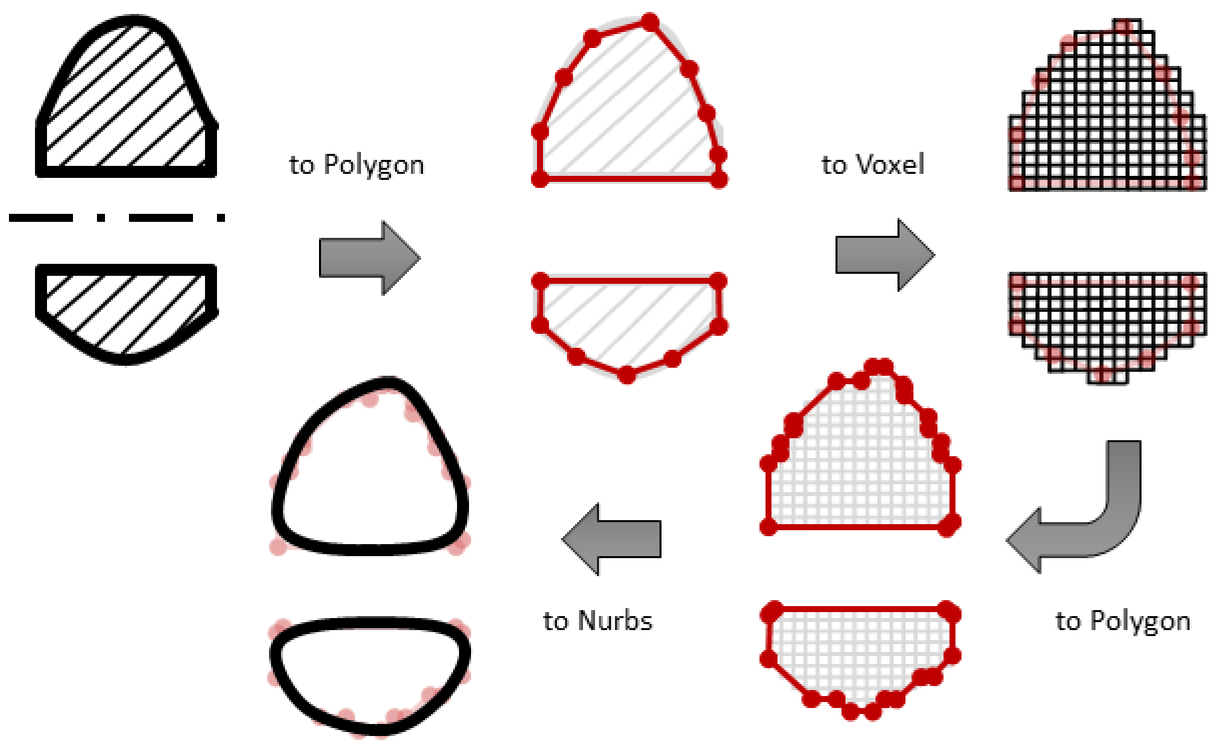

Figure 13: Conversions from NURBS via Polygon to Voxel and back

For a real efficient use the interim step of polygons should be avoided and the NURBS need to be transferred into voxel directly. Theoretically this should be possible but still needs to be proved and developed. First steps on developing a software including a voxel based topology optimization and transitions out of CAD files and back again to enable the voxel based representation methodology to get a usable tool have already been made at Paderborn University. Further work on still open questions and for compressing the voxel representation in feasible sizes still needs to be done.

Conclusion and outlook

This paper has given a detailed description of existing geometry representation and modeling schemes for the generation of high complex CAD designs and the requirements coming from additive manufacturing on these geometries. Based on this a methodology for the generation of high complex CAD designs feasible for additive manufacturing was broken down to six requirements which than has been assessed on their practicability and solution approaches have been shown. Many of these lead to the use of a voxel based direct representation of high complex geometries. The following assessment of this voxel approach has shown that it is feasibly to generate high complex geometries on basis of voxels.

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Literature

[Ada15] ADAM, G. A. O.: Systematische Erarbeitung von Konstruktionsregeln für die additiven Fertigungsverfahren Lasersintern, Laserschmelzen und Fused Deposition Modeling, Vol. 1, 1. Auflage, 2015 - ISBN 978-3-8440-3474-5

[Ago05] AGOSTON, M. K.: Computer Graphics and Geometric Modeling - Implementation and Algorithms. Springer-Verlag London Limited, London, 2005 - ISBN 9781852338183

[DRK15] DEPPE, G.; REIHER, T.; KOCH, R.: Cost and Lifetime Benefits of a Topology Optimized Aerospace Part applying Additive Manufacturing (Vortrag), Trieste, Oktober 2015

[EKH+07] EHRLENSPIEL, K.; KIEWERT, A.; HUNDAL, M. S.; LINDEMANN, U.: Cost-efficient design. Springer, Heidelberg, New York, 2007 - ISBN 9780791802502

[Fra09] FRAß, C.: Grundlagen der 3D-Modellierung (Vortrag). Technische Universität Dresden, Dresden, 28. April 2009

[GRS10] GIBSON, I.; ROSEN, D. W.; STUCKER, B.: Additive Manufacturing Technologies - Rapid Prototyping to Direct Digital Manufacturing. Springer Science+Business Media LLC, Boston, MA, 2010 - ISBN 978-1-4419-1119-3

[Har03] HARTMANN, E.: Geometry and Algorithms for COMPUTER AIDED DESIGN, Departmend of Mathematics, Darmstadt University of Technology, Darmstadt, 2003

[HHD05] HOPKINSON, N.; HAGUE, R.; DICKENS, P. M.: Rapid Manufacturing. John Wiley & Sons, Ltd, Chichester, UK, 2005 - ISBN 9780470033999

[Mat06] MATTHECK, C.: Verborgene Gestaltgesetze der Natur - Optimalformen ohne Computer. Forschungszentrum Karlsruhe, Karlsruhe, 1. Aufl., 2006 - ISBN 3-923704-53-4

[MB03] MATTHECK, C.; BETHGE, K.: Warum alles kaputt geht - Form und Versagen in Natur und Technik. Forschungszentrum Karlsruhe, Karlsruhe, 1. Aufl., 3. Nachdr, 2003 - ISBN 3-923704-41-0

[PAS+95] PASKO, A.; ADZHIEV, V.; SOURIN, A.; SAVCHENKO, V.: Function representation in geometric modeling - Concepts, implementation and applications. The Visual Computer, Vol. 11, Iss. 8, 1995, p. 429–446

[RK15] REIHER, T.; KOCH, R.: FE-Optimization and data handling for Additive Manufacturing of structural parts (Vortrag), Austin, Texas, 2015

[RK16] REIHER, T.; KOCH, R.: Product Optimization with and for Additive Manufacturing (Vortrag), Austin, Texas, August 2016

[RLJ+17] REIHER, T.; LINDEMANN, C.; JAHNKE, U.; DEPPE, G.; KOCH, R.: Holistic approach for industrializing AM technology - From part selection to test and verification. Progress in Additive Manufacturing, Vol. 21, Iss. 2, 2017, p. 216

[Sha01] SHAPIRO, V.: Solid Modeling - Technical Repot SAL 2001-2, Spatial Automation Laboratory, University of Visconsin, Madison, Wisconsin, 2001

[SRE76] SAMUEL, N. M.; REQUICHA, A.; Elkind S. A.: Methodology and Results of an industrial part survey - Production Automation Project. Technical Memorandum 21, University of Rochester, Rochester, New York, 1976

[VMG16] VILLANUEVA, A. J.; MARTON, F.; GOBBETTI, E.: SSVDAGs: Symmetry-aware Sparse Voxel DAGs (Vortrag), Redmond, WA, USA, February 2016