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On achieving accuracy and efficiency in Additive Manufacturing: Requirements on a hybrid CAM system

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Abstract

The potential of additive manufacturing is increasingly investigated with regard to an application in combination with milling processes. However, for an economical use of this hybrid method, workpieces must be produced cost-efficiently and at the same time meet high quality requirements. In this paper, a combination of additive and subtractive technologies is presented, by which the demanded accuracies can be achieved. To further decrease currently high planning efforts, an existing CAM system is extended by modules for creating additional additive manufacturing steps. In this context, requirements for such a hybrid CAM system and its realization are derived and presented.

Keywords: Additive Manufacturing, hybrid CAM, path planning, preprocessing, hybrid manufacturing

1. Introduction

Ever since the upcoming of Industry 4.0, industrial manufacturing is undergoing a continuous and ever-accelerating change of its requirements. The growing demand for personalized and complex products leads to a steady decrease of ordered batch sizes which in turn shifts the cost of production from manufacturing towards process planning and process ramp-up activities [1]. For well-established technologies like milling and turning these efforts highly depend on part complexity. This contrasts with farther demanded fast time-to-market and low production costs. To solve this dilemma, the potential of new manufacturing technologies is further investigated in terms of planning and ramp-up efforts as well as their economical applicability for complex part geometries. In this context, Additive Manufacturing (AM) is a technology which stands out due to several characteristics. AM planning is almost independent of design, allowing complex structures and individual design with costs that mostly depend on the parts volume. Therefore, AM promises economic efficiency when small batch sizes and a high product individuality are required [2]. Furthermore, due to its additive nature, material only needs to be added where a certain function or stability is required [3]. This allows for a larger saving of material compared to subtractive technologies.

These aspects qualify AM as a promising technology for industrial purposes. However, AM is not a well-established manufacturing technology in todays industrial applications due to cost-efficiency and quality related issues. At present, a sufficient quality in AM can only be achieved by iterating design and production processes where process parameters and strategies are altered [4]. Such an iterative approach cannot be avoided since the influences of process parameters and material properties on the final parts are manifold and not fully understood, yet. In particular, the effects of thermal gradients that arise in printing cause form and surface errors [5], which are by far higher than the results achieved in milling or turning applications. Along with far worse surface roughness values compared to metal cutting, these observations currently render fully additive produced parts unattractive for many industrial applications.

Due to the shown advantages and drawbacks of additive and subtractive technologies, the idea of Hybrid Additive Manufacturing rises. A combination of additive and subtractive technologies can benefit from the advantages of AM technologies and subtractive technologies [6]. Current hybrid approaches range from construction of hybrid machines to the development of process planning software tools which allow for a definition of hybrid process plans.

In literature there exist a couple of publications concerning hybrid AM. In [7] the authors developed a hybrid machine that combines a direct metal deposition process with a five-axis Computerized Numerical Control (CNC) machine. They focus on a strategy on how the part can be decomposed in subparts with different build directions. The authors provide a collision detection module and support path planning for AM and machining. They sweepingly scale the part for machining and then finish the overall part. Similarly in other work [8] a hybrid ma-

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chine consists of a laser-welding technology and a 5-axis CNC machine. The authors develop a hybrid process where milling and AM are processed for each slice sequentially. Thus nonuniform slice thickness for one layer can be realized. To obtain machine paths for both technologies a common CAM software is used. In addition, in similar work [9] collision detection is provided. Considerations concerning the machining path are limited to the analytical path determination for non-uniform slice thickness. The combination of five-axis Fused Deposition Modeling (FDM) and machining is addressed in [10]. Machining paths are obtain by a commercial CAM tool. In contrast to the previous work, in [11] the authors combine two printers and one milling machine to a workstation. Transportation between different stations is realized with a robot. The study focuses on machine construction and transport issues.

Several studies approach the question of part decomposition and how to chose the right technology for sub-parts. In [12] for example, parts are decomposed on the basis of STEP features and manufacturability is determined via fuzzy logic. Another way to decompose parts is presented in [13]. Herein, surfaces are decomposed based on their curvature to an octree structure. The authors present complexity indices for AM and machining respectively to decide for the right technology. Both publications do not approach the hybrid process itself.

The explicit integration of AM in commercial CAM systems is addressed in [14]. This work lists the differences in path planning for AM and machining. The authors explain the challenge of filling a database with correct parameters and how to link them to path properties of AM. The authors of [15] similarly integrated a slicer into a CAM system and explain how subtractive path planning can be used for various additive technologies. They realize additive simulation of one slice.

Especially in metal based AM technologies it is already common to finish parts with the aid of subtractive technologies [16]. However, the combination of two complex process chains as well as data transfer in between both technologies is a huge challenge today. A unified methodology that allows the process planning of additive and subtractive manufacturing operations within one software solution is lacking. This paper addresses this topic by proposing a hybrid process planning approach. In section 2 the common established process chains for additive and subtractive manufacturing are presented. In this context, current challenges regarding their compatibility that are faced in practical applications are highlighted. Subsequently, a hybrid computer aided manufacturing framework is presented in chapter 2.3 where information flows and workflows are proposed in order to overcome currently occurring problems. Contrary to existing hybrid considerations, this hybrid CAM will be realized by extending an existing (subtractive) CAM software with slicing capabilities. Based on the presented solution, a list of requirements for a hybrid CAM tool is derived. These aspects allow the implementation of a unified process chain.

2. Development of a Hybrid Process Chain

2.1. Subtractive Process Chain

The classical subtractive process chain in job shop manufacturing starts inside a CAM system with receiving a CAD geometry of the part to be manufactured. Furthermore, a drawing which includes dimensional, shape and position tolerances is added. Raw part geometry is defined on the basis of these documents. Both geometry data sets must be available in form of a high-quality information representation. Hence, geometry is represented by its boundary (BREP) and stored as Non-uniform rational basis spline (NURBS). The Standard for the Exchange of Product Data (STEP) [17] is an established data format for data transfer and supports NURBS geometry. Path planning algorithms are computed for boundary surfaces which are determined by selecting BREP surfaces of the raw part as well as the finished part. Paths are parametrized via definition of workpiece zero points, manufacturing tools and technology parameters. In a next step, necessary toolpaths are calculated. To verify planning results, a processing simulation is performed. To do so, a BREP of the raw part is first converted into a volume representation. Nowadays, a so called multi-dexel representation is the industrial standard. To obtain a dexel representation, the BREP is cut with a high number of beams in all main spatial directions. A dexel representation is constructed by the resulting beam sections located completely within the raw part volume. This can be used to simulate material removal. After relative positioning of the manufacturing tool, its corresponding volume is cut with the dexels while simulating. Depending on the resulting intersections, a dexel is then either removed, shortened or split into further partial dexels. To determine the material left over from a previous operation a residual material removal, which is parametrized similarly to the described path planning representations, also operates on this volume representation. Dexel representations usually cannot be translated back into a BREP-based solid representation. Therefore, storing of so-called ”in process workpieces” is performed using the STereoLithography (STL) format. This format is characterized by a faceted triangular representation, which describes only the shell of a component's geometry [16]. Unlike BREP representations, this is not a volumetric representation. A further economic CAM-based process planning using this geometry presentation is impossible.

After successful verification of planning, the CAM-generated tool paths are translated via a post processor into a machine-specific NC program, which can then be used to manufacture the desired part. In addition, tool lists, clamping positions and zero points are exported from the CAM system to documentations which are given to the shop floor level for correct setting up of machine tools. After successful production, a quality inspection of the machined parts takes place. For this, the drawing supplied at the beginning is used, which contains tolerances to be met. The final geometry is used to define quality features, which are then checked by a coordinate measuring machine. If the final quality check is successful, the finished part can be delivered.

2.2. Additive Process Chain

This process chain also begins with receiving of a final part geometry. In contrast to the subtractive process chain, the component geometry is sent in form of a STL file. Work preparation starts with determining zero points for machining, as well as orienting the part in the work area of the printer. In this step, introduction of additional support structures might be necessary in order to successfully produce the required geometry. For this purpose, overhang areas of the part are determined. Support

structures can then be parametrized by a user and are calculated and added to the initial raw part geometry. Usually, the STL format is also used for these structures. In a next step, the extended model is then cut into individual layers by a slicer. For each individual layer, an automatic 2D path planning is performed. The resulting path defines movements of the print head for this plane. By fusing all computed movements the final tool path results [18]. Subsequently, a simulation of the additive process can be performed.
Again, dexel representations are used for a volumetric descriptions of in process workpieces. Inside a virtual working area of an additive machine, a dexel space grid is placed. At the beginning of processing, this grid is empty. According to planned movements, the printer head is moved in the virtual workspace and the volume to be added at each position is cut with the dexel space grid. By this, new dexels are computed which must be inserted in the corresponding positions in the space grid. If an overlap occurs with dexels already inserted in a previous step, the affected dexels are either lengthened or merged. As in the case of the subtractive process chain, it should be noted that a back translation of the "in process workpiece" in a solid representation is not feasible.
After verifying the planning, a machine-specific program is created by a post processor. When the workpiece is built, it is further processed. In this context, eventually generated support structures are removed and quality-relevant features are reworked. For powder based technologies, powder has to be removed. Finally, the product is delivered.

2.3. *Current Implementation of Hybrid Process Chain*

Although it is popular to finish additive manufactured parts by subtractive technologies only few software exists supporting hybrid AM. To work around this void, companies combine existing software. This renders the actual workflow complicated and loss-prone with respect to design and information. Figure 1 shows an exemplary workflow combining several software and required discussion between experts is shown. The process starts with an initial design which mostly originally was constructed to be processed by classical machining (1). Therefore it is necessary to edit this native design (2) in order to ensure success of manufacturing later on. To distinguish between classical design and design for additive purposes the term Design for Additive Manufacturing (DfAM) is used in literature [3]. In this paper the term DfAM will be used for adapting of the native design. This adaption includes many decisions and considerations:

- Identify features that cause problems while building. These features could be boreholes or channels perpendicular to the build orientation. Such features either need to be re-formed or removed. If they are removed but implicate functionality they will be machined.
- Determine surfaces and features that have to be machined afterwards. This heavily depends on functional and accuracy requirements as well as the location of support structures. Their location, again, depends on the build direction. In most cases support structures need to be removed. Depending on the additive technology they are removed by a subtractive technology or manually. If they can be removed manually surface quality suffers and surface post processing may still be necessary [16].

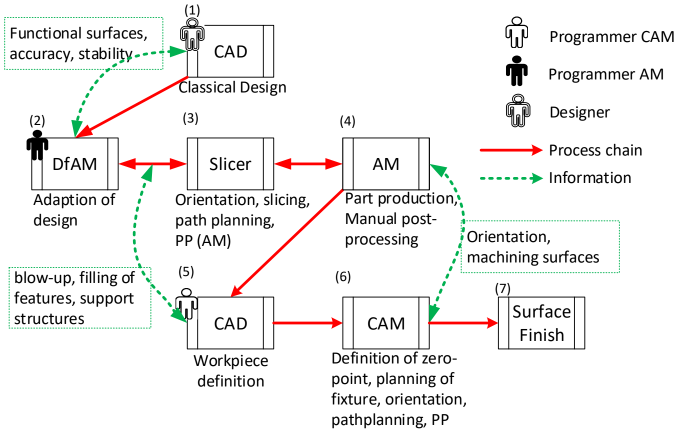

Fig. 1. Sample process chain of hybrid AM today

- Decide for a build orientation. Since build orientation affects most design adaptions this decision should be made carefully and with the previous considerations in mind.
- Add supplement material at surfaces that will be machined.
- Remove material that is not needed. In parts that were constructed for subtractive processing volume is only removed if necessary. Contrarily, for saving of material and time, AM parts only should have material where it is needed depending on function and strain. For maximal saving of material, topology optimization should be performed. However this may require access to a software simulating occurring strain and causes manufacturability problems.
- Define and exclude surfaces for support generation. On quality-related surfaces it could be necessary to avoid support structures. This is interesting for surfaces, were reachability for machining is not given. Similarly, for example to avoid warpage, some surfaces are explicitly selected to be supported.
- Decomposition of the design into regions that will be manufactured additively and regions that will be machined subtractively. This results from the previous considerations. A raw part geometry has to be created according to these regions.

Obviously, these decisions and considerations require fundamental knowledge in AM as well as in machining. Since one is expert in one of these technologies, lots of communication (information flow) is necessary. This communication is indicated by the green dotted lines in figure 1. For design adaption experts for AM have to know which features are essential for the part's function. Similarly, this expert needs information on required surface accuracy.
After the design adaption for printing, this design will be input to the AM process chain (3). At this point data transfer issues between software, namely CAD software and slicer have to be considered. The design data will be exported in STL format to be imported into a slicer where standard preproccessing for AM is performed (see section 2.2). When the part is built the subtractive process chain (see section 2.1) starts. Again, data transfer issues and preservation of information has to be considered. Since Workpiece definition (5) is based on the adapted design

this requires information flow: Where are support structures, where are they explicitly required or not allowed, where is supplement material, which features have been removed and therefore have to be machined? Some slicers allow to export support structures in STL format. If this is not possible they have to be designed manually in the CAD or CAM software. Next, for machining, the additively produced part has to be fixed on the machining table. Due to thermal induced warpage originally flat planes of the design are possibly curved and features underlay certain displacements. This renders fixing as well as orientation determination of the part difficult. Finally, the part can be machined. The presented hybrid AM chain is one of many possibilities. Process steps depend on software and hardware used. If the part was originally designed for additive manufacturing then the process starts at step (2). However, several problems in the forgoing process can be identified which hold in general. These will be discussed in the following section.

2.4. Requirements for a Hybrid CAM System

In this section process steps of the previous section that are suboptimal in terms of one of the following reasons are elaborated. (a) time consuming; (b) loss-prone data transfer relating to surface information and surface design; (c) workflow complexity. In addition solution approaches for each deficit are presented and requirements for a hybrid CAM are concluded.

Long and complicated tool chain: The longer the tool chain and the more software is involved the more time and data loss will take place. Therefore a shorter and compacter tool chain from design to machining is appreciated. The idea of a hybrid process chain including a hybrid CAM tool is proposed instead. This hybrid CAM tool allows manufacturing preparation for both, additive and subtractive manufacturing.

Lack of information exchange between software systems: As described in section 2.1 and 2.2, both process chains are unidirectional. Starting from a high-level BREP representation the amount of information is reduced significantly. Both chains only output programmed cutting tool or extruder movements having no direct connection to the part geometry to be manufactured. In a scenario where additive and subtractive processing steps should be planned in random orders, a direct information exchange between both additive and subtractive subsystems of a hybrid CAM system must be established. This is especially true for support structures that are usually created within the slicing functionality of an additive manufacturing module. If no integration between the subsystems exists, information about support structure volumes that were generated are not available within the subtractive module. This might lead to collisions when subsequent subtractive processing steps are planned. In addition, this lack of information results in difficulties when those usually unwanted structures should be removed by a milling operation, as their geometry is not known to rest material removal operations.

Printing on pre-exiting Geometry: Classical additive manufacturing modules presume that the working area of a target 3D-printer is empty. When combining additive and subtractive processing steps, this assumption does usually not hold true. Slicing as well as support structure algorithms must be able to build geometry on top of already exiting part geometry. Therefore extruder path generators must be able to handle existing geometry elements. On top, collision avoidance methods that are usually available in subtractive manufacturing planning systems must be integrated for realizing advanced additive support.

Communication: Since the hybrid process requires additive and subtractive expertise lots of communication takes place inbetween the forgoing process steps. To reduce this communication substantially the designer as well as the AM expert should add information to the design. To do so, surfaces and volumes could be color-coded. Meta information can already be added to the input file or will be generated inside Hybrid CAM. In the first case it is possible to use STEP to transfer such information. However, implementation of STEP imports and exports is realized manifold in CAD software. Therefore it is necessary that meta information can be added to the design in the hybrid software. Then functional faces, accuracy requirements, support structures and their location and regions where lots of strain occurs will be highlighted. The part has to be separated into volumes that have to be processed additive and subtractive respectively. With this information the subtractive expert can define a raw part geometry and do path planning as usual. Inside a hybrid CAM it should be possible to set and define views of which visibility can be turned off or on. For example the machining view comprises workpiece definition, machining surfaces and machining paths. Possible views are additive/subtractive view, information views for meta information such as accuracy, and functional requirements.

Complex adaption of design: As long as the considered parts originally are not designed for a certain AM technology, design adaption can not be avoided. Nevertheless it is possible support such adaptions at least. In some cases it will be easier to fill features such as boreholes completely instead of forming them while manufacturing. This filling of features can be facilitated by software where first border faces are selected and then automatically an additional surface is added which closes the pocket. Similarly, a surface offset module can help for adding supplement material on machining faces (padding of surfaces).

Iterations: The presented process steps include two iteration loops. One for design adaption due to slicer information. This loop involves several software, being time-consuming and lossprone. Within a hybrid CAM, support generation is possible at any time such that support can be used for orientation determination and DfAM. Another iteration loop includes AM preprocessing and the manufacturing process itself. It is essential to provide application simulation in order to avoid unsuccessful builds [19].

Time consuming fixing and positioning: There are two circumstances that render fixing the part and determination of its position and orientation on the machining table to be difficult. First, the complexer the design the less flat surfaces are present. Second, due to warpage, the part's geometry possibly differs from the original geometry. Fixing theses problems for each part is very time consuming. If the part was built on a portable platform, this platform can be used for initial fixing. However, if great warpage occurs this also deforms the platform. Therefore, it is proposed to add markers (optically or physically) to the design. In a hybrid CAM, the marker's positions have to be set such that they unambiguously allow to determine position and orientation of the part.

Summarizing the requirements listed so far, a hybrid process chain as shown in figure 2 is presented. Again, the process is initiated by a CAD file. Contrary, the input file is assumed to be a geometry represented by a BREP presentation. Ideally, design is adapted in a CAD tool because such software provides powerful resources for design modifications. Nevertheless, as stated earlier, simple modifications should be supported inside a hybrid CAM. In addition, it should be supported to set different slice height for different volumes. This is interesting for faces that are machined later on anyway or when surface quality of a certain volume is not that important. Because then, as a consequence of thicker layers, building time can be reduced.

In a hybrid setup, slicing information directly can be used to define machining surfaces. Vise versa, machining problems such as collision and reachability as well as fixture planning can influence build orientation and design straightforward. Finally, this holistic process planning results in both, machine commands for AM and machining commands.

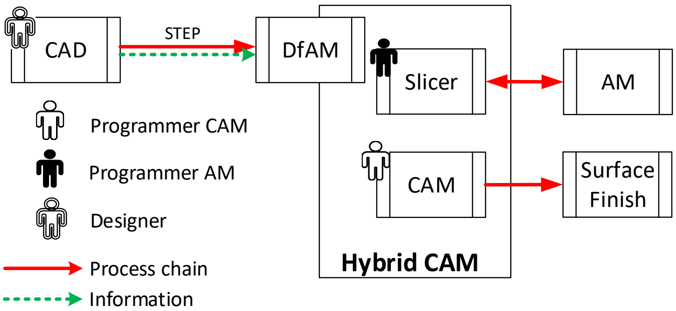

Fig. 2. Hybrid process chain with hybrid CAM

3. Aspects of Implementation

It is proposed to realize a hybrid CAM by integrating slicer functionality to existing (machining) CAM software. This is due to several reasons: (1) This enables reuse of machining functionality needed for certain purposes. Since no CAM software is usable for all kind of drilling and milling purposes there exists different CAM software for different technologies. For instance, machining strategies and path planning depends on the material that is processed. (2) Common CAM software is complex to handle in general. Therefore changing existing software instead of providing completely new software is much more user-friendly. (3) Integrating of slicing abilities will be easier by reusing existing data import and export, design and path visualization, geometry definition and geometry handling as well as using available data base and queries. In the following, solutions and aspects of implementation in order to fulfill the requirements given in subsection 2.4 are presented.

Integration of slicing functionality: When integrating slicer functionality it is important to support process organization. This is realized by a hybrid process planner. This planner triggers its intern additive (slicing, path planning, code generation) and hybrid (blow-up, pocket filling) modules. Likewise, it has access to subtractive modules of the native CAM. The hybrid process planner handles dependencies of process steps like printing and milling sequences. A hybrid Graphical User Interface (GUI) enables the user to control planning strategies and set parameters for the AM process. The slicer needs access to the database which in turn is extended by additive machines and their properties and parameters. Therefore, neccessary database entries have to be defined and mapped to the structure of database entries of the native CAM. To be able to create and change geometries as well as to visualize paths the hybrid extension has a geometry library. This library has to support complex (NURBS lines and surfaces) and simple (lines, triangles, meshes) geometries and has to be interoperable to the native library. Geometry elements in both libraries have to support property definitions like visibility, coloring and technology information.

Representation of support structures: Support structures are

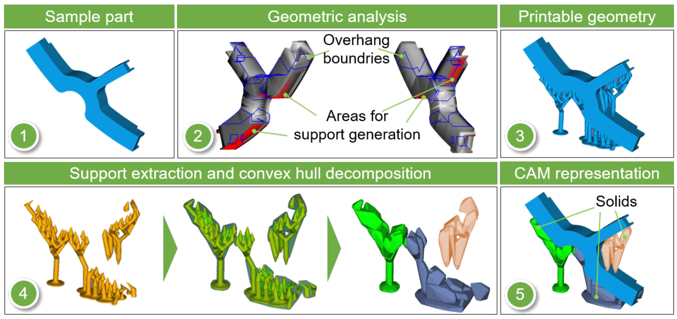

Fig. 3. Solid (BREP) generation using a hierarchical convex hull decomposition

generated and added to the model for slicing. For further operations they must be fed back to the subtractive CAM system. As shown in subsection 2.2, this additional geometry is represented in a triangle-based format that cannot be used efficiently and economically for process planning within a CAM environment. Therefore, a transformation back into a BREP representation (see subsection 2.1) must be performed to allow a user selection of individual part surfaces. In figure 3, a solid generation is used that approximates the support geometry up to a user-defined threshold. The process is performed in several subsequent steps. After part orientation (1) a geometric part analysis is performed where overhang boundaries and areas for support structure generation are detected (2). These resulting areas are then used for generating support structures that are then added to the initial part geometry. This results in an extended raw part geometry (3). To separate this additional geometry (4) the extended and the raw geometry are represented by dexels and then subtracted from each other. The resulting support structure geometry is then transformed back into STL format. Subsequently the geometry is approximated by a number of convex geometries using the "volumetric hierarchical approximate convex decomposition" algorithm described in [20]. The algorithm returns a set of planes that finally allow a creation of solids (5) using the CAD kernel of the CAM system. Those solids are then selectable within the CAM environment for planning further (subtractive) operations.

Preparation of surface areas for rework operations: It is mentioned in subsection 2.4 that for subtractive rework operations additional material has to be added to the design. For this, corresponding areas are geometrically padded by the CAM-internal CAD kernel before the design is translated into a compatible format for the slicer. Figure 4 shows an example of this implementation. By selecting a part surface and assigning a predefined property, the affected area for padding is marked. An additional geometry element is then created by the CAD kernel and added to the initial part geometry (Figure 4, right). Similarly the complete geometry element could be filled.

Simulation: In a hybrid CAM it has to be possible to simulate and verify the obtained tool paths. This is straightforward, since

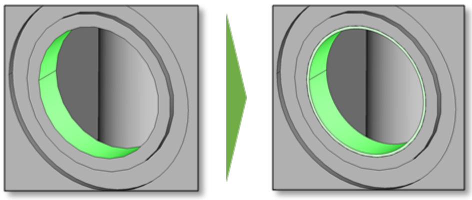

Fig. 4. Padding of reworked surface areas

simulation is based on dexels for both technologies. Hence, simulation algorithms can alter while simulating, where the algorithm used (subtractive or additive simulation) depends on the technology the path resulted from.

4. Conclusion and future work

In this work, process steps of a hybrid AM process chain were listed. Problems arising when standard CAM software and slicers are combined for a realization were shown. Based on these elaborated deficits it is proposed to realize a hybrid CAM software by inserting slicer functionality into a common CAM software. In future, to provide a proof of concept, this hybrid CAM will be realized for a given CAM and FDM. An existing slicer will be used which receives STL meshes from the hybrid planner and returns slices, path geometry and g-code. Facing interoperability issues a consistent geometry data base has to be developed. A planning module has to be implemented as well as a user interface. As stated in literature [14] it will be necessary to define process parameters for FDM. Those parameters have to be linked to data base entries of the native CAM. Finally, hybrid modules as presented in 3 can be realized. Regarding future projects it could be interesting to include part decomposition and analysis of [12] to provide suggestions for the preferred manufacturing technology.
This work is motivated by the application by small and medium-sized businesses. Therefore it's main focus is to develop software that provides support for hybrid AM. Further connection to Product-Lifecycle-Management software or Manufacturing Execution systems is therefore not considered but nevertheless conceivable for other applications.

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