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DATA MANAGEMENT FOR ADDITIVE MANUFACTURING: SURVEY ON REQUIREMENTS AND CURRENT STATE

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1. Introduction

Additive Manufacturing (AM) has the potential to substitute conventional manufacturing for various applications in many branches of industry [The Ad-hoc Industrial Advisory Group of the Factories of the Future PPP and EFFRA, the European Factories of the Future Research Association 2012], [Allison and Scudamore 2014]. The process from design through pre-processing to manufacturing is fully digitalised. Consequently, data management is essential and carries significant role in rationalisation. Currently the StereoLithography format (STL) is widely used as an existing standard for 3D product data being not exact but pragmatic and sufficient with regard to tolerances which are realistic in AM machines [Jamieson and Hacker 1995], [Jurrens 1999]. The Additive Manufacturing Format (AMF) was developed to overcome some shortcomings with the addition of information about the manufactured product specifically in respect to AM technologies [Hiller and Lipson 2009]. 3MF is an initiative which even extends that vision [3MF Consortium 2015]. Nevertheless there is neither evidence about actual requirements for data management and data formats nor about the use of different formats and their shortcomings. Consequently this paper focuses on actually used data formats and data management. Questions are risen such as "What are the reasons for the usage of the StereoLithography format (STL)?" and "Why are modern data formats like Additive Manufacturing File Format (AMF) not able to substitute the STL format?”. Based on empirical analysis of the actual situation, necessary improvement of data management and exchange formats in context with AM technology is derived. Experts of several target groups like AM machine manufacturers, software developers and AM technology users provide input for the survey conducted during the fair "formnext" in Frankfurt and online. Additionally interviews were conducted with experts at the "formnext" to analyse the interest in the topic of requirements for an AM specific format. The results give an overview of data management and formats in context of AM, deficits of actually used formats and necessary requirements for improvement of data managements and creation of new data formats.

Chapter 2 describes the state of the art of data formats which are used for the production with AM technology. Further, an overview of the actually used data management infrastructure is given. The structure of questionnaire pointing out reasons for the usage of certain data formats and the acceptance of these is outlined in chapter 3. Chapter 4 contains the results of the expert survey and recommendations for action items in context of data management infrastructure and formats in AM. Conclusions of the investigations and an outlook on future investigations are presented in chapter 5.

In summary, the purpose of this paper is to understand the actual use of data formats and data management in the field of AM and contribute to scientific and practical discussions facilitating a wide application of AM. Furthermore, the paper draws conclusions based on an empirical analysis of the used data formats dependent on stakeholder groups and it provides advices for the improvement of data formats in AM.

2. State of the art

2.1 AM technology

Dickens defines AM as "the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components" [Dickens et al. 2006]. Past usage of AM was limited to rapid prototyping. The actual development of AM increases the usage in production environments for small batch series [Ford 2014]. AM technologies offer various advantages compared to conventional manufacturing methods such as subtractive and formative manufacturing. AM is a technological discipline consisting of a wide range of manufacturing methods.

The mainly used manufacturing methods for industrial products can be differed into extrusion processes and powder based processes. Beside these, a lot of other processes exist, like inkjet processes, stereolithography or blown powder processes [Gebhardt 2013]. In extrusion processes, such as Fused Deposition Modeling (FDM), filaments are molten by a hot nozzle and added layer by layer in the work space. With plastic filaments this is well known as "3D Printing". FDM is already obtainable at low cost and thereby used for private homeprinting purposes. Nevertheless more expensive machines for high quality parts are also available and already used in direct manufacturing of parts in actual usage for aircrafts. Selective Laser Melting, Laser and Selective Laser Sintering are AM technologies which melt layers of raw material powder with a laser to merge the powder. In contrast to Selective Laser Melting using metal powder as raw material, Selective Laser Sintering takes plastic powder as raw material for the manufacturing process. One core characteristic of AM is the ability to manufacture parts of nearly any geometric complexity.

For conventional manufacturing technologies, tools for the creation of the geometry must be developed. Thus high complexity of product geometry leads to high costs for manufacturing tools. AM technologies do not need tools to form the surface and geometry of a product which saves cost [Dickens et al. 2006], [Campbell et al. 2012]. Thereby, AM offers huge potential of reducing cost and increasing efficiency of complex shapes. Thereby products are optimised in respect to their use, not their manufacturing [Zäh and Hagemann 2006].

AM fulfils various requirements to characterize it as a disruptive technology. For a breakthrough of AM as series manufacturing technology, challenges as surface finish, accuracy, repeatability and standardized processes must be taken. Basis of these challenges are data management and existing exchange formats [Reiher and Koch 2015]. One possibility to create a uniform AM data format is described by Nassar and Reutzel proposing an AM specific format on the basis of AMF which can be adjusted for different steps in the Additive Manufacturing chain [Nassar and Reutzel 2013].

Hiller and Lipson describe the approach of the AMF data format and the advantages in comparison with STL [Hiller and Lipson 2009]. Another approach is the investigation of several already existing formats and the development of a data scheme designed for AM [Yan et al. 2015]. Pratt describes the requirements for data formats and creates a solution on basis of ISO 10303 (STEP) [Pratt et al. 2002]. Novelty degree of this paper are the analysis of the requirements based on an expert survey and the assignment of data formats to different steps of the Additive Manufacturing chain.

2.2 AM- specific data formats

In additive manufacturing, different data formats are used depending on the task, such as geometry modelling, slicing process or process monitoring. This section includes the important data formats for geometry modelling and data preparation.

- STL: Surface Tessellation Language (STL) is the preferred data format for 3D printing [Jurrens 1999]. It describes the geometry surface of the product by approximation with triangle facets. The included normal vector describes the orientation of the triangle facet. The file structure of STL is written in ASCII format or binary. The simple structure of the format prevents syntax errors. It does not include additional information about manufacturing process or product specific characteristics such as colour [Hiller and Lipson 2009], [Eragubi 2013].

- AMF: The Additive Manufacturing File Format is an interchange format using triangle surfaces like STL for the generation of geometry. The significant benefit in comparison to STL is the possibility to manipulate edges of triangles to create bent triangles. The XML based data format [World Wide Web Consortium (W3C) 2008] includes additional information like product colour or material. The format is designed to fulfil various requirements such as technology independence, simplicity, scalability etc. [ISO/ASTM 52915].
- 3MF: The 3D Manufacturing Format describes a 3D based geometry in a markup format (XML). Requirements for the exact visualization of the geometry with resources like surfaces and textures are included. Additionally different aspects like digital signatures and core properties are contained [3MF Consortium 2015].
- PLY: The Polygon File Format (PLY) relieves implementation and has flexible visualisation possibilities for 3D geometry. Additional information like colour values or material are added in the PLY format. The file structure is written in ASCII format [Turk 1994].
- DXF: Drawing Interchange File Format (DXF) is a CAD format developed by Autodesk. It is well suited for cross-system data exchange of 3D models. The file format consists of header, tables, blocks and entities. General information are included in the header of the file. Information about colour, layers and geometry are implemented as additional characteristics of the object [Autodesk 2011].
- 3ds: 3ds format was developed by Autodesk and is a specific format for the 3D modelling software "3D Studio Max". The format consists of Chunks with a Chunk_ID, Chunk_length and a Chunk_value. Geometries are built by triangulation without normales. A grouping of contiguous polygons to form a smooth surface called "smoothing groups" can calculate the normales [van Velsen et al. 1997].
- ISO 10303 Standard: ISO 10303 called STEP is a standard for exchange of product model information. STEP is a compilation of international standard. An integrated architecture of domain specific application protocols (AP) builds the standard. STEP uses ESPRESS as specification language [SCRA Applied Technologies 2006].

2.3 Data management infrastructure

Figure 1 shows the AM data management process describing data flows and different process steps from design to production. A network of steps forms a process for the creation of an AM product [Klemp and Pottebaum 2015].

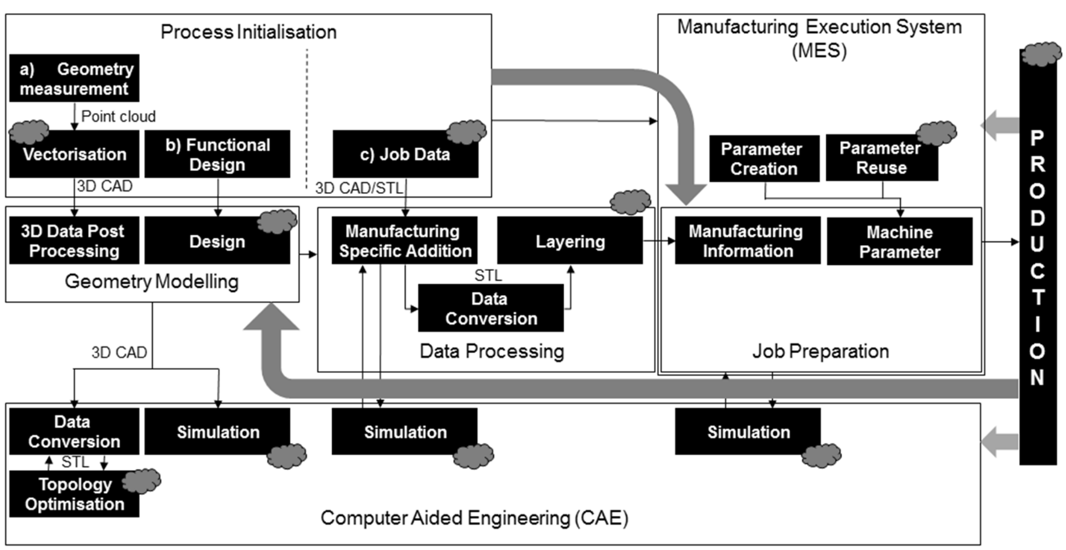

Figure 1. AM data management infrastructure based on [Klemp and Pottebaum 2015]

The manufacturing chain starts with the "Process Initialisation" including possible sub steps of job data, a functional layout or a geometry scan resulting in a point cloud. The last two described sub steps require post processing of the model or the design in the "Geometry Modelling" step. The generated 3D-CAD model is used for two different steps, Computer Aided Engineering (CAE) and Data Preparation to validate the construction by simulations, topology optimization or data conversion, followed by the preparation of a layer structure for the manufacturing method. The CAE step escorts manufacturing process from "Geometry Modelling" step until "Job Preparation" with simulations.
Data Preparation is followed by Manufacturing Execution System (MES) including manufacturing data and machine parameters generated in machine parametrisation and product information of "Job Preparation". Production is the last process step which may serve as input to different steps such as "Geometry Modelling", CAE or machine parametrization to optimize parameters.
A real AM manufacturing chain includes a post processing of the product after production which contains tasks such as removal of support structures. Due to manual mechanical post processing which is not displayed in Figure 1, there is only few data required for post processing at the moment. Taking future advances into account, it will be important to investigate automated post processing and the impact on AM data management.

3. As-is status analysis of AM data management and infrastructure

For an analysis of the actual state, it is necessary to investigate the application of AM data management and infrastructure within companies exposed to AM in AM-related industries. Therefore, an expert survey was conducted to answer questions of data management and exchange formats for AM technology. The questionnaire was concepted in advance of the "formnext" exhibition in Frankfurt from Nov., 15th to Nov., 18th, 2015. It was distributed in paper format and as an online questionnaire.
The survey consists of three different parts. In the first part, general information about the company, its branch of industry, position in AM manufacturing and experience therewith is collected. Participants are being separated by branch of industry (AM service provider, AM user, AM machine manufacturer, software developer, consultancy or research), size of companies measured by number of employees, annual revenue and experience in AM.
The second part is focused on usage of different data formats during several steps in data management infrastructure like "Geometry Modelling" or "Data Processing". Possible answers are AM specific formats such as STL and AMF or generic standard formats such as STEP, IGES or VRML. The list of data formats includes the most common formats in research and industry. For a better orientation in AM data management process, the survey includes a simplified diagram of Figure 1 illustrated in Figure 2.

Figure 2. Simplified illustration of the AM data management process

The figure shows the overall data flow of Additive Manufacturing chain from "Process Initialisation" to "Job Preparation". The manufacturing chain is supported by CAE including simulations of design and MES consisting of machine parameters and product information for the manufacturing process.
The answers in this part of the survey will outline the actually preferred design software for modelling AM manufactured products. Another important aspect will be usage of data formats in various steps of the manufacturing chain as well in between them. Finally, the second part of the survey outlines the motivation for the usage of different exchange formats.
User satisfaction and usability of data flows and the actually preferred data formats are addressed in the third part. Answers will outline the requirements for data format in context of AM from practitioner´s perspective. Another important point is the user satisfaction with data management and usage of data formats characterised by usability aspects such as efficiency, effectiveness and user friendliness (describes the user handling and understanding). Requirements not being fulfilled yet by existing data formats are analysed in the third part of the survey. Answers to these questions offer important

information on the need for development of a standardized data format which can substitute STL format. Another result will be a more concrete illustration of the data management in AM required to investigate potentials in the data management process.

4. Potentials of improving data formats and data management

Results of the conducted survey with 26 participants with high expertise in AM are outlined in this section. Additionally there is an analysis of differences between industrial und research environments in context of AM data formats and management for some aspects. Various criteria such as usage, requirements and user friendliness of the data formats are emphasized by the analysis. Afterwards a recommendation for improvement of data formats and management is given in order to increase usability and fulfilment of requirements. Figure 3 gives an overview of participants´ branches. It shows a wide field from AM researchers to consultants with a high amount of AM researchers and AM manufacturers and service providers.

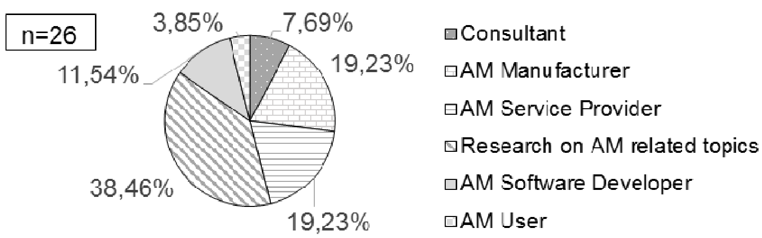

Figure 3. Branches of survey participants

4.1 Results of the AM survey

The survey contains assessments of the participants based on their own knowledge of AM technology. The majority estimates their personal experience in the field of AM rather high or very high, correlating to the description of different answer possibilities. A minority of the participants describes expertise as rather low. No participant estimates his or her own experience as very low or not existing. A comparison between participants of industrial and scientific environments shows that there are just minor differences in the assessment of AM knowledge. Only two participants of the industrial sector estimate their experience as low.

One aspect of the survey deals with the degree of familiarity with the 3MF initiative which promotes the development and usage of the 3MF format and substitution of the STL format. Only two participants of the survey are members of the initiative as displayed in Figure 4.

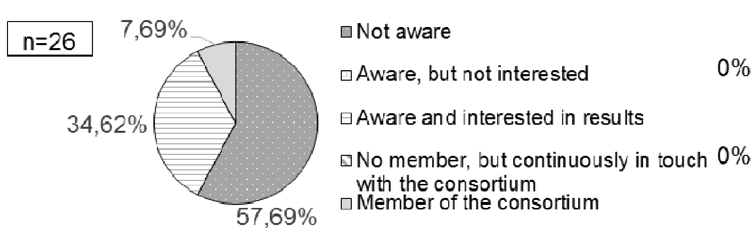

Figure 4. Awareness of 3MF initiative

One third of participants know the 3MF initiative and are very interested in the results of its work whereas a majority are not aware of the initiative. There are not any participants who know the 3MF consortium, but are not interested in the results. In conclusion, the interest in the topic of data formats exists, but it is necessary to announce the initiative in order to distribute results to several industrial sectors of AM.

As shown in Figure 5, the STL format is still the standard format in context of AM specific data formats. The majority of the participants always use STL for AM. Only one AM Machine Manufacturer and one software developer use STL rarely and frequently. No matter whether in research or industry, the AMF

format is not or only rarely used. There could be different reasons for the usage of STL. The improvements of AMF format could not meet STL format, but there is also the possibility that the awareness of AMF is not high enough for an extensive penetration in the field of AM.
Specific questions for usage of other data formats such as proprietary CAD, 3D scan based, polygon based and other standard data formats (STEP, SAT, IGES, etc.) show that only proprietary CAD and the standard format STEP play an important role in data management of AM (Figure 5). CAD formats and STEP format are used frequently or rarely by the participants whereas 3D scan based and polygon based formats are used never or rarely. There is no difference between industrial and scientific environments. Other investigated standard data formats such as SAT, VRML or IFC are not displayed in Figure 5 due to low relevance for AM data management because they are used never or rarely. So these formats are negligible for the AM data management and for a more detailed analysis of usage in the different steps of AM.

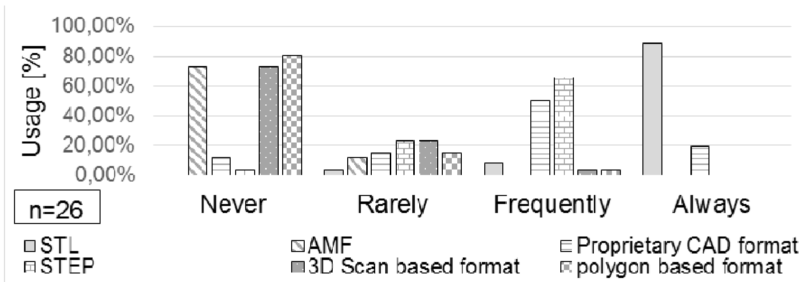

Figure 5. Usage of various data formats for AM

Another important aspect is usage in different steps of the Additive Manufacturing chain. Figure 6 includes the assignment of AM specific (STL, AMF), proprietary CAD and other standard formats (STEP, IGES, SAT,…) from "Process Initialisation" to "Job Preparation".

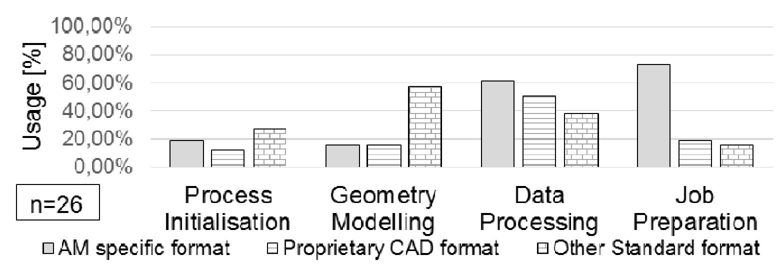

Figure 6. Usage of data formats in different steps of AM chain

The AM specific formats such as STL are important during the last two steps ("Data Processing", "Job Preparation"). Proprietary CAD formats are mainly used in "Geometry Modelling". Other Standard formats such as STEP play an important role in "Geometry Modelling" and "Data Processing". It is noticeable that participants do not utilize mainly used formats in "Process Initialisation" step. In "Job Preparation" only AM specific formats are important for participants. Results of the survey point out that participants of AM technology use various data formats in different steps of AM chain with a perceptible shift to last steps. Allocation of data formats depends on the specific tasks. For example the proprietary CAD and other standard formats are important for the "Geometry Modelling" because of usage of 3D-CAD Software for modelling the product and the compatibility of this data for other software. The high inclusion of AM specific data formats in the last two steps is conditioned by the integration of the AM machines due to the exchange between development software and AM machines. For the investigation of the actual state of AM data management it is important to know the participants´ opinion about usability of data formats such as effectiveness, user friendliness or error rate illustrated in Figure 7.

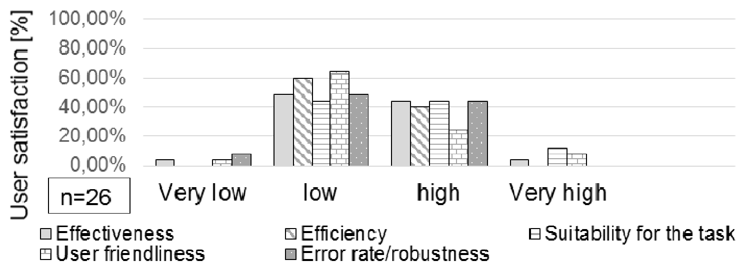

Figure 7. Usability of used formats for AM

The performance of used formats is regarded low or high by a majority of participants in context to different aspects such as user friendliness. Only a minority evaluates the usability very low or very high according to the chosen aspects.

Differences in relation to suitability for tasks and user friendliness are shown by the comparison between small (x < 50 employees, x < 10 Mio. annual revenue) and large (x > 250 employees, x > 50 Mio. annual revenue) companies among the participants.

Almost three quarters of large companies evaluate suitability for the task as high or very high whereas half of small companies assess the aspect as low. Results reveal that the used data formats possess acceptance for AM but there are not already ideal solutions for AM data management. The aspect user friendliness is also evaluated differently by small and large companies. Almost three quarters of the participants employed by a large company assess the user friendliness low whereas half of the participants being employee of a small company evaluate user friendliness as high. According to this aspect, large companies see a higher demand for action. The comparison between industrial and scientific environment contains a significant difference of usability according to effectiveness. Three quarters of participators being involved in the scientific environment assess effectiveness low whereas industrial participants are indecisive between low and high. The results of usability show that usability aspects are partly regarded as adequate but especially large companies and scientific staff see fundamental demand for action to increase usability of AM formats.

For development of new data formats for AM it is necessary to know requirements for AM specific data formats. For this reason the survey includes a question with twelve different requirements such as low failure rate, preparedness for future digitalisation (Industry 4.0) or product piracy prevention to assess results of different stakeholders in AM. It is not only important to identify requirements for AM specific data formats, but also to outline deficits and unfulfilled requirements. Table 1 shows the five most often chosen requirements and not yet fulfilled requirements of existing formats from participants' perspective. Basically all requirement possibilities of the survey are considered important by a majority of participants and have to be fulfilled for an ideal data format. It is noticeable that mostly marked requirements and not fulfilled requirements chosen by participants are identical, but differ in ranking. Results show that the most important requirements for AM specific data formats are not yet fulfilled.

Table 1. Requirements and not fulfilled requirements on existing data formats

	Requirements for AM	Not fulfilled requirements
Exact description of the product geometry	88,46%	61,54%
Low failure rate, reliability	76,92%	61,54%
Small size of data files	61,54%	69,23%
Possibility for multi material	53,85%	61,54%
Interoperability between design and production stages	42,31%	53,85%
Fixed alignment of the product for manufacturing	38,46%	34,62%
Preparedness for future digitalisation (Industry 4.0)	30,77%	46,15%

Inclusion of product lifecycle data	26,92%	30,77%
Product Piracy Prevention	19,23%	26,92%
Traceability	19,23%	26,92%
Quality Management parameter	19,23%	26,92%
Marking	15,38%	15,38%
other, please specify	7,69%	11,54%

These are fundamental requirements which are not fulfilled yet. More specific requirements such as product piracy prevention, traceability, quality management parameters or marking of parts play a subordinated role until the fundamental requirements are not fulfilled completely.

4.2 Improvements for AM data management and formats

The results of the survey, especially the usage in different steps of Additive Manufacturing chain, deliver input for AM data management illustrated in Figure 8.

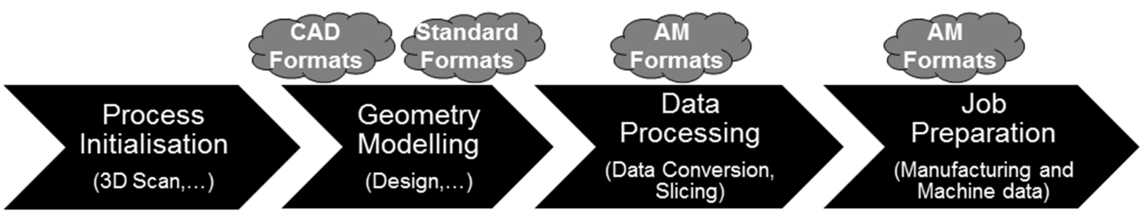

Figure 8. Usage of data formats in the AM data management

The first step "Process Initialisation" has a minimal usage of data formats (<30%) according to participants illustrated in Figure 5. Proprietary CAD and other standard formats are mainly used in "Geometry Modelling" (>50%) while CAD formats are used in 3D-CAD software for modelling of product geometry. Standard data formats serve as a general communication format between different development software tools. In AM it could be used for exchange of CAD data for different CAD software. Principals in AM send their product data in standard formats to AM service provider for example. Based on the results of Figure 5, AM specific data formats are predominantly used in the last two steps ("Data Processing", "Job Preparation"). These formats serve as an exchange possibility between development software and manufacturing machines. Mostly needed data formats of different steps (>50% usage in the step) are illustrated in Figure 8 to show the importance between step and data format. The illustration in Figure 8 implies that the support of "Process Initialisation" has to be improved by suitable data formats which implement applications of 3D scan and point clouds. Another outcome of the survey is that three different types of data formats (AM specific, CAD based and standard formats) play an important role in different steps for the AM data management.

The necessary requirements outlined in the survey form the basis for a suitable data exchange format. An alignment of general and not fulfilled requirements and possibilities of existing AM specific formats such as STL, AMF and 3MF show that formats are only suitable enough to fulfil fundamental requirements such as description of the geometry or low failure rates (Table 2).

The STL format describes the product with a triangular mesh. The more innovative AMF and 3MF formats include the possibility to describe geometry with curve based triangles increasing precision of geometry description. Because of this aspect new data formats are more suitable for an exact description of the geometry [Nassar and Reutzel 2013].

Table 2. Fulfilment of requirements by AMF and 3MF

Requirements	STL	AMF	3MF
Exact description of the product geometry	--	-	-
Low failure rate, reliability	+	+	+
Small size of data files	-	+	+

Possibility for multi material	--	+	+
Interoperability between design and production	--	-	-

++: Very high fulfilment; +: High fulfilment; -: Low fulfilment; --: Very low fulfilment

The failure rate of the STL format due to multiple vertices for different facets and a resulting lack of topological information (gaps or overlapping facets) is higher than failure rate of AMF or 3MF. Because of the possibility of curve based triangles the failure rate of AMF is lower [Hiller and Lipson 2009], [3MF Consortium 2015].

The data size of the AMF format in ASCII form is much lower (44%) than file size of the STL format because of used compression routines [Hiller and Lipson 2009]. 3MF format has also a lower file size because of used compression routines and the basis archive called "3D payload" for all necessary information [3MF Consortium 2015]. Usage of multi material is possible by the usage of AMF (with palette tags) or 3MF (with <basismaterials> element) in comparison to STL.

The interoperability between design and production is not implemented for the STL format. AMF offers the possibility to integrate meta data about material, texture, constellation and lifecycle data that help to improve interoperability with additional information. Additional requirements such as traceability or quality management parameter have to be integrated in these two AM specific or a new data format.

The analysis of the survey focusing usability aspects reveals that fundamental requirements are fulfilled as far as possible. The user satisfaction for the suitability of the task, but low evaluation of the user friendliness, reflects that used data formats are suitable enough for the tasks, but are not user friendly. For an increasing usability, further requirements have to be fulfilled.

5. Conclusions and outlook

The data management for Additive Manufacturing is supported by three different types of data formats: AM specific, proprietary CAD and other standard formats. The process from design to manufacturing of the product is digitalised utilising a heterogeneous combination of these formats. Important needs in the area of AM can be described as requirements for a suitable data format: low failure rate or small size of data files. These fundamental requirements are hardly fulfilled by the actual AM specific standard format STL, the actual quasi standard for AM. Other advanced AM specific formats such as AMF and 3MF will fulfil further requirements. Other account requirements enable the future usage in AM such as preparedness for future digitalisation (Industry 4.0) or Product Piracy Prevention. The demand of action to develop an AM specific data format with the possibility to include data for all requirements, the advantages of fulfilled requirements and the increasing of the usability is outlined thereby.

A next step in enhancing the AM format development is an in-depth analysis, in how far new AM specific formats (AMF; 3MF) can fulfil all requirements which are included in the survey. The further development of new formats is also a possibility to reach the aim to fulfil all requirements.

Future research will be focused on improving data management for Additive Manufacturing chain. Based on a closer investigation of task- specific data formats, a new AM- specific data format shall be developed which is capable to substitute the three existing types of data formats.

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