FILE FORMAT SELECTION FOR EFFICIENT DIGITAL PROCESS CHAINS IN ADDITIVE MANUFACTURING

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ABSTRACT

Selecting a suitable file format for data exchange in additive manufacturing is fundamental when designing these digital process chains. Within the scope of this investigation, alternatives to the de-facto industry standard STL are to be found to overcome the disadvantages of the STL-based digital process chain.

Therefore, suitable file formats are identified by conducting literature and market research and evaluated regarding their suitability to support a continuous digital process chain. In addition, typical use cases in additive manufacturing are defined, and their requirements for a file format for data exchange are derived. Finally, for each use case defined, recommended and suitable file formats are proposed.

Keywords: Additive Manufacturing, 3D printing, Digital / Digitised engineering value chains

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1 INTRODUCTION

With its first commercial application in 1987 (Hull, 1984), additive manufacturing (AM) is a comparatively young family of processes. It enables the production of complex geometries through layer-by-layer manufacturing, which traditional subtractive manufacturing processes cannot realize. It was initially used to produce prototypes (Gebhardt, 2016). Due to increasing research and development in usable materials and processes, it is now possible to manufacture fully-fledged end products in small to medium series (Gebhardt *et al.*, 2019; Leutenecker-Twelsiek *et al.*, 2016). However, the underlying process chain and the file formats used today are still the same as when additive manufacturing was first introduced. First, a 3D model is created in a CAD system, and then the 3D geometry is converted into an STL file. Afterward, this file is used to perform process-specific pre-processing like determining part orientation, creating support structures, slicing and generating machine code. For the STL file format can only store geometric information in the form of triangulated part geometry, much information generated in the CAD system cannot be transferred to the pre-processing software. (Gebhardt *et al.*, 2019; Krückemeier *et al.*, 2021; Kumar, 2020)

For further development and successful industry dissemination, additional information must be generated, stored, and used in subsequent process steps along the digital additive process chain. Even though different file formats have been developed to store more than just geometric information, STL is still the de-facto industry standard in the additive process chain. (Kim *et al.*, 2015; Kim *et al.*, 2017; Lu *et al.*, 2016; Mies *et al.*, 2016)

This paper aims to analyze existing file formats, evaluate them for their potential use in the digital additive manufacturing process chain and give use case-specific recommendations for selecting an appropriate file format. Therefore, section 2 presents the process chain in additive manufacturing and derives evaluation criteria for file formats. In section 3, eligible file formats are identified and evaluated regarding the defined evaluation criteria. Typical use cases for additive manufacturing are developed in section 4, and in section 5, the use case-specific recommendations are derived. Section 6 concludes and provides an outlook for future research areas.

2 PROCESS CHAIN IN ADDITIVE MANUFACTURING

Regardless of the manufacturing technology, the general process chain of additive manufacturing is divided into pre-process, in-process and post-process (Gebhardt *et al.*, 2019). The pre-process starts with the generation of part geometry in a CAD system. Subsequently, the native 3D CAD data is transformed into a facet model (Gibson *et al.*, 2015; Kumar, 2020). The STL format has become the industry standard for the facet model file format (Kim *et al.*, 2017). Then, AM-specific pre-processing, comprising the definition of part orientation, position and the generation of support structures, is conducted based on this facet model (Gebhardt *et al.*, 2019). Finally, machine-independent layer data is generated and converted into machine code. During the in-process, the part is manufactured according to the process plan defined during the pre-process. Afterward, process-dependent steps of post-processing are necessary. Those may include heat treatment, support structure removal or surface finishing. (Kim *et al.*, 2017)

The aim is to provide a single file format that can be used during the entire process chain to prevent information loss due to transformation between different formats. Therefore, the file format must represent the information necessary for and generated in each process step in the pre-process and transfer those to downstream process steps. In the most basic case, the file format has to represent the part geometry with adequate accuracy, including support structures, and include machine code to ensure printability. Additional material and color information is required if multi-material or multi-colored components are produced. In order to extend the idea of a uniform file format to the simultaneous printing of several components in one build job, information on the positions and orientations of the parts in the build volume is necessary. Since most additively manufactured parts require post-processing, the transfer of quality requirements, e.g., surface roughness, is to be aimed for. These considerations lead to the following criteria used in section 3.3 to evaluate the file formats.

- **Accuracy of approximation:** The criterion of approximation accuracy describes the achievable accuracy of the geometry approximation of the data format.

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- **Material information:** This criterion describes the ability of a file format to represent information about the materials used. An essential aspect of evaluating this criterion is the number of materials supported in a file.
- **Color information:** For different additive manufacturing processes allow the use of multiple colors, the ability of a file format to store color information is crucial. This criterion describes whether color information is supported, multiple colors are supported, or color gradients can be represented.
- **Support:** Support structures are mandatory in different additive manufacturing processes. This criterion describes the ability of a file format to represent support structures and distinguish them from the rest of the geometry.
- **Nesting:** This evaluation criterion describes the ability of a file format to represent different parts within the build volume and determine each part's orientation individually.
- **Product and manufacturing information (PMI):** Information about tolerances, surface finish, and required post-processing is essential for using a file format throughout the process chain. The ability to store tolerance information becomes especially important should the manufacturing and design be performed in different companies.
- **Printability:** A file format is considered printable if it can be transferred to the manufacturing machine, and production can start directly without additional information or data transformation. For this purpose, a file format has to include tool paths. If additional software is required to generate G-code or NC programming of tool paths from a file format, this format is not considered printable within the scope of this work

3 OVERVIEW AND EVALUATION OF FILE FORMATS

The file formats of concern for this paper are data exchange formats for additive manufacturing. They shall at least establish data transfer between the CAD system and the software for AM-specific pre-processing and ensure compatibility between the two systems. The long-term aim is to use a single file format in additive manufacturing throughout the entire digital process chain.

3.1 Approach

In order to identify appropriate data formats, a two-step approach is used. Firstly, extensive market research is conducted by analyzing the export options of the nine most commonly used CAD systems (see Table 1) and the import options of 68 software tools for AM-specific pre-processing. In principle, CAD systems support a variety of neutral and native data formats. Neutral data formats are manufacturer-independent formats that are suitable for software-independent data exchange. Native data formats, on the other hand, are proprietary and tailored to specific CAD software. For data exchange, they are only suitable to a limited extent. (Pasterk, 2018)

Table 1. List of CAD systems and available export file formats.

CAD system	3DS	3MF	AMF	JT	OBJ	PLY	STEP	STL	VRML	X3D
Autodesk Inventor			X	X	X		X	X	X	
Autodesk Auto CAD Mechanical				X			X	X		
Autodesk Fusion 360		X	X		X		X	X		
Dassault Systèmes CATIA		X		X			X		X	
Dassault Systèmes Solid Works		X	X		X	X	X	X	X	
PTC Creo		X		X	X		X	X	X	
Open Source Program Free CAD	X		X		X	X	X	X	X	X
Siemens NX	X	X		X	X	X	X	X	X	
Siemens Solid Edge		X		X			X	X	X	

The market for AM-specific pre-process software can be divided into two groups of vendors−those vendors who only sell software applications and those which sell AM machines and software applications. For the market research, 68 software applications are identified, and their file format compatibilities are documented. The second step is researching file formats already known or developed

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in academia yet not commonly known or used in industrial applications. They have a high range of functions, are superior to the more widely used data formats in some aspects, and thus can replace them. The combined list of all file formats identified in market and academic research, as shown in Table 2, is analyzed regarding criteria specified in section 2.

Table 2. List of identified file formats

Abbr.	**Name of File Format**	**Abbr.**	**Name of File Format**
3DS	3D Studio	STEP	Standard for the Exchange of Product data model
3MF	3D Manufacturing Format	STEP-NC	Standard for the Exchange of Product data model - Numerical Control
AMF	Additive Manufacturing File Format	STL	Standard Triangulation Language
CLI	Common Layer Interface	SVX	Simple Voxels Format
JT	Jupiter Tessellation	VRML	Virtual Reality Modelling Language
OBJ	Object Format	X3D	Extensible 3D
PLY	Polygon-File-Format		

3.2 File formats

Due to the page limitation in this publication, a detailed description of all data formats must be omitted in this section. The following subsections describe the STL format that is the current state of the art, the file formats 3MF and AMF that have been developed for additive manufacturing and STEP-NC, which is a promising neutral file format often used in academic publications.

3.2.1 STL

The acronym STL originally stood for Stereolithography, but today it is more commonly known as Standard Triangulation Language or Surface Triangulation Language. The file format represents the de-facto industry standard for transferring 3D models in additive manufacturing. The file format was developed by 3D Systems in 1987 and has gained acceptance over the years due to its simplicity and robustness, but the format has limitations. (Wang and Chang, 2008; Wu and Cheung, 2006)
Simple triangles without curved faces or edges represent the part surface when approximating the geometry. The coordinates of the three vertices and the corresponding surface normal vector are stored for each triangle. The surface normal vector indicates the orientation of the surface and the direction of the outer or inner surface. Only geometric information is stored, not object attributes, color information, material information or similar metadata for additive manufacturing. (Qin *et al.*, 2019)

3.2.2 3MF

The 3MF format was developed by an industry consortium led by Microsoft in 2015. It aims to create a file format suitable for additive manufacturing by incorporating companies from this industry sector (Qin *et al.*, 2019). The data format was developed in XML using the UTF-8 standard and thus allows further development of the file format by users. This strengthens the ability to interoperate with different systems and integrate the data format into existing process chains (Gonzalez *et al.*, 2018b). The geometry of a CAD model is approximated by a grid of noncurved triangles (Qin *et al.*, 2019). A triangle is defined by its three vertices, which are always enumerated counterclockwise and assembled to form a triangle (Gonzalez *et al.*, 2018b). Due to the individual definition of each vertex, it can be assigned different properties like color or material. The constant evolution of additive manufacturing requirements has led the consortium to release several extensions to the data format (Gonzalez *et al.*, 2018a; Gonzalez *et al.*, 2018c; Gonzalez and Wright, 2018). The functional scope of the extensions includes, for example, the possibility to assign composite materials to the vertices, to enable color gradients at the vertices utilizing linear interpolation of the color information, and to define colors as a separate class and thus reduce redundancy. Furthermore, the extensions allow graphics to be printed on the components and have a higher resolution than the triangular grid (Gonzalez *et al.*, 2018c). The extensions to the basic version also make it possible to define support structures within the 3MF file. (Gonzalez *et al.*, 2018a)

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3.2.3 AMF

The additive manufacturing file (AMF) is a standard introduced by ISO and ASTM International to represent 3D data (International Organization for Standardization, 2020). It is specially tailored for additive manufacturing and was developed to replace the STL format. Until 2013, it was therefore called STL 2.0 (Qin *et al.*, 2019). The format contains more information than STL, such as color, material, and nesting of multiple parts in the build volume, but no process-specific information, making the format neutral and machine-independent. Because it is stored as XML code in ASCII format, it is simple in structure, platform-independent, and thus can be read and edited by humans (Gebhardt, 2016; International Organization for Standardization, 2020). Triangles approximate the geometry. For the definition of the triangles, previously defined vertices are referred to so that there is no multiple storage of the vertices. From the triangles, a basic mesh is represented. In order to approximate curved surfaces, curved edges can be specified. The curved triangle is then recursively subdivided into shallow sub-triangles until the desired tolerance of the approximation is achieved (Gebhardt *et al.*, 2019; International Organization for Standardization, 2020). The AMF format is expected to support voxels, CSG representations, textures, and more product manufacturing information (PMI) in future developments. (Savio *et al.*, 2019)

3.2.4 STEP-NC

The Standard for the Exchange of Product data model (STEP) is an important neutral data exchange format. It is a set of standards defined in the series of ISO 10303 Automation systems and integration-Product data representation and exchange (Gartzia González and Barreiro García, 2019). The standard defines several application protocols (AP), which cover specific sub-aspects of the entire standard. For additive manufacturing, AP 242 Managed model-based 3d engineering is identified as the most important part of the standard (Gartzia González and Barreiro García, 2019; Qin *et al.*, 2019; Venkiteswaran *et al.*, 2016; Xiao *et al.*, 2018). This AP is the basis for the geometry approximation, the required information for automated manufacturing, and tolerances. In recent years, the use of the STEP file format in additive manufacturing has steadily increased as STEP files have become standard in other manufacturing processes, such as milling and turning (Xiao *et al.*, 2018; Qin *et al.*, 2019). In addition to the STEP format, there is another data format that, in part, is based on ISO 10303. This format is the Standard for Exchange of Product data model-Numerical Control (STEP-NC). This data format is based on the AP 238 of ISO 10303 and ISO 14649 Industrial automation systems and integration -Physical device control - Data model for computerized numerical controllers. ISO 14649 was already published in 2004 for turning and milling processes and is continuously being adapted for additive manufacturing. (Bonnard, 2018; Qin *et al.*, 2019; Rodriguez and Alvares, 2019)

Since STEP-NC is based on ISO 10303, a STEP-NC file is structured in the EXPRESS programming language. The most significant difference to a STEP file is the presence of a direct machine interface by generating tool paths. Since the tool paths cannot yet be represented for additive manufacturing machines, research is being carried out on the STEP-compliant extension of the STEP-NC data model (Milaat *et al.*, 2022a; Milaat *et al.*, 2022b; Xiao *et al.*, 2021). In contrast to the STEP file, a STEP NC file does not contain a triangulated geometry model but only the unaltered geometry from the CAD data (Lipman and McFarlane, 2015).

3.3 Evaluation

A suitable file format must hold specific information and fulfill additional criteria to be used in the digital additive process chain. The additive process chain was analyzed in section 2 to derive evaluation criteria for file formats. Those seven criteria represent the necessary functionality of file formats to serve as a consistent file format throughout the entire process chain. Each file format presented in Table 2 is analyzed concerning these evaluation criteria, and the results are displayed in Table 3.

Different extensions are available for the 3MF format, so the evaluation concerns the base configuration. If an extension enables the improvement of the evaluation, this is indicated in brackets. The evaluation results show that the current standard format STL has low accuracy of geometry approximation and only allows storing multiple parts in one file. No other criterion is fulfilled. It is worth noting that several file formats allow the representation of multiple colors, and AMF, OBJ and 3MF with an extension even allow the use of color gradients. The only file formats able to transfer product and manufacturing information are JT, STEP and STEP-NC. Currently, none of the considered formats allow storing machine code in the file to make it immediately printable. However,

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there are efforts to develop the STEP, STEP-NC and SVX formats accordingly (Bonnard, 2018; Bonnard *et al.*, 2018; Ghadai *et al.*, 2021). The AMF and 3MF formats, developed explicitly for additive manufacturing, show good results. They allow the representation of multiple materials, using color gradients and the nesting of multiple parts. In addition, 3MF provides support structures but can only achieve a low accuracy due to the triangular approximation. The AMF format optionally allows curving the triangle patches to improve geometric accuracy.

Table 3. Overview of the evaluation results of file formats

	Accuracy	Material information	Color information	Support	Nesting	PMI	Printability
3DS	Low	Multiple	Multiple	No	Yes	No	No
3MF*	Low	Multiple	Multiple (Gradient)	No (Yes)	Yes	No	No
AMF	Moderate	Multiple	Gradient	No	Yes	No	No
CLI	Moderate	No	No	Yes	No	No	No
JT	Moderate	Multiple	Multiple	No	Yes	Yes	No
OBJ	Moderate	Multiple	Gradient	No	Yes	No	No
PLY	Moderate	Single	Multiple	No	No	No	No
STEP	High	Single	Single	No	Yes	Yes	Under Development
STEP-NC	High	Single	Single	Yes	Yes	Yes	Under Development
STL	Low	No	No	No	Yes	No	No
SVX	Moderate	Multiple	Gradient	Yes	No	No	Under Development
VRML	Moderate	No	Gradient	No	Yes	No	No
X3D	Moderate	No	Gradient	No	Yes	No	No

* There are different extensions available for the 3MF-Format. The evaluation is regarding the base configuration. Possible improvements by extensions are shown in brackets.

4 USE CASES

Although there is a general digital process chain for additive manufacturing, the requirements for a consistent file format depend on the specific use case. For example, when manufacturing metallic end products using laser-powder bed fusion, it is not necessary to be able to represent multiple colors. In this scenario, high accuracy of the approximation is of greater interest. This section aims to develop various scenarios for additive manufacturing and, if different scenarios have the same requirements for a file format, to group them into use cases. The scenarios are derived based on the type of additive product manufactured and the additive manufacturing process used. In the first step, a distinction is made between the various additive manufacturing processes, some of which place different requirements on a file format, such as approximation accuracy. In the context of this paper, the following additive manufacturing processes following the definitions of (Verein Deutscher Ingenieure e.V., 2014-11-00) are considered: Stereolithography (SL), Laser powder bed fusion (LPBF/LS), Fused Layer Modeling (FLM), Multi-Jet Modeling (MJM), Poly-Jet Modeling (PJM) and 3D Printing (3DP).

The types of additive products can be divided into rapid prototyping, rapid tooling and rapid manufacturing (Gebhardt *et al.*, 2019). However, it is helpful to differentiate into further subcategories (Figure 1). Rapid manufacturing, which produces end products, is subdivided into finished and semi-finished products. Finished products need no other post-processing steps than the process-specific ones, like removing support structures or thermal treatment. In contrast, semi-finished products need further processing steps before they are used. The distinction between form negatives and auxiliary tools is made in rapid tooling. Form negatives can be manufactured as permanent molds from durable materials, usually metal, and used, for example, for polymer injection molding or deep-drawing processes. In addition, there are form negatives referred to as lost forms and models and used, for example, for metal casting processes. These are usually created from sand or gasifiable materials and are destroyed by either demolding or the casting process. Therefore, to achieve the desired

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behavior, the focus is on the material properties of the additive product. Auxiliaries are all other additive products used, for example, to facilitate assembly processes or similar work steps.

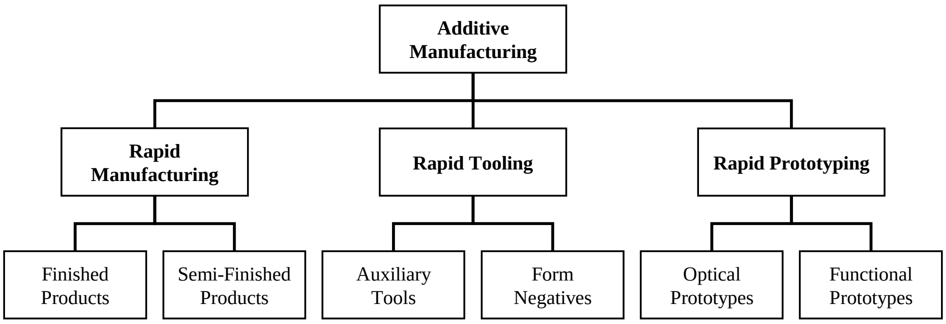

Figure 1. Categories of additive products used for deriving the scenarios

Since functional and visual prototypes' requirements differ greatly, rapid prototyping is divided into these subcategories. The objective of functional prototypes is to enable assembly tests, mechanical tests, or other tests to be conducted at an early stage of product development or shortly before production start. These tests provide information about the actual behavior of the product in the intended application. In this context, the requirements for additive products are production speed, accuracy, or the use of material close to series production. Visual prototypes are primarily used for the physical and visual representation of products and therefore need file formats with special requirements for surface texture and coloration.
The additive processes are combined with the categories of additive products to develop use cases. Table 4 lists the resulting six use cases identified as relevant ones. In addition to the specification by AM process and type of additive product, the requirements posed onto a file format are defined using the evaluation criteria presented in section 3.3. The requirements are divided into mandatory requirements that must be met to enable the use case and beneficial requirements.

Table 4. List of use cases and their respective requirements

Use case	AM process	Types of additive products	Requirements
1	FLM/ MJM	prototypes, auxiliary tools, finished products	Mandatory: multiple materials, support Beneficial: nesting
2	SL/ PJM	prototypes, auxiliary tools, finished products	Mandatory: multiple materials, accuracy, support Beneficial: nesting
3	LPBF	functional prototypes, form negatives, auxiliary tools, finished products	Mandatory: moderate accuracy, single material, support (metal) Beneficial: nesting, color information (polymer)
4	LPBF	semi-finished products	Mandatory: moderate accuracy, PMI, support (metal) Beneficial: nesting
5	3DP	form negatives, semi-finished products	Mandatory: material information, PMI Beneficial: accuracy
6	3DP	optical prototypes	Mandatory: multiple materials, moderate accuracy, color information, Beneficial: color gradient

The first use case represents the production of functional or optical prototypes, finished products and auxiliary tools using FLM or MJM. The production of functional prototypes, optical prototypes, end products, and tools using FLM or MJM are manufacturing processes completed after the additive manufacturing chain is completed. Therefore, no PMI for downstream processes is required, but support structures and multiple materials must be available. The capability to represent a build job with multiple nested parts is beneficial. The manufacturing of prototypes, finished products, and auxiliary tools by SL and PJM processes specify the second use case. The difference in requirements compared to use case one is the need for higher accuracy due to the more precise manufacturing capabilities of the processes. The laser powder bed fusion process characterizes use cases three and four. Both use cases need high-fidelity

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geometry representation to utilize the process capabilities fully. For processing metallic materials, support structures are required, but LPBF of polymers does not require support structures. Whereas in use case three, functional prototypes, tools and finished products are manufactured, use case four describes manufacturing semi-finished products that need further post-processing. Therefore, PMI for these process steps must be stored in the file format in use case four. Use case 5 covers additive products manufactured by the 3DP process that do not have any color requirements. These are tools and semi-finished products like form negatives and molds for casting processes. Particularly in the production of casting molds, subsequent work steps, such as infiltrating or coating, are required. Representation of PMI in the data format is therefore recommended. The last use case refers to producing optical prototypes by the 3DP process. Since section-by-section coloring is achievable with 3DP, a file format that can represent color gradients is advisable.

5 USE CASE-SPECIFIC RECOMMENDATIONS

In section 2, the list of relevant file formats and requirements for these file formats were identified. In section 4, six use cases were developed based on the characterization of additive products and AM processes. In this section, these two results will be combined to give recommendations for selecting file formats concerning the requirements of a specific use case. This comparison of file format capabilities and use case requirements only considers the functionalities of the file formats. Distribution of the format and compatibility with software systems is not considered.

The file formats can be rated as recommended, suitable or improper for each use case. The rating as a recommended format is given if all mandatory and beneficial requirements are met. A file format is suitable if all mandatory but not all beneficial requirements are met and improper if a mandatory requirement is not satisfied. Table 5 summarizes all recommended and suitable file formats for the use cases defined.

Table 5. Recommended and suitable file formats for the defined use cases

Use case	**File format**	
	Recommended	Suitable
1	3MF, STEP-NC	SVX
2	-	SVX
3	Metal: STEP-NC Polymer: AMF, JT, OBJ, STEP, STEP-NC	Metal: SVX Polymer: PLY, SVX
4	Metal: STEP-NC Polymer: JT, STEP, STEP-NC	-
5	JT, STEP, STEP-NC	-
6	AMF, OBJ, SVX	JT

STEP-NC is the most recommended file format. The de-facto industry standard STL is the most widely used file format. However, functionally, it is neither recommended nor declared suitable for any use case. STEP-NC offers a high potential and enables the complete penetration of the process chain but has not yet arrived in industrial applications. It is the only file format capable of representing both support structures and PMI. There is no file format fulfilling all requirements of use case two. For use cases 4 and 5, the deciding factor for file format selection is PMI support, which leads to the formats JT, STEP and STEP-NC being the only formats available. Despite being developed for additive manufacturing, the 3MF format only supports use case one. Part of this is the approximation accuracy, which is rated as low. The accuracy can be increased by using more facets, leading to larger memory size. When neglecting the criterion of accuracy, the 3MF format is recommended for use cases one, two, three and six.

In addition to the functional view, it is relevant to consider the distribution of the file formats. It is striking that the CAD systems do not support both STEP-NC and SVX. JT, 3MF and OBJ are supported by 66%, and AMF is still supported by 44% of all CAD systems considered in the market research. In contrast, all CAD systems reviewed process the de facto industry standard STL. Regarding pre-processing software, the file formats JT, STEP-NC and SVX are not supported. The still relatively new format 3MF is already widespread among 50% of the software providers due to the industry consortium involved with its development. The distribution of AMF is at 20%. OBJ can be processed by 75% of the software available.

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Currently, no data format is suitable for all use cases described. So there is no general recommendation for a file format. Nevertheless, the 3MF format is increasingly penetrating the market and is further developed by additional extensions. So, in the future, the 3MF format may become the best selection regarding functionality and software support.

6 CONCLUSION AND OUTLOOK

In this paper's investigation, alternatives to the de-facto industry standard STL as the data exchange format in additive manufacturing are to be found. This research aims to design a use case-specific continuous digital process chain. Selecting the proper file format as the basis for each digital process chain is no trivial task. Therefore, this paper investigates various file formats to identify alternatives to the STL format based on literature and market research on potential file formats. The identified data formats are evaluated for their suitability according to the requirements of the digital additive process chain. Furthermore, typical use cases are defined, and suitable and recommended file formats are presented.

During the research, it became apparent that the current variety of file formats is very different in information content. Thus, the generally valid applicability of only one file format for all additive use cases is not given at the current time. The future goal should therefore be to formulate uniform and universally required information content. STEP-NC, in particular, offers the most functional potential to take on the role of a universal file format along the entire additive process chain since future versions can cover the required information content. SVX can also assume this role if the trend changes towards voxel-based additive manufacturing. Therefore, further effort should be made to develop these two data formats.

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