



prostep ivip

Recommendation

# Additive Manufacturing Interfaces

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**AMI Recommendation**  
Additive Manufacturing Interfaces

## Abstract

Additive manufacturing, often simply referred to as 3D printing, is creating new business opportunities for manufacturing industry.

Additive manufacturing processes have been available for at least three decades and therefore have a long tradition in the field of prototyping, e.g. in automotive engineering. The motivation behind the use of this type of manufacturing technology was essentially the speed at which physical models of the designed components could be made available. Hence, the term "rapid prototyping" was born.

The resulting physical models were predominantly used for visualization, packaging, etc., while series production of the components was implemented – without exception – using conventional manufacturing processes, which often required dies and fixtures (e.g. casting).

This situation still exists to a large extent today, which means that existing prototyping processes are not currently exploiting key potential that additive manufacturing offers. This includes:

- Extensive freedom in product design in terms of geometry, material distribution and functional integration
- Economic and fast production of small and very small lot sizes compared to resource- and processing-time-intensive production methods (often mentioned in the context of objectives like "individualization", "lot size of 1" or "rapid manufacturing")
- Greater opportunities for cross-company collaboration, e.g. with external print service providers, than is possible with conventional manufacturing technologies.

Companies are gearing up for the transformation of existing processes needed to implement additive manufacturing for series production. However, while 3D printer technology and print material capabilities are advancing at a remarkable speed, existing digital tool chains and data formats face the challenge of trying to keep pace.

Design freedom, new manufacturing strategies and the need for a high degree of automation to speed up print job generation require the loss-free exchange of data between best-in-class process tools. Protecting valuable know-how and intellectual property (IP) when product data is exchanged between departments or companies is a key requirement. This recommendation presents a summary of the above-mentioned potential and challenges and defines the requirements for current and future data exchange formats. This provides us with a basis for making recommendations regarding digital interfaces, methods and architectural concepts for collaboration including IP protection.

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## Abbreviations, Definitions

AM	Additive Manufacturing
AMI	Additive Manufacturing Interfaces
B2B	Business-to-Business
B2C	Business-to-Consumer
PMI	Product Manufacturing Information, e.g. GD&T, surface and roughness definition
PP	Process Planning

## 1 Introduction

Additive manufacturing is a disruptive technology that is having an increasing impact on many areas of discrete manufacturing. Although a number of different printing technologies are available for creating parts, 3D printers have not yet been integrated in PLM process chains and ERP systems to a sufficient extent. The approach that PLM vendors take towards 3D printer manufacturers when it comes to system integration is typically limited to bilateral talks. A joint initiative between software vendors, 3D printer manufacturers and industrial users was launched in 2018 as a new prostep ivip group, "Additive Manufacturing Interfaces" (AMI). The main objective is to reach a common understanding of AM interfaces and standardized formats throughout the AM lifecycle that enables integrated interoperability. This document describes the corresponding AMI reference process and the challenges posed by the state of the art.

Rapid prototyping is an example of a domain in which a set of data formats and interfaces, together with well-established processes and proven tools and methods for additive manufacturing, exist today. While of great value in the context of prototyping, most of these interfaces and tools cannot meet all the requirements of series production.

The additive manufacturing of physical artifacts provides several advantages compared to more conventional manufacturing methods. There are three main advantages that we will focus on in this recommendation:

First and foremost, additive manufacturing offers a high level of product design-related freedom when it comes to part geometry and the distribution of material inside the part (depending on the 3D printer's capabilities). Even for single material 3D printing, properties can be varied to some extent by changing process parameters.

No longer does the designer have to consider the accessibility of geometric features by manufacturing tools, e.g. deep cavities. Optimized geometries for the best utilization of material properties or designed according to "bionic" creation patterns can be modeled without constantly have to check whether, for example, the resulting artifact can be molded in a die. Functional integration is made possible, even to the extent of mixing materials to "embed" functionality in a part. All these possibilities regarding geometry, materials and functional integration place a huge strain on the digital product specification of the artifact, since every aspect of it must be described digitally when it is designed. Established data formats used in prototype production (in particular STL) cannot handle this amount and variety of information.

The second advantage that additive manufacturing offers is the ability to manufacture small and very small lot sizes quickly and economically compared to resource- and processing-time-intensive production. Often mentioned in the context of objectives like "individualization", "lot size of 1" or "rapid manufacturing", additive manufacturing makes it possible for companies to manufacture one-off products or heavily individualized parts. As a result, the need to do so and yet still creating monetary value for the company imposes severe economic and speed-related constraints on the processes used to produce these kinds of parts.

The third advantage is cross-company collaboration, e.g. with external print service providers. Unlike conventional subtractive part creation methods, 3D print data will include the full description necessary to build the part. When done right, all the information needed to manufacture the part will be included in the files exchanged. At the same time, this poses one of today's biggest challenges when it comes to information exchange, interfaces and protocols.

While providing full-featured product descriptions offers great advantages to companies in the value chain, it carries the risk of revealing valuable know-how and inadvertently sharing intellectual property (IP). Avoiding this is a key requirement in the context of data formats, security and data protection.

The question of how to realize these advantages will guide us through the process and through this document. We will first describe our methodology and the AM environment, with additional emphasis placed on security, and later describe our findings.

## 2 Methodology

In the first step, we describe typical use cases for 3D printing (see section 2.1). Roles and activities are defined based on assumptions regarding how these use cases will be implemented.

The activities and roles are then combined to create a complete reference process. The reference process is capable of implementing all the use cases defined in advance. When a specific use case is implemented, sometimes all the roles are involved, and other times only a subset is involved.

Finally, since the reference process is executed in a complex ecosystem that is based on multiple internal and external communication channels, we also discuss the security landscape.

### 2.1 Additive manufacturing use cases

#### 2.1.1 Use case 1: Printing an AM-specific part design

This use case can be regarded as the “typical” use case involving a part that is designed specifically for 3D printing and is produced using additive manufacturing technologies. All the part geometry is created from scratch; there are several requirements relating to the size and shape of the part. A CAD system or a tool for generative design is used to create the 3D geometry, which results in an AM-specific design that is stored in a file in a native or neutral format.

#### 2.1.2 Use case 2: Printing conventional spare parts

Use case 2 involves a part that has been already been manufactured using conventional manufacturing methods and is to be manufactured again using additive manufacturing, presumably with as few changes as possible. Therefore, there is no need to create the geometry since the existing 3D representation will be used. A typical example here is the manufacture of spare parts.

#### 2.1.3 Use case 3: Printing scanned parts

In this case, a physical part is to be reproduced, e.g. a part for an oldtimer. As only the physical part is available but no digital information, the first step involves scanning the part. The 3D print is to resemble the original part with regard to appearance and other properties as closely as possible. The part geometry is created from the scan data and needs to be prepared for use in the AM process steps.

#### 2.1.4 Use case 4: Collaboration with external service providers (B2B)

This use case involves a part that has been engineered in-house but is to be printed by a print service provider. Therefore, all the corresponding print information has to be transferred to the service provider. All the necessary information has to be created and sent in order to print the part. There are different aspects of IP protection and security levels included within the use case, e.g. it should be possible to trace who ordered the print and verify how often the component was printed.

#### 2.1.5 Use case 5: Provision of print data for the end user (B2C)

The B2C use case involves a process that is similar to the B2B use case with regard to the part definition but differs when it comes to the printing step. All the information is to be prepared in a way that allows it to be sent to an individual end user who has their own 3D printing device for building the part. In this case, it must also be possible to trace a variety of activities, such as who received the data, who printed how many parts and others.

### 2.2 AM reference process

The top-level process required to produce an additively manufactured component can be divided into three steps: design, process planning and manufacturing (Figure 1). The reference process is defined in such a way that any of the defined use cases can be implemented, either using a subset of the process steps or using the process as a whole. every artefact in the development process.



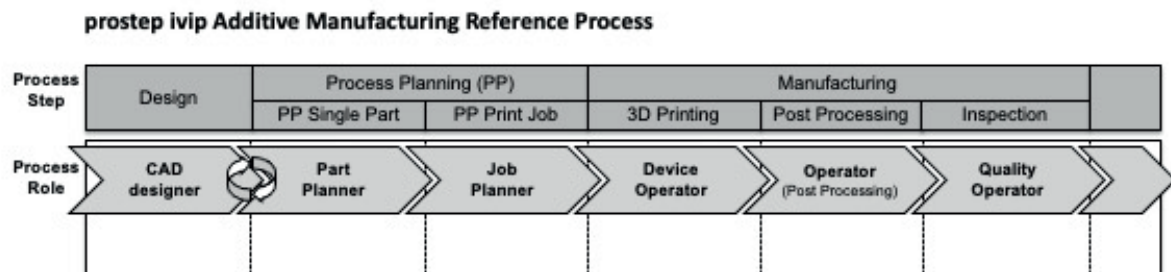


Figure 1: Top-level additive manufacturing process

The flow of data along the entire process indicates that each step requires input data and generates data outputs, which results in a data exchange or data sharing scenario. Since the software applications used in each step are heterogeneous and diverse, the interfaces between the different applications become relevant. Therefore, the interoperability of the AM data flow depends on the mechanisms used to exchange the data. Ultimately and similar to any current production context, taking the whole digital process including the feedback of data into consideration means that we are talking about a concept commonly known as the digital thread (Bonnard et al., 2018; Singh and Willcox, 2018).

When applied to a single part or component, the digital thread concept means linking the data across the digital domain (part models) and the physical domain (executed processes and manufactured part) to allow a closed-loop data flow (e.g. feedback of process data and part quality data). To achieve this, an interoperable data-driven architecture is needed. The interoperable architecture requires standards that define the interfaces. However, as already pointed out in the relevant literature, no single standard or format exists that covers the whole closed-loop data flow for the AM process, including both the forward-directed data flow and the feedback data flow. The feedback of data, which involves incorporating data collected in the physical domain into the digital models, makes it possible to perform predictive and decision-making processes (Lu et al., 2015; Baumann et al., 2016; Qin et al., 2017; Bonnard et al., 2019).

This document acknowledges the importance of the digital thread concept and its relevance within the AM context, e.g. an upstream data flow from the actual printing step back to design that communicates knowledge gained downstream to earlier steps in order to continuously improve the design and process. We consider upstream data and information flows to be important, too, since they represent a great deal of knowledge regarding how things defined earlier impact on the process and part quality later. Feeding back data and the knowledge gained from experience will lead to better designs and overall process flows. In the first step this recommendation deals with the main forward data flow. A proposal for an upstream data flow is not yet considered.

Using the top-level AM process as a reference (see Figure 1), the main forward data flow goes from the Design step all the way through to the Manufacturing step (3D printing). Prior to the Design step, we might give thought to a Requirements Definition step, in which requirements are collected, formalized and specified. The requirements specification provides the input for the Design step, which is for the most part performed using CAx authoring tools. The result of the Design step is the part specification. The part specification contains the 3D solid model with engineering and manufacturing information. The latter information is usually referred to as product manufacturing information (PMI) and primarily comprises geometric dimensions and tolerances, surface finish specifications and material specifications. This part specification provides the input for the Process Planning step, which defines how the part will be manufactured. The output from this step is a set of data (e.g. NC programs) that is used in the Manufacturing step. The final result is an inspected AM part.

In the next sub-sections, we discuss each process step individually using the full additive manufacturing process shown in the figure below.

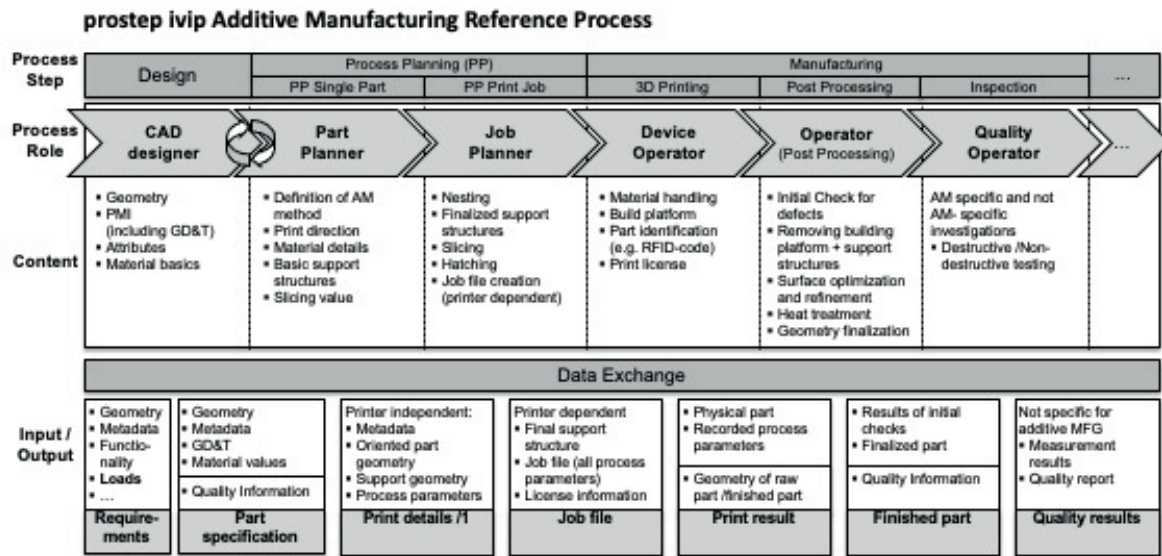


Figure 2: Additive manufacturing process

### 2.2.1 Design

In the Design step, the CAD designer creates the CAD 3D model including geometry definition, PMI (non-geometric attributes required for manufacturing e.g. material information, geometric dimensions and tolerances, 3D annotations and surface finish) and metadata (e.g. lifecycle attributes according to the product development process). The Design step may comprise designing for AM practices. In this case, the topological optimization of the part, with the optional definition of lattice or infill structures and the definition of shells and surface textures, may be executed in this step. It also comprises the definition of the part material and the definition of geometric dimensions, surface finishes and tolerances. When considering the design process, we assume that the part will be designed specifically for 3D printing or that the definition of geometry and material distribution makes it necessary to use 3D printing technologies. Instead of expressing the design using manufacturing parameters (e.g. layer thickness or powder details), the designer should use design parameters only (e.g. material properties in finalized part).

The design process should ultimately provide a complete 3D digital description of the part to be produced. This implies that all properties of the part, i.e. material, dimension, surface finish, etc., resemble that of the final part after it has been printed and post-processed. Design processes that are intended for conventional manufacturing technologies fall outside the scope of the reference process.

The process step Design is included in

- Use case 1: Printing an AM-specific part design

### 2.2.2 Process Planning Single Part

This process step describes how the role of the part planner applies their manufacturing know-how to a single part and derives manufacturing parameters like the print direction and layer thickness from the design parameters they received from the previous step. Since parts are often produced in batches of many parts, eventually even different parts, not all the printing parameters can be derived at this point in time. In some AM technologies, parts are positioned in a build volume so that the volume is filled with a maximum number of parts with a minimum amount of space left in between, a procedure called nesting.

The process step Process Planning Single Part is included in

- Use case 1: Printing an AM-specific part design
- Use case 2: Printing conventional spare parts
- Use case 3: Printing scanned parts

### 2.2.3 Process Planning Print Job

In this process step, either multiple identical parts are positioned in the build volume, based on the actual demand for the number of physical parts, or the build volume may comprise different parts that are nested and define a single job file. Information content left open in the previous step is now added, e.g. the final position of the parts within the build volume and the detailed geometry of the individual support structures.

The process step Process Planning Print Job is included in

- Use case 1: Printing an AM-specific part design
- Use case 2: Printing conventional spare parts
- Use case 3: Printing scanned parts

### 2.2.4 3D Printing

The 3D printer is the machine entity used to create the physical part. Different types of printers can be used, depending on the printing technology involved. To start a print job, the printer needs a print job file and the desired material(s). The information needed will depend on the printing method, for example slice trajectories and processing parameters. The process step 3D Printing is included in all use cases.

### 2.2.5 Post-Processing

After printing, AM-specific and non-AM-specific processes need be carried out before the part can be finalized for usage. AM-specific steps are

- Powder removal
- Removal of build platform and support structures
- Heat treatment

Non-AM-specific post-processing steps, such as machining operations can also be included. A machining step requires the definition of a machining process plan, machining process simulation, CNC program generation, e.g. drilling or milling.

The process step Post-Processing is included in all use cases.

### 2.2.6 Inspection

The quality operator performs destructive or non-destructive testing (DT/NDT). There are various methods and technologies available for examining a part for all kinds of defects.

In the case of in-process monitoring systems, it is determined whether the printing process should be interrupted. These measurements are based on the current status of the printing process parameters and/or printing part properties. Quality assurance (QA) testing to find defects can be performed prior to post-processing to check whether the part is ready for post-processing, e.g. using process parameters or computer tomography. These activities are AM-specific. Additional QA activities will be performed on the finished part. These activities are non-AM-specific.

The process step Inspection is included in all use cases.

PROCESS STEPS & UCS	Design	Process Planning		Manufacturing		
		Single Part	Print Job	3D Printing	Post-Processing	Inspection
Use case 1: Printing an AM-specific part design	X	X	X	X	X	X
Use case 2: Printing conventional spare parts	-	X	X	X	X	X
Use case 3: Printing scanned parts	-	X	X	X	X	X
Use case 4: Collaboration with external service providers (B2B)	-	-	-	X	X	X
Use case 5: Provision of print data for the end user (B2C)	-	-	-	X	X	X

Table 1: Reference process steps included in the use cases

## 2.3 Security landscape in AM

The execution of the AM reference process requires a secure communication context. AM data transferred between different geographic locations, distributed parties, machines and interfaces must remain secure for the duration of the process. A single weak point could easily undermine the security of the whole process, resulting in the compromised safety, quality and authenticity of the manufactured parts, jeopardized intellectual property rights or threatened business operations. Interoperability offers great benefits by enabling workflow integration across multiple systems, but it must be designed with security built in to ensure that interfaces do not introduce data security vulnerabilities. Requirements for data protection when defining interoperability interfaces need to be carefully analyzed, understood and implemented. AM data will even be exchanged across various geographically diverse legal landscapes with different privacy and security legislation and rules and can be governed by regulations specific to individual verticals (e.g. automotive, aerospace, healthcare, and others). Different parties in an additive manufacturing interfaces (AMI) interoperability workflow must therefore be able to satisfy different rules and regulation. This means that interfaces that have been designed to allow end-to-end workflows must meet every legal requirement (e.g. compliance).

At the same time, end-to-end workflow security requirements need to accommodate appropriate and authorized data availability to support smooth manufacturing operations whilst ensuring adequate data protection (like confidentiality). Achieving end-to-end security in AM across organizational boundaries, whether inside a single company or across business partner infrastructures, also requires maintaining coherent and homogeneous privacy and security protections for the data being exchanged across interoperability interfaces throughout the production workflow.

Amongst the multitude of potential security threats in AM, the most prominent examples relevant to designing interoperability interfaces are summarized in Table 2.

Attacks on	Description	Examples of undesirable outcomes
Data confidentiality	Theft of 3D designs and know-how of manufacturing processes	Uncontrolled reproduction of 3D parts of comparable or inferior quality
Intellectual property rights	Unauthorized submission of 3D designs for manufacturing	Unauthorized reproduction violating the rights to manufacture
Data integrity	Tampering with 3D design data and process parameters	Compromised compliance, quality, functionality, and/or safety of manufactured parts and factory processes
Data availability	Corruption and/or destruction of 3D designs and process data	Compromised factory operations and/or production delays

Table 2: Examples of security threats in AM

### 3 Analysis and findings

The reference process described earlier provides the basis for all the use cases examined. In the following, we take a look at the challenges posed by and limitations of the process steps in terms of security aspects and AM interfaces.

#### 3.1 Process overview

Based on the analysis of the above-mentioned use cases and the associated roles and process steps, we have identified certain communalities in the data that moves through the digital process in the context of additive manufacturing. Several assumptions have been made in the process:

- Every step is linked to the preceding and succeeding step by means of a data interface.
- Roles are examined separately, even though one person may assume several roles in actual company processes.
- The design process aims to benefit from additive manufacturing but does not fully describe the digital representation of the part in detailed manufacturing terms. For instance, the design process does not decide on the print direction but defines the anisotropy of the material properties instead.
- By carefully considering material anisotropy when optimizing the part design, the print direction may be defined implicitly, and potential anisotropies may be leveraged to implement product functions.

The result of the analysis is based on the collection of separate input and output parameters for each step. These parameters are then mapped to existing or proposed data formats to gain an understanding of what data format should be used at each point to provide the greatest benefit in terms of interoperability. At the same time, it indicates the shortcomings and potential for future extensions.

This section describes the process steps; the interfaces are discussed separately in the subsequent section.

##### 3.1.1 Design

Generally speaking, designing a part involves finding a geometry and a distribution of one or more material properties that can fulfill the function for which the part is intended. The design should also comply with guidelines and rules aimed at facilitating the manufacturing of the part using AM.

The requirements that the desired part must meet usually serve as input data for the design process. This fact is mentioned here but no further modeling is performed. The reason for this is that numerous representations already exist, of which only a few are truly digital/computer-interpretable and the specification falls outside of the scope of this document at this point.

The requirements describe the functionality the part is intended to deliver. Sometimes a geometry may be added to the requirements, e.g. to describe the environment the part has to fit into or dimensions the part must not violate. Metadata, i.e. administrative or descriptive attributes, is associated with the part in a meaningful way. Examples of metadata are a part ID number or name, the name of author, creation date or lifecycle status.

Input data	Process Step Design	Output data
Requirements regarding <ul style="list-style-type: none"> <li>• geometry</li> <li>• metadata</li> <li>• functionality</li> </ul>	Definition of the part's <ul style="list-style-type: none"> <li>• geometry</li> <li>• PMIs</li> <li>• GD&amp;T (geometric dimensioning and tolerancing)</li> <li>• material</li> </ul>	<ul style="list-style-type: none"> <li>• metadata</li> <li>• geometry</li> <li>• GD&amp;T</li> <li>• material properties</li> <li>- isotropic, anisotropic or graded</li> <li>- single or multi-material option</li> </ul>

Table 3: Process step Design, input/output data

After iterating through multiple alternatives, the designer ultimately creates a part geometry (output) that they think provides the desired functionality and can be manufactured using AM. The result is often based on simulations performed in the CAE domain. Geometric dimensioning and tolerancing (GD&T) for certain geometric features will be defined with the aim of ensuring that the part functions correctly.

The designer will select an appropriate material, or more than one if multiple materials is an option, e.g. from a database of certified materials. If the material exhibits anisotropy properties, the designer will either mitigate the impact of anisotropy or to use it to their advantage. Designing parts with multiple and/or functionally graded materials is currently a challenge. This topic is discussed in section 3.3.3.

AM materials may exhibit properties that are anisotropic (or orthotropic), which means that properties like load-bearing capability, elongation under load, etc., are not the same in all spatial directions. Especially in the printing direction, i.e. the direction in which the layers are added, elongation under load can differ by as much as 20% (powder sintering technology) or even 60% (filament extrusion technology), compared to the properties in the other two (lateral) dimensions.

This anisotropy has to be taken into account in the design process when determining the load-bearing capabilities of the part. But here, instead of thinking about printing direction, the designer should “think” in terms of material properties and a three-dimensional material tensor so that the effects of the anisotropy can be mitigated or maybe even used to an advantage in the design.

The same is true for all other parameters, which have to be mapped to typical design categories. The designer is responsible for delivering the final version of the design model and communicating with the process planner in feedback loops. Ensuring that the information provided via a specific file format is complete and fully interoperable and that a corresponding interface is available is a challenge today.

Level of fulfillment		Native CAD	Neutral CAD	STL	AMF	3MF
Information transfer	• Metadata	X	X	-	X	X
	• Geometry	X BREP* & feature history	X BREP* &	X Mesh	X Mesh	X Mesh
	• PMI	X	(X)	-	-	-
	• Material properties (isotropic)	X	X	-	X	X
	• Material properties (anisotropic)	X	-	-	-	-

Table 4: Process step Design, examples of format options, BREP\* = exact BREP

Numerous output data formats can be taken into consideration: native proprietary formats defined by CAD vendors as well as neutral CAD formats defined by standardization bodies. If the native format of a CAD system is used, it can be assumed that any data that the designer has created will be stored in a native file. This typically includes the part history, features, parameters and capability to modify the part. It is intended to be complete within the CAD environment. If this format, which in most cases will be proprietary, moves through the process, appropriate interfaces for reading the data have to be provided by the downstream process steps.

An alternative is neutral CAD formats. Although the topological and geometric description of the part (e.g. BREP NURBS) are retained, in most cases some information will be lost, e.g. GD&T and certainly (at least today) the anisotropic parameters.

There are several formats related to 3D printing, e.g. STL, AMF, 3MF, that do not store exact geometry but rather a triangulated "mesh" approximating the geometry. In most cases, the recipient will not know the level of precision because it is not included in the file content. The above-mentioned formats differ with respect to the amount of additional information they are able to store, but none of them can store GD&T data or anisotropic material properties, for instance.

### 3.1.2 Process Planning (PP) Single Part

In PP Single Part, manufacturing know-how is applied to the part definition created by the designer. Taking the geometry, material and GD&T definitions into consideration, the part planner selects the appropriate additive manufacturing processes and derives manufacturing parameters such as printing direction and layer thickness from the digital description of the part based on their experience.

All the definitions are made independently of a specific printer since printed parts can be produced individually or in batches together with other parts - something that is unknown at this point. Also unknown is which specific printer will be used to print the part and where in the build volume (what distance from the build plate).

The anisotropic material parameters that the designer has selected are used to derive the printing direction. The part is oriented according to this direction.

Input	Process Step PP Single Part	Output
<ul style="list-style-type: none"> <li>• Metadata</li> <li>• Geometry</li> <li>• GD&amp;T</li> <li>• Material properties, isotropic or anisotropic</li> </ul>	Definition of the part's <ul style="list-style-type: none"> <li>• Printing direction</li> <li>• Support structure attachment</li> </ul>	<ul style="list-style-type: none"> <li>• Metadata</li> <li>• Material definition</li> <li>• Oriented part geometry (print direction)</li> <li>• Support structure attachment points</li> <li>• Printing parameters (layer thickness, etc.)</li> </ul>

Table 5: Process step PP Single Part, input/output data

If the manufacturing process calls for the creation of support structures, suitable attachment points for the structures need to be defined according to the part's orientation. The final geometry of the support structure is as yet unknown since the part is not yet been positioned in the build volume. Printing parameters like layer thickness can be defined, but they can be also left open for the next process step.

In this process step, it may be necessary to modify the part geometry, e.g. if certain aspects of the geometry are not suitable for printing (e.g. wall thickness) or the choice of material has to be changed. This may have a big impact on the capabilities of the part, and a proper organizational framework has to be maintained regarding what validation is necessary after such a change (change management procedures).

Metadata is completed and the data is passed to the next process step. From the end users' point of view, it would be ideal if the information created by the part planner in this step were independent of a specific printer, as this would provide flexibility when planning moves into production. At the moment, this is seldom the case.

	Level of fulfillment	Neutral CAD	STL	AMF	3MF
Information transfer	• Metadata	X	-	X	X
	• Material	X	-	X	X
	• Oriented part geometry	X	X	X	X
	• Support attachment points for part	X	-	-	X
	• Printing parameters	-	-	X	X

Table 6: Process step PP Single Part, examples of format options

In the context of in-house production, printers from different providers may be installed on the shop floor. Currently, if production need to be switched from one printer to another, a great deal of effort is involved as printer-specific preparation is required. If printing is outsourced, the client is also more interested in the quality of the printing result than in the printer used. In both cases, device-specific output imposes restrictions on the transition to production.



**3.1.3 Process Planning (PP) Print Job**

In this process step, all the information is collected and a print file (job file) is created. A print job can comprise a single part or multiple parts. A combination of different part geometries in one job file is also possible.

When nesting parts in the build volume, their positions will differ, which may have an impact on the properties of the same parts at different locations in the volume. Anisotropy has to be taken into account when defining the orientation of a part in the build volume. When support structures are created, the geometry of these structures will depend on the distance between the part and the bottom of the build volume, i.e. the build plate on which the printer starts producing the parts. Support structures are only needed for certain print technologies.

The main parameters responsible for the properties of the resulting part are the material, process parameters, printing direction and layer thickness. They are largely independent of the final position of the part in the build volume, while support structures are not. Surfaces to which support structures can be attached will, for instance, be selected based on surface finishing tolerances.

The parts are nested in such a way that the available build volume is filled as completely as possible. Part orientation and requirements regarding the support structures are always taken into account. The geometry of the support structures can now be created based on the information provided by the preceding process step.

All the requisite process parameters are embedded in the job file. The geometry of the part can now be sliced (creating contours describing the outline of the geometry). Hatching algorithms (defining material deposition in the part’s interior in this slice) are usually used to create the output.

In certain B2B and B2C use cases, it is best to limit the number of parts the recipient can print using a single job file. Solutions for controlling the number of printed parts are already available. They are based on blockchain technology. They must however be implemented in the printer.

Input	Process Step PP Print Job	Output
<ul style="list-style-type: none"> <li>• Metadata</li> <li>• Material</li> <li>• Oriented (printing direction) part geometry</li> <li>• Areas to which the support geometry can be connected/attached</li> <li>• Printing parameters (layer thickness, etc.)</li> </ul>	Definition of <ul style="list-style-type: none"> <li>• Nesting</li> <li>• Support structures</li> <li>• Slicing</li> <li>• Hatching</li> </ul>	<ul style="list-style-type: none"> <li>• Job file (including all necessary process parameters)</li> <li>• Optional: number of parts allowed to be created from job file</li> </ul>

Table 7: Process step PP Print Job, input/output data

When creating a print file, the printer must be known as some parameters are determined by the capabilities of the printer used. Layer thickness, temperatures or the travel speed of the printhead may vary from printer to printer. Therefore, the information created in this step will depend on the printer in question. It would be useful for future scenarios if job files were printer independent as this would provide the flexibility needed to print on different printers. One big advantage this would offer is the option of load balancing. Today, job files are vendor specific as vendors do not want to disclose certain details about their process parameters. Open, standardized data formats do not yet exist. No neutral data format for job files currently exists, which means that all job files are output in a vendor-specific, proprietary file format. However, a wide range of solutions, from simple contour descriptions through to sophisticated, parameter-rich definitions, exist. It could be that a file containing specific geometric information is defined, but if it is not included in the standardized file definition, it is meant to be proprietary.

Technology for limiting the number of parts to be printed is just starting to be implemented commercially.

Level of fulfillment		Neutral CAD	STL
Information transfer	<ul style="list-style-type: none"> <li>• Job file</li> </ul>	X	-

Table 8: Process step PP Print Job, examples of format options

### 3.1.4 3D Printing

The 3D Printing process step creates the physical part. During the printing process, a wide range of process parameters may be recorded (“in-process” parameters), e.g. atmosphere in the printing chamber, grain shape and size in the powder bed, viscosity of expendables, known contamination or defects, and many others.

The process parameters and monitoring data can be stored for later analysis or documentation purposes or can be analyzed during printing.

Input	Process Step 3D Printing	Output
<ul style="list-style-type: none"> <li>• Job file</li> <li>• Optional: Number of parts</li> </ul>	Execution of <ul style="list-style-type: none"> <li>• Material handling</li> <li>• Printing the part(s)</li> <li>• Identification</li> <li>• Print license handling</li> </ul>	<ul style="list-style-type: none"> <li>• Physical part(s)</li> <li>• Recorded process parameters</li> </ul>

Table 9: Process step 3D Printing, input/output data

No standardized specification for recording process parameters in the AM domain exists today. However, there are some formats that can be read by vendors only. To realize the full potential of the as-is process parameters, the information must be available in a way that allows it to be fed it back in optimization loops.

A neutral, open format is useful as it allows the recorded data to be used for a wide variety of purposes, e.g. process optimization or predictive maintenance. If the current values are to be compared with the target values, including a corresponding optimization loop, it must be possible for users to evaluate the input parameters. This is often not the case today.

Level of fulfillment		Neutral CAD	STL
Information transfer	<ul style="list-style-type: none"> <li>• Recorded process parameters</li> </ul>	X	-

Table 10: Process Step 3D Printing, examples of format options

### 3.1.5 Post-Processing

It is recommended that the first step in post-processing involve checking for printing defects such as blowholes to decide whether or not it makes sense to continue with post-processing. If not, the part would be disposed of without starting full post-processing.

Input	Process Step Post-Processing	Output
<ul style="list-style-type: none"> <li>Physical part</li> <li>Geometry of support structure</li> <li>Optional: geometry of raw part/ finished part</li> </ul>	Executing <ul style="list-style-type: none"> <li>Initial quality check</li> <li>Separation of support structure and build platform</li> <li>Surface treatment</li> <li>Heat treatment</li> <li>No AM-specific post-processing</li> </ul>	<ul style="list-style-type: none"> <li>Post-processed part</li> <li>Optional: recorded process parameters</li> </ul>

Table 11: Process step Post-Processing, input/output data

In the case of 3D printing with metal powder, removing the support structures involves a considerable amount of effort. It would therefore be extremely useful if support structures could be removed automatically. In order to be able to distinguish the part geometry from the support structure, the post-processing step requires two kinds of information: the part geometry information from the Design step and the support structure geometry from the Print Job step.

Support structures are typically generated in the print preparation software tool and are converted directly into tool paths. This means that the information about the support structures is available only to the additive machine’s control software. To automate removal, 3D information about the support structures is needed outside the control software so that CNC code for the milling machine that is supposed to remove the structures can be generated. Today, no generic interface for accessing the support structures from the planning software is available on the market.

Furthermore, valuable recorded process parameters might exist. Since post-processing is not regarded as being AM-specific, post-processing parameters fall outside the scope of this document.

Level of fulfillment		Native CAD	Neutral CAD	STL	AMF	3MF
Information transfer	<ul style="list-style-type: none"> <li>3D part geometry</li> </ul>	X (exact BREP)	X (exact BREP)	X (Mesh)	X (Mesh)	X (Mesh)
	<ul style="list-style-type: none"> <li>3D support geometry</li> </ul>	3D representations of support geometry is typically available in the process				

Table 12: Process step Post-Processing, examples of input format options

### 3.1.6 Inspection

The process step Inspection is part of Quality Assurance as a whole, whereas quality assurance is not limited to a single step. It should start during printing, when certain process parameters are monitored and documented to ensure a correct printing environment and printing process. At worst, the printing job can be cancelled before it has been completed so that resources are not wasted. A quality check can be performed prior to the process step Post-Processing, see also “Process step Post-Processing”. AM-specific and non-AM-specific checks can be performed after post-processing.

Input	Process Step Quality Assurance	Output
<ul style="list-style-type: none"> <li>Physical part</li> <li>Part specification of finished part</li> </ul>	Execution of <ul style="list-style-type: none"> <li>AM-specific testing</li> <li>Non-AM-specific testing</li> </ul>	<ul style="list-style-type: none"> <li>Test results</li> <li>Quality report</li> </ul>

Table 13: Process step Quality Assurance, input/output data

Infill geometry cannot be checked as it is created automatically by the software, often after the Design step has been finalized. Therefore, no representation of the infill geometry is available. Like support structures, infill is available only as a tool path not as a solid model representation. This presents challenges at many points in the process. One example is FEM part simulation: it simulates a different geometry to the one that the manufacturer then prints. When quality assurance is performed, no reference is available to which the components can be compared.

The topic infill and inspection throughout the entire process needs to be examined in more detail. On the one hand, infill offers potential in terms of weight reduction for example; on the other hand, adding infill geometry can result in imperfections or gaps as early as in the model definition. Therefore, the desired target geometry must be made available as a 3D model so that the detailed geometry can be checked prior to printing and to verify the printed result.

	Level of fulfillment	Proprietary formats	Neutral standards
Information transfer	<ul style="list-style-type: none"> <li>3D part geometry</li> </ul>	X	X
	<ul style="list-style-type: none"> <li>Test results</li> </ul>	X	X
	<ul style="list-style-type: none"> <li>Quality report</li> </ul>	X	X

Table 14: Process step Inspection, examples of format options

### 3.1.7 Summary of process findings/ recommendations

#### Design

The designer today usually has no information about the capabilities that the printer offers, such as the tolerances that can be achieved or the maximum component size. Although there is a much greater level of freedom than with casting technology, ensuring that the information provided using a specific file format is complete and fully interoperable is today a challenge. Naming the materials is not enough; the final properties of a part also have to be defined. In the case of multi-material parts, there is a lack of implemented formats that cover these capabilities. Such formats must be available if the potential that AM offers is to be exploited.

### Process Planning Single Part

It is intended that the result of this step be printer independent. Print preparation is divided into two steps: single part and job creation. When defining attachment points for support structures, it is useful to have exact B-spline-based geometry including PMI information. This makes it easier to decide where to position the support structures. It is therefore recommended that not just tessellated geometry is used. A 3D master concept that includes all the information in 3D models would be an appropriate approach. As there is no standard format that includes all the required content, we recommend using precise geometry formats for as long as is reasonable.

### Process Planning Print Job

The information created is printer dependent. As a future option, it would be advantageous to generate printer-independent information in a standardized form that is interpreted by the printers, e.g. load balancing for in-house or external manufacturing could be improved significantly. It is recommended that the option of limiting the number of parts to be printed be included in the overall printing process. It is also recommended that the potential offered by the current blockchain approach be analyzed in detail. There is currently no neutral data format available; all job files contain some vendor-specific information.

### 3D Printing

No standardized and open interfaces/formats that would enable both users and system providers to evaluate data and feed it back into the loop are currently being used for writing recorded process parameters.

### Post-Processing

In post-processing, there is a need to have support structures removed, preferably automatically by machines. In the future, the required 3D part geometry and the geometry of the supports must be made available in a format that allows the process to be automated.

### Inspection

In the process step Inspection, it is important to distinguish between inspecting quantitative aspects of the part (dimensions, tolerances, surface finishes) and qualitative aspects of the part (holes, gaps, defects, etc.). In the first case, a detailed part description that includes PMI is required. In the second case, approximated geometry is sufficient. This is required for validating the manufactured part. This becomes an issue when the infill geometry is created when the print job is created, because the infill geometry is represented only as tool paths, without any additional PMI information. This makes a quantitative inspection impossible.

## 3.2 Security considerations

### 3.2.1 AM Interfaces data security problems

Interfaces enable interoperability and facilitate data transfer across AM workflows, manufacturing systems and organizational boundaries. At the same time, they create potential for data-specific attacks like the following:

- Impersonation attacks
  - A data receiver is impersonated by an attacker for the purpose of stealing confidential information from an unsuspecting data sender via an interoperability channel
  - A data sender, compromised or impersonated by an attacker, is feeding back bad/compromised data to a data receiver via an interoperability channel
- Attacks on an ignorant or unaware data sender, resulting in compromised data that is passed by a data sender to a data receiver

- Attacks focused on exploiting interoperability interfaces
  - Unauthorized modification of an interoperability interface in order to gain access to additional information from a data sender
  - Introduction of malware at an interoperability interface results in a malware attack on a data receiver
  - A data eavesdropping attack at an interoperability interface results in a confidential data leak
  - A data tampering attack (e.g. malicious destruction, manipulation, editing) at an interoperability interface results in bad/compromised data sent to a data receiver and many others.

### 3.2.2 AM Interfaces data security problems

Interoperability interfaces must be designed to protect:

<b>Data confidentiality</b>	the confidentiality of sensitive data (high-value proprietary data and intellectual property), such as 3D designs and manufacturing data
<b>Data integrity</b>	the integrity of 3D designs and manufacturing data to ensure they are not tampered with throughout the entire AM workflow, can only be modified by authorized participants/roles, and that any modifications can be validated, verified and attributed
<b>Data availability</b>	all the information required to execute a particular process or operation to ensure that it is available to the authorized parties when required and that manufacturing processes are not delayed or impeded

### 3.2.3 Access control

In view of the highly sensitive nature of the AM data being transferred between entities/processes via AM interfaces, the information should be shared on a need-to-know basis. This means that processes must be assigned roles so that they are only given access to the information they require when that information is needed. Data can be created and subsequently modified by an authorized process, but the creation of new data and the modification of existing data must be validated, verified and attributed to an authorized process and corresponding role.

Functionality and the access required are represented by the triad CRU, where

C = create

R = read

U = update, modify, adjust

Any missing property is indicated by "-". Thus, for example, -R- means read only access, -RM means read and modify access and so on. When read access is involved, a distinction can be made between a high level of detail or simplified information.

Here we make a distinction between the following data operations:

- creation with proven data origin
- authorized modification with attributed tracking
- read only access to information without ability/right to modify data

as summarized in Table 15.

	Process Roles	Data access on				
		Part specification	Part specification	Part specification	Part specification	Part specification
1	CAD Designer	CRU	---	---	---	---
2	Part Planner	-R-	CRU	---	---	---
3	Job Planner	-R-	-RU	CRU	---	---
4	3D Printer Operator	---	---	-R-	---	---
5	Operator Post-processing	-R-	---	-R-	CRU	---
6	Quality Operator	-R-	---	---	---	R

Table 15: Process roles and process data

**3.2.4 Summary of security findings/ recommendations**

Due to the heightened risk identified with regard to AM/DM technology (safety, part quality concerns), we recommend that the principle of least privilege be applied to ensure adequate data security. This means that an AM service, machine or user is given the minimum access required to perform their tasks. Minimal access might also mean that original confidential data can be reduced or replaced by proactively prepared metadata to enable some steps to be executed without the need for confidential data. In the context of nesting, for example, it might be sufficient to use a bounding box or the tighter enclosure of an object without revealing the actual geometry, thus allowing it to remain encrypted during nesting. This eliminates potential confidentiality problems and risk when creating a 3D build (nesting).

Participation in B2B and B2C implies that information is communicated across organizational boundaries, especially use case 4 (section 2.1.4) and use case 5 (section 2.1.5).

**Cryptographic identities of participants:**

Establishing secure cryptographic identities for all participants – users, machines, services participating in a workflow via AM Interfaces.

It is recommended that the identity of each participant be known to all relevant parties and be a dual cryptographic identity comprising both a

- signature validation certificate, linking the public signature validation key of the participant to the corresponding verifiable [known] identity (e.g. e-mail, affiliation) and
- encryption key certificate, linking the public encryption key of the participant to their known identity (e.g. e-mail, affiliation, website)

## Data integrity and provenance

In addition to certifying the information, it also needs to be tracked so that not only its integrity but also its authenticity and full provenance can be established in multi-party, multi-hop workflows across organizational boundaries and AMI interfaces.

- Supporting the ability to communicate confidential data to a specific recipient (not necessarily the next workflow step) – based on public encryption key of the recipient.
  - a. A sender should be able to accurately identify the public key of a recipient and encrypt all confidential content accordingly.
  - b. It might be that multiple recipients receive the same contents – access should be provided to each recipient individually.
  - c. Data sensitivity and reduction analysis should be performed in order to
    - i. identify what information is actually required to perform a task, and whether confidential data can be effectively replaced by proactively created metadata for some steps
    - ii. separate confidential/private data from non-confidential data
    - iii. separate confidential data according to the recipient
  
- Supporting the ability to verify the integrity and origin of communicated data

To ensure information integrity, verifiable origin and provenance, any party tasked with creating or modifying data must certify (sign) the data created or modified using their encryption identity.

To protect data, any party communicating confidential data must encrypt it using the encryption identity of the recipient.

## Recommendations:

### 1. Confidentiality

The sender of confidential data needs to establish the encryption identity of the recipient (e.g. X509 cert) and encrypt all the confidential data elements. The recipient could be in the next or any subsequent workflow step.

### 2. Integrity/origin

The sender needs to certify (sign) all created/modified data so that subsequent participants can validate the origin of data creation/modifications as well as its integrity.

### 3. Integrity

The sender must certify (sign) all communicated data (confidential or not) before communicating it via an interface. The recipient must check the integrity and origin of received data prior using the data.

### 4. Data handling

Data needs to be categorized according to sensitivity and roles (creator, editor, viewer), and security protection applied accordingly.

### 5. Reducing attack surface

The number of access points to sensitive data needs to be kept to a minimum to reduce the potential attack surface.

### 6. Data reduction

Re-evaluate the reason for providing access to confidential data in each workflow step and where possible replace it with aggregated or reduced metadata that has been proactively prepared.



### 3.3 Findings regarding AM interfaces

#### 3.3.1 Main forward-directed data flow in/for AM

When examining the main forward-directed data flow in the AM reference process (see Figure 1), three main data interfaces can be identified (see Figure 3):

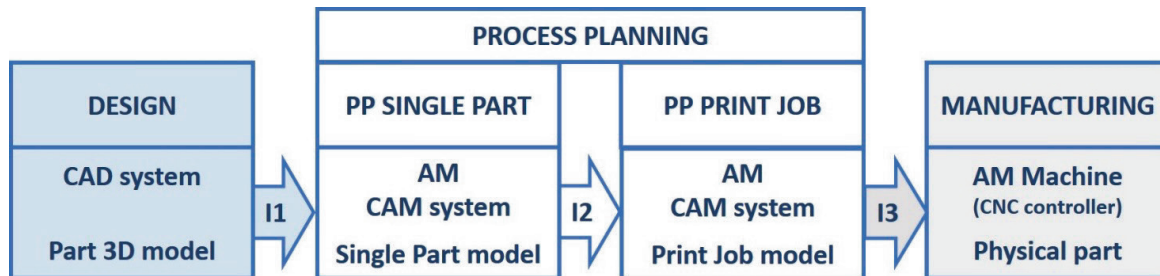


Figure 3: Interfaces in the main forward flow of the AM process

The first data interface (I1) is relevant when importing the part specification into the Process Planning Single Part step (Figure 3). The Process Planning Single Part step may vary depending on the tasks executed in the Design step (e.g. if Design for AM practices have already been applied), the design of the part and the AM technology to be used (e.g. extrusion-based or powder-based). Process Planning Single Part may involve defining how the part should be oriented for the AM process, machining offsets for surfaces with tolerances that requires post-processing (machining), shutting/closing holes to be machined (post-processing), lattice and infill structures, shells and surface textures, generating support structures, defining exposure/printing strategies, calculating scan paths and slicing (see section 2.2). The origins and development of the AM technologies often mean that Process Planning Single Part is executed using an application proprietary to the AM machine manufacturer where the part will be produced.

In the Manufacturing step, AM technologies allow for combining multiple materials or functionally graded materials when creating the physical part. Unlike other part manufacturing methods that involve additional processes, e.g. a thermal process or a surface-coating process, AM allows parts to be manufactured without additional processes and in a much more flexible way, e.g. components that have different areas with different materials and therefore properties. In the Design step, one research issue is how to define these areas when creating the 3D solid geometric model of a component. This issue is discussed in section 3.3.3. It has also an impact on the data interface I1, since the I1 data interface needs to support the exchange of this type of information (see section 3.3.2).

As presented in section 3.3.2, the stereolithography process, an antecedent to current AM technologies, determined one of the main formats used for this interface (STL), which became a de facto standard (Kai et al., 1997; Qin et al., 2019). The main implications of using the STL format and other formats developed later (e.g. AMF and 3MF) as input for Process Planning Single Part are described in more detail in section 3.3.2.

It is important to point out that the Process Planning Single Part step comprises not only tasks related to the geometrical definition of the part and support structures but also to the definition of the process parameters, which are grouped within the definition of exposure or printing strategies (see section 2.2.2). Depending on the selected material, certain parameters inherent to the material will affect the AM process, e.g. thermal conductivity, specific heat capacity, specific weight, melting temperature, etc. In the case of powder-based processes, the powder particle size and shape also affect powder flow behavior and its packing density. This means that the process conditions must be adapted to the selected material, both in terms of its composition and its physical state. For instance, in a selective laser melting (SLM) process, the main process parameters are layer thickness, hatching distance, scanning speed and laser power. Therefore, the information to be transferred to the subsequent step comprises geometrical information and manufacturing process-related information (Kim et al., 2015).

It is worth mentioning that, when analyzing the AM software context, the current situation can be represented as shown in Figure 4.

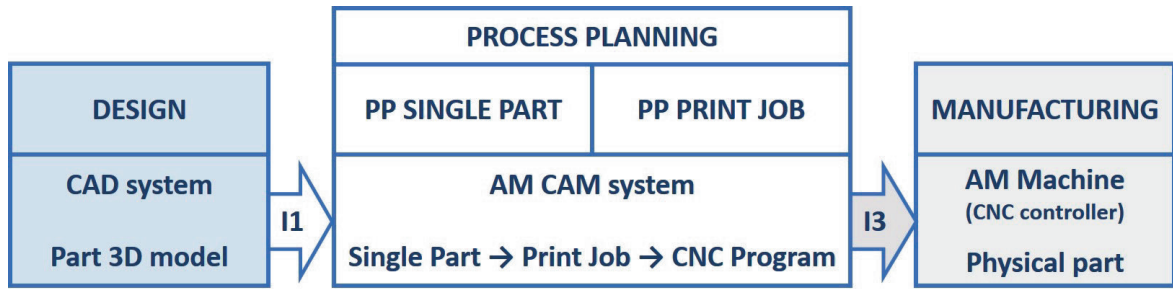


Figure 4: AM software context and main interfaces

Generally speaking, AM involves a set of relatively new technologies, which means that the AM software context is still evolving. In some ways, it is coming to resemble the market situation in conventional manufacturing, where a distinction is made between two different types of software tools: CAD for product design and CAM for manufacturing process design. Different actors (e.g. AM machine manufacturers, traditional CAX/PLM software vendors, new AM CAX software vendors, hybrid CNC machine manufacturers) are positioning themselves in one or both arenas. This situation has an impact on the need for interfaces.

The following is an example that illustrates the situation: AM machine manufacturers provide AM CAM systems (e.g. Ultimaker Cura, Stratasys GrabCAD); new specific AM CAM applications (e.g. Materialise Magic) support process planning, print job creation and communication with the AM machine; some CAX authoring tools vendors already provide CAD and CAM tools for AM (e.g. Siemens PLM, Dassault Systems, DP Technology, OPEN MIND); and new capabilities that are not available in conventional CAD tools are being integrated in new AM CAD tools (e.g. GramMaCAD, for information on defining material gradients in CAD models, see Section 3.3.3.3).

The CAM tool comprises both the process planning step and the print job creation step. Only when both the AM CAD and AM CAM applications are fully integrated by means of native CAD data files is there no loss of information. If the AM CAD application and the AM CAM application are independent of each other, the CAM application can accept not only the approximated geometry as input but also an exact part geometric model by importing native CAD data files or neutral 3D models (e.g. STEP). This avoids the problem that the part geometric model is less accurate. The development of hybrid CAM applications for AM is being driven by the development of hybrid CNC machines that combine both AM (laser metal deposition) and metal-cutting (milling) (e.g. by DMG MORI).

The second interface (I2) is relevant when importing the outcome of the Process Planning Single Part step to Process Planning Print Job Creation. If both steps are executed using the same AM CAM tool, there is no such interface as shown in Figure 4. Process Planning Print Job Creation involves combining several individual parts to be manufactured in a single AM job. The input format could be a native CAM file or a layer file (e.g. in CLI format). Since multiple parts can be manufactured together in the same AM job, multiple files generated during the Process Planning Single Part Step may need to be imported. The nesting of the parts involves the complete definition of the support structures and the alignment of the parts to fully utilize the capacity of the selected AM machine. However, it is worth noting that only if the native CAM file created in the previous Process Planning Single Part step is used will no manufacturing information be lost. Currently, apart from native formats, only the 3MF format and the AMF format provide a solution for exchanging AM information that includes the interfaces I1 and I2.

The third interface (I3) is relevant when exporting the outcome of Print Job Creation and importing it into the AM machine. The information required in the Manufacturing step relates to scan paths and process parameters. When the AM CAM application used is from the same company that manufactures the AM machine, then a specific proprietary format could be probably used. When using Stratasys GrabCAD voxel printing, for example, the interface is a proprietary format (\*.GCVF). If this is not the case, then a flavor of the G-code file (ISO 6983) is the format used. G-code is the computer numerical control (CNC) programming language typically used at tool path level to control metal-cutting and hybrid machine tools. Different flavors of G-code are also supported by AM machine controllers. Although CAM applications usually output a G-code flavor, it might also output a company specific-format.

It is worth mentioning that, in the context of CNC machines for material removal, the creation of G-code by a CAM application requires a piece of software often referred to as a “post-processor”. The post-processor is configured according to the specific characteristics of each machine, e.g. axes configuration, axes stroke, speed ranges, etc. The role of the post-processor is to generate the appropriate G-code flavor for each specific CNC machine.

It is important to note that the G-code is at path level and the dynamic behavior of the machine axes drives (e.g. acceleration, deceleration, inertia affecting positioning error) is not taken into consideration when the G-code is created using a conventional CAM program. An alternative is to use path optimizer software. A different approach is the use of adaptive control units, which take account of real-time operating parameters and compensation is executed using a closed-loop feedback system provided by the CNC machine manufacturer and integrated in the CNC controller. This means that the G-code generated by a CAM program requires further processing prior to the real-time execution of the path. The relevance of the dynamic behavior of the machine and of the closed-loop feedback system for AM machines is even greater, since several types of compensation (e.g. dynamic behavior of the machine, part deformation and real-time operating parameters) must be determined prior to the deposition of material when executing an AM path. The manufacturer of the AM machine decides how and where to locate the systems designed to perform such compensation. This could be two systems, one external to the AM machine CNC controller itself and one (operating closed-loop feedback) in the CNC controller. This situation may be the reason why most of the high-end AM machine manufacturers have opted for a proprietary solution when communicating the Print Job outcome to the machine controller.

### 3.3.2 Summary of AM exchange formats and their limitations

First of all, it is important to mention that the way in which part manufacturing is executed (mostly layer by layer), the way in which the technology and manufacturing machines are developed (with proprietary applications from each machine manufacturer) and the need to export the part geometry from the authoring CAD tool so that it can be imported into the AM process planning tool, have all had an impact on the interoperability solutions and data formats developed for AM. Each data format specifies the AM data to be exchanged and its syntax. There is quite a wide variety of formats that can be classified using different criteria. In this document, we have used the classification scheme adopted by (Qin et al., 2019), where the formats are divided into three main groups

1. based on 3D approximated geometry (e.g. STL, AMF and 3MF)
2. based on 2D slice geometry (e.g. CLI and SLC)
3. based on integrated product model data (e.g. STEP)

Section 0 (Appendix) provides a summary of the AM formats. In this section, we focus on formats that offer wider implementation and formats that are subject to ongoing development.

**STL** (STereoLithography) is a file format that was developed by 3D Systems (Kai et al., 1997) and adopted as the de facto standard within the rapid prototyping (RP) and AM communities, and to some extent this is still the case. It only provides an approximated geometry with lineal triangular patches that define a mesh for the part. It does not allow colors, textures, materials or any other properties of the part to be represented. The limitations of the format regarding the resulting model accuracy, redundant data, geometric quality issues and the lack of material information have been widely acknowledged in the relevant literature, e.g. (Kai et al., 1997; Jurrens, 1999; Hällgren et al., 2016; Altenhofen et al., 2018; Qin et al., 2019).

**AMF** is an international standard that comprises data about geometry with curved triangular patches, mixed and graded materials, porous materials, stochastic materials, color gradations, texture mapping, texture specification, constellations and metadata (ISO/TC 261, 2020).

**3MF** is an AM geometry-based specification developed by an industrial consortium that comprises data about geometry, topology, materials and properties, lattice structures, slices and build information to support cross-printer and cross-print-job identification. It is not intended to support any data related to exact geometry definition (e.g. NURBS), AM processes or how to manufacture a part (3MF, 2020).

The exchange of slice data was taken into consideration as an alternative to the STL format because most AM processes are executed in slices or layers. This approach led to the development of several formats (e.g. CLI and SLC) (Kai et al., 1997; Qin et al., 2019). However, most of these formats only support the use of polyline entities (segments of straight lines) for defining contours and thus do not offer any advantage over STL in terms of accuracy.

When it comes to integrated product model data, ISO 10303 (STandard for the Exchange of Product model data - STEP), which comprises multiple parts, is the most comprehensive and widely accepted standard. Some parts constitute a library of definitions, the STEP Module and Resource Library (SMRL), other parts comprise application protocols. An application protocol (AP) specifies the information requirements for an engineering application context. An initial attempt to use STEP in the AM context was presented in 1994 (Kai et al., 1997). In 2002, the use of a STEP faceted boundary representation to replace STL was proposed by the STEP community (Patil et al., 2002; Pratt et al., 2002). Some of the relevant literature also propose an alternative that involves representing inhomogeneous and non-isotropic materials in STEP (Patil et al., 2002; Pratt et al., 2002).

The STEP community is currently addressing AM from two different perspectives: design and manufacturing. From the design perspective, in addition to the tessellated geometry supported by AP 242 ed. 1, the objective is to include information about the definition of the part build orientation and position on the build plate, definition of the required minimum manufacturing build volume and identification of the support structure geometry (STEP AP242 Project, 2020) in AP 242 ed. 2. According to the STEP AP242 project community, there are three main aspects related to AM that could be taken into consideration for STEP AP242 ed. 3: heterogeneous materials, representation of lattice structures and the semantic representation of product manufacturing information (PMI) for AM (STEP AP242 Project, 2020). From the manufacturing perspective, the STEP-NC community has defined a new standard part related to process data for AM (ISO/TC 184/SC 1, 2020) in the context of data models for computerized numerical controllers. The aim of this part is to describe AM at micro process planning level independently of any specific machine, process or technology.

Regardless of whether a format supports 3D approximated geometry (STL, AMF, 3MF) or 3D BREP NURBS (STEP), the ability to represent and thus exchange information about multiple and/or functionally graded materials is a common issue. The formats that are currently the subject of ongoing development, such as AMF, 3MF and STEP, aim to address this problem. For instance, 3MF provides a solution for assigning a material to the whole object or at the triangle level. The roots of this problem not only lie in the AM exchange format itself but also in how current 3D geometric modeling techniques enable the modeling of locally varying material information in a 3D part. This is discussed in the section 3.3.3 below.

		AMI INTERFACES			
		I1 (From Design to PP Single Part)	I2 (From PP Single Part to PP Print Job)	I3 (From PP Print Job to Device Controller)	
STANDARDIZED FORMATS	AM data exchange	STL de facto	Approx. Geom. - lineal triangular patches / Limited model accuracy / Redundant data / Geometric quality issues / No material data / No PMI data / Surpassed by AMF and 3MF	N/A	N/A
		AMF ISO/ASTM 52915	Approx. Geom. - curved triangular patches / Limited model accuracy / Material data / Graded, porous, stochastic materials / Colour gradations / Texture data / No PMI data / XML-based / It can be compressed into a ZIP file.	Provides the constellation concept to arrange several objects to be printed.	N/A
		3MF industrial consortium	Approx. Geom. - curved triangular patches / Limited model accuracy / Based on objects to be printed (e.g. solid, model support) / Material data can be assigned at the object and triangle level / No PMI data / XML-based / Document package: ZIP compressed file. It comprises a mandatory 3D Model Part file (start part/root) and optional files (i.e.: print data, textures and digital signature).	Several parts can be included in a compressed 3MF file together with print job control instructions / A Print Ticket contains parameter and printer specific information / It provides settings to be used when outputting the 3D object(s) / The Print Ticket can be customized for each AM machine, which may result in semantic incompatibility when aiming to create a neutral file for several AM machines.	N/A
	Product data exchange	STEP ISO 10303	STEP AP 242 / Exact Geom. B-rep based on NURBS / Approx. Geom. - triangular patches / Single material data / Currently it does not support multi or graded materials / PMI data are supported / Information structures needed for AM are under development, e.g.: build direction and support structure / STEP file and XML.	STEP AP 242. Information structures needed for AM are under development / It is not clear when this development will be finalized and implemented in commercial translators.	STEP NC-Code for AM. ISO 14649-17:2020. Part 17: Process data for additive manufacturing / It is not clear when this development will be implemented in commercial translators.
	3D & PMI visualization	JT ISO 14306	Exact Geom. B-rep based on NURBS / Approx. Geom. - triangular patches / It provides visual attribute elements (e.g. colour, texture, material, lights, etc.) that are objects associated with nodes / PMI data are supported / No information structures specific for AM / XML-based.	N/A	N/A
Numerical Control of Machines	G-Code ISO 6983	N/A	N/A	Generated from a slicing software after the print job is defined / Different flavours of the G-code are implemented by different AM equipment manufacturers / Mainly used in hybrid machine tools (cutting and additive) and low-cost AM based on open source.	

Table 16: Summary of the findings on the standardized formats for each interface

When it comes to selecting an appropriate interface solution for a particular scenario, we recommend that an analysis be performed to evaluate how to achieve the best balance between loss of information, security and translation resources for that particular case.

As a summary of this section, and taking the main characteristics and status of the standardized formats and the level of industrial support that they exhibit into consideration, we can provide the following suggestions for each interface:

**1) Interface I1**

- a) In order for there to be no loss of information, the best alternative is to use the original formats in which the 3D part model was created.
- b) The formats 3MF and AMF are an appropriate alternative if the original formats cannot be used and an approximated geometrical definition without PMI information is acceptable.
- c) If the original formats cannot be used and an exact geometrical definition and PMI information are required, the only alternatives are the formats STEP AP242 and JT.
- d) Use of the STL format should be avoided due to its limited model accuracy, its geometric quality issues, its lack of support for material and PMI data, and the fact that it has been superseded by 3MF and AMF.
- e) An in-depth analysis of the multi-material capabilities of the available formats is needed.

**2) Interface I2**

- a) If a native format cannot be used and an approximated geometrical definition is acceptable, the first option would be to use the format 3MF. The format AMF is also an alternative.
- b) An in-depth analysis is needed to identify exactly which of the information used and generated during the PP Single Part step needs to be transferred without loss to the PP Print Job step using the current formats.

**3) Interface I3**

- a) Solutions for this interface tend to be proprietary formats when dealing with AM machines in the high-end market segment. On the other hand, when AM machines in the low-end market segment are involved, the solutions are mainly based on the use of G-code flavors.
- b) An in-depth analysis is required to identify the detailed requirements for this interface.

### 3.3.3 Parts with multiple and/or functionally graded materials

Modern multi-material 3D printers make it possible to print parts using different materials in different areas. Experiments also indicate that parts with different properties in different areas can be manufactured using additive technologies and just a single material by varying the process parameters during the job.

Functionally graded materials are nothing new: hardening steel parts manufactured using traditional subtractive technology is a well-known example. Multi-material additive manufacturing simply adds another dimension of flexibility beyond the purely geometric one. 3D-printed parts using graded materials offer a wide range of new applications, be it with regard to mechanical properties, e.g. incorporating soft, dampening elements in a single part without needing to assemble it, in high-frequency antenna design, 3D printing of prostheses using ceramics to name just a few. The following figure shows a few examples of multi-material 3D parts.



Figure 5: Examples of multi-material 3D parts.

A helmet printed using different colors (Stratasys), a yin and yang medallion with different materials used for relatively large areas (aerosint), and a part with smooth, functionally graded materials with different elasticities used in different areas (Fraunhofer IGD)

A growing number of AM machines and technologies are being brought to market that support the use of more than one material or provide interfaces so that the parameters can be varied locally within the part during a print job in order to influence the properties of the resulting part.

This gives rise to the question of how to “model” locally varying material information for a 3D part.

The answer is no trivial matter and can be divided up into sub-questions related to the representation scheme of the CAD part (1), the functional or interactive definition of the material distribution (2) and the data format to transfer the information to the actual 3D printer (3), respectively.

### 3.3.3.1 Representation schemes

The traditional representation scheme used in CAD is boundary representation (BRep), i.e. the surface of a part is described by a set of (freeform) faces that are stitched together – the configuration of these faces separate the inside of the part from the outside. Freeform faces are typically represented as non-uniform rational B-splines (NURBS). NURBS surfaces belong to the class of tensor-product surfaces and require trimming if holes are present in the face’s interior (inner loops). If a geometry is to be printed using different materials in different areas, the CAD part needs to be segmented – which implies the more areas (segments), the more manual work involved. Creating smooth gradations from one area to another one is not possible using this approach.

An alternative approach has been developed in the context of AM, namely voxel (volume elements). Voxels discretize the CAD part that usually contains smooth continuous freeform surfaces in a (typically large) set of individual elements (note the similarity to finite elements in numerical simulation). Attributes such as material information can be assigned to each individual voxel or even the corner vertices of voxels and be interpolated from there. Similar to the planar approximation of a freeform surface by triangles in meshes, voxels are another discrete approximation to the continuous nature of the CAD geometry. Voxelization therefore entails a loss of information. Whenever the CAD geometry changes, the process of voxelization has to be repeated and the material information assigned to the voxels (but not to the CAD model itself), needs to be maintained (propagated from the former model where possible or completely re-generated again – in the worst case, fully manually).

Trivariate spline volumes (as used in the IGA (iso-geometric analysis) community), subdivision solids (SDS) and signed distance fields (SDF) are three alternative representations that are currently being explored in research and AM-centric geometry modeling systems. These alternatives are not compatible with conventional BRep-NURBS geometry. All three representations have their own strengths and weaknesses. A discussion of these strengths and weaknesses falls outside the scope of this recommendation. What they all have in common is the ability to represent smooth gradations of properties in volumes, but with a varying degree of flexibility. In any case, all three can be used as a representation that exists in parallel to BRep-NURBS models describing volumetric variations of properties such as material (superposition principle).

### 3.3.3.2 Interactive or functional/procedural definition of material distribution

In the previous section, it was pointed out that assigning multiple materials to traditional CAD BReps is a tedious task and limited to discrete approximations of smooth transitions if no extra measures are taken.

Since voxels are a discrete decomposition of the CAD geometry, assigning materials/material properties is straightforward. It is also easy to voxelize a CAD geometry into a simple regular grid in automatic processes. The challenge here is the sheer number of voxels needed. 3D printers may require hundreds of billions of voxels for one part (if voxelization is done to the level of printer resolution). Interactively assigning material information on a per-voxel basis is completely impractical from a user’s perspective. User interfaces, scripting and/or computational approaches are needed to counteract this impracticability.

Trivariate spline volumes and subdivision solids (SDS) are alternative representation schemes that aim to represent the smooth surface of the part and at the same time provide a smooth volumetric parameterization of the part’s interior using the same mathematical basis. Unlike voxels, these two representation schemes do not linearly approximate the shape but instead represent the continuous shape (some limitation may apply to SDS). They provide control points

similarly to NURBS surfaces to model the geometry with as small a degree of freedom as required by the shape. Control points in the volume's interior can be used to model smooth material gradations. The number of control points can be minimized with respect to the shape/material frequencies that the designer likes to model.

Conventional CAD does not provide appropriate user interfaces/interaction techniques to specify material properties efficiently for voxels and smooth volumetric representation schemes - it does not support them as a representation scheme.

All representation schemes can be combined with simulation and optimization techniques to "find" (determine by many calculations, e.g. design of experiments) material distributions that are fit for a distinct purpose defined as constraints placed on the optimization problem.

### **3.3.3.3 Data format for transferring functionally graded information to the actual 3D printer**

As mentioned earlier, as things stand today, STL is still the dominate data format for the interface to AM machines. As STL lacks the ability to express functionally graded properties, some AM machine manufacturers provide software tools for adding this information during pre-processing, prior to actually printing the part.

However, if geometric modeling systems (CAD tools) are enhanced to generate smoothly graded volumetric parts, data formats that transfer this information to the AM machine will be needed. This fact has been recognized by the community, and several improvements have been developed - and are being developed further - that compensate for this shortcoming.

In addition to STL, the other two leading formats are 3MF and AMF (see also section 3.3.2) - although the relevance of latter appears to have decreased in recent years. It is worth noting that there are many other formats from the CAD and visualization communities that are used to some extent throughout the digital AM pipeline, e.g. STEP, JT, X3D, OBJ, native CAD file formats, etc.. They cannot typically be processed directly by AM machines and are therefore not discussed here. For a more in-depth analysis, please see a recent publication [3] with an extensive study of representation schemes and formats in AM ranging from STL to trivariate representations. However, subdivision-based approaches recently presented by Fraunhofer IGD are not covered in this study. They therefore referenced here explicitly [1,2].

One of the differences between AMF and 3MF is that AMF introduced curved triangles to better approximate the actual CAD geometry using a smaller number of triangles. 3MF currently lacks this feature. However, 3MF not only receives much broader support from industry (3MF community) than AMF but also makes it possible to represent graded material/property information. Of course, being based on a discrete approximation to the geometry, the information modeled, e.g. in a trivariate spline approach, needs to be mapped and a certain approximation error cannot be avoided, but describing fine-grained graded properties becomes possible.

However, 3MF still requires geometric tessellation, which entails approximation errors and potentially increases the size of the files to be exchanged with the AM pre-processing tools. From a scientific point of view, it is still recommended and a worthwhile objective to "tessellate" the continuous geometric representation of a CAD model as late as possible in the process, e.g. on the computer running the AM machine, with printing resolution. This also means that features known to the CAD representation, e.g. cylindrical holes, etc., are not lost and printing strategies can take them into account.

This strategy, namely to "discretize as late as possible and with printer resolution", is followed by Fraunhofer IGD and explores two alternative approaches:

1. subdivision solids and
2. traditional CAD models (NURBS BReps) augmented with graded material information (GraMMaCAD).

1. For modeling subdivision solids with smooth volumetric material gradients efficient slicing has been introduced [1]. These parts are currently being printed with multi-material printers from Stratasys that provide multiple primary materials. Since each voxel in printer resolution can be occupied by one primary material only, the possibly continuous locally varying properties in the 3D model need to be approximated by the deposition of different primary materials in a way that approximates this property over a small region - a technique known from 2D printing called dithering or half-toning. Fraunhofer IGD's universal 3D printer driver cuttlefish is used to calculate the half-toning (<http://www.cuttlefish.de>). Stratasys' VoxelPrint interface is used to transfer the data to the AM machine.



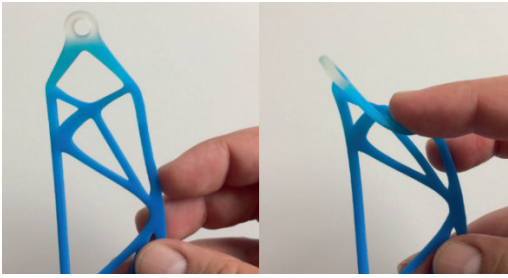


Figure 6: Example of a subdivision solid model with graded material properties (© Fraunhofer iGD)

2. In GraMMaCAD (<https://www.igd.fraunhofer.de/en/projects/grammacad-graded-multi-material-cad>), a similar technique is used to print BRep CAD models enhanced by smoothly graded material properties. However, for efficiency reasons, the CAD model is tessellated beforehand in a user-selectable resolution that can be selected to yield errors smaller than printing resolution. Slices are calculated taking the tessellated geometry and the functionally graded material distribution into account. Again, the information in each slice is half-toned and transferred via VoxelPrint to a Stratasys machine.

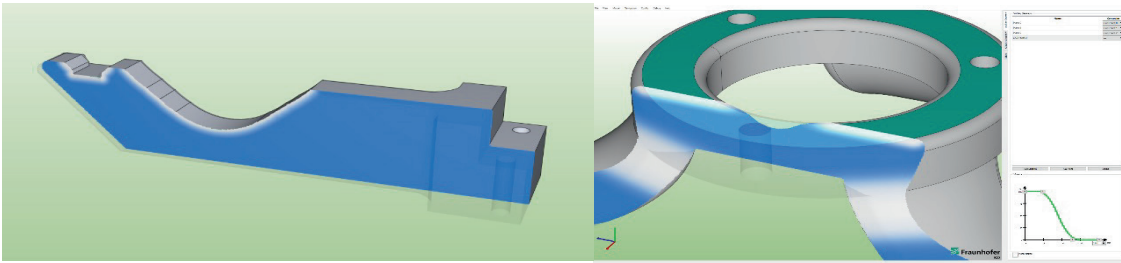


Figure 7: Examples of CAD models (NURBS BReps) modeled with commercial CAD systems enhanced with smooth material gradients in GraMMaCAD (© Fraunhofer iGD)

Please note that the approach does not depend on a specific machine manufacturer. Similarly, it could be mapped to control codes such as G-code and/or CLI if the AM machine manufacturer provides access to this level. Experiments have shown that this type of mapping is possible for machines with open interfaces. For instance, it was shown that metal printing can generate anisotropic properties within the same metal material by changing process parameters across or within layers. Very recent developments also demonstrate the feasibility of multi-metal printing for powder-based laser systems (<https://3dprint.com/264346/aerosint-achieves-multi-metal-powder-bed-fusion/>).

### 3.3.3.4 Findings with respect to multi-material 3D printing

The AMI working group is mainly concerned with interfaces along the AM process chain. The objective of multi-material 3D printing is to vary the properties of a part locally, i.e. visual or physical properties. This makes it possible to create parts that have different colors in different places, parts that are stiffer in some places and softer in others, or parts that conduct current in some places and isolate in others. The properties can be varied by using multiple materials but also by varying the parameters of the printing process for single-material 3D printing. The variation of properties can be discrete or (quasi-)continuous. Thus, multi-material 3D printing and multi-property 3D printing pose challenges for different kinds of “interfaces”:

- the user interface of a geometric modeler or pre-processor for 3D printers to allow for definition of this kind of properties in a CAD model/geometry representation,
- the interface of the 3D printer itself so that process parameters can be varied for inputs that define locally varying properties and
- the data being exchanged between these two interfaces; the file format used to transfer the information.

Because data formats in 3D printing are ever evolving, it is difficult to say at any one point in time which modern data formats might be able to provide support for the (continuous) variation of properties in the future, and whether the form of representation can be loaded back into a CAD system so that it can be adapted.

Of the three data formats that we have analyzed more closely in this recommendation, 3MF comes closest to being able to transfer this type of information. AMF has not been widely adopted, and STL is far from being able to transfer locally varying properties unless each subpart with a single property is expressed as a single STL. In the case of many printers, e.g. for multi-material FDM, this is currently the way users and 3D printing service providers have to work. In some cases, the shape of the subparts has to be modified slightly to ensure that the printed part does not fall apart – an extremely tedious process.

In addition to the file format itself, the printer also has to be able to support it, i.e. the pre-processor may need to map the expressed/intended properties to the capabilities of the 3D printer, e.g. by mixing primary materials, varying properties, etc.

The user interfaces of modeling tools need to be extended to help the designer distribute properties volumetrically. Deciding which material should be used where to achieve a certain local property and thus the behavior of the object as a whole can prove extremely challenging for the designer.

One way to tackle this challenge in the future is to allow designers to specify the intended behavior and shape and then let an algorithm use simulation and optimization technology to calculate which property to use and where. In other words, a kind of topology optimization that focuses on property distribution instead of on geometry modification, as is the case with original topology optimization.

This discussion reveals that there are still some fields that require further research and development, especially when it comes to multi-material and/or multi-property 3D printing:

- modeling tools
- representation schemes that handle property variation as an intrinsic part
- information exchange formats (files/streams)
- interfaces and functionalities of 3D printers
- simulation and optimization for goal-oriented property distribution

## 4 Conclusion and outlook

3D printing technology is becoming increasingly important in discrete manufacturing due to the possibilities it offers in terms of geometry generation, topology optimization and flexible fields of application. The embedding of the work method in the IT environment requires the digital mapping of all necessary information. As things stand today, not all of the required information is available digitally or the clarity of the information is not specified. Often, the quality of the results is only ensured by the transfer of additional information via telephone and e-mail.

In the context of prototyping, it was initially the speed that made additive manufacturing attractive. In addition to the production of prototypes, it also is intended that AM technology be used in series production in an increasing number of areas. On-demand production of spare parts and individualized products are examples. A key challenge is the ability to generate a complete and unambiguous digital description of the properties of the finished part. The degree of freedom that AM provides when it comes to geometry generation, functional structure and material selection means that it offers many more possibilities for variation than is the case with conventional manufacturing processes.

File format capabilities within the AM processes available today are not sufficient to ensure digital continuity. Reusing proprietary data would transfer the full part definition, but this is only feasible in monolithic system environments, as otherwise readability of the formats in downstream processes cannot be guaranteed. A flexible manufacturing environment needs to use standardized formats. This is just as true for in-house processes as it is for collaboration with external partners. The 3MF, AMF and STL formats examined in this recommendation are only suitable to a limited extent since PMI and anisotropic material information, for example, cannot be mapped or cannot be mapped adequately. In AM processes, it is useful if the geometry can be transferred as accurately (e.g. as a B-Spline) and for as long as possible. One example of where this is necessary is when defining the attachment points of the support structures. With a view to post-processing, it would be helpful if support structures were available as 3D representation as this would make it possible to automatically generate CNC code for removing the support structures.

Special attention should be paid to multi-material and multi-property printing. Different properties in different parts of a component can be generated using multiple materials or by changing process parameters - even if it is just for one material (at least to some extent). The expected benefits could be great, but the challenge here is the low number of systems available that can generate and share this information. We see great potential if both the options for definition in the CAD systems and the interfaces for transferring information are developed in the direction of multi-material printing. The wide availability of suitable formats for exchanging information about multi/graded materials would facilitate simulations using multiple materials. The definition of property distribution in the component could then be made the objective of an optimization process. The selection and distribution of the actual material, geometry and the manufacturing process parameters would be provided by the simulation. Today, it is almost impossible for this complex task to be performed by a designer.

The potential offered by information feedback is not examined in detail in this document. The use of a target/actual values comparison approach that is based on in-process measurements or post-processing results will make it possible to derive findings that can be fed back into the process. Future approaches must provide suitable interfaces and formats for this purpose.

Security in the manufacturing chain covers a multitude of aspects. Some are valid for manufacturing processes in general, others are AM specific. Because of the high degree of flexibility involved, particularly in terms of manufacturing sites and the possible number of iterations, special attention has been paid to the infrastructure along the data flows. Outside of closed company networks, aspects such as access control, an assessment of intended or unintended changes to the information, and the traceability of transactions and events are essential prerequisites. Therefore, future processes will need to offer secure cryptographic identities for all participants, which can be users, devices or services. The data that is sent must be certified so that recipients can check the integrity of origin and the sender.

In the future, additional AM-specific potentials, such as component optimization via material distribution, will play a larger role in the context of the collaboration partners' increasingly complex safety requirements. Due to the challenges described, these potentials are not yet being exploited across all processes.

## 5 Appendix

By the time the first AM machine (SLA-1, a stereolithography machine from 3D Systems) became commercially available in 1987, the novelty of AM meant that CAD systems did not provide the functionalities needed to create the AM process plan for manufacturing a part. Instead, the AM machine manufacturer provided a software application that could be used to create it (e.g. 3D Systems). This meant that the part geometry had to be exported from the authoring CAD system and imported into the AM process plan application (i.e. AM CAM application).

Here an overview of the geometric data exchange situation at that time: the first version of the Initial Graphics Exchange Specification (IGES) was approved in 1980 by the National Bureau of Standards in the USA. The first version defined wireframe and basic surface geometry. The third version of IGES was approved in 1986 and comprised freeform surfaces. Similarly, the first version of VDAFS to exchange freeform surfaces was approved in 1983 as a DIN 66301 standard (Encarnaç o, Schuster and V oge, 1986). It is also worth mentioning that the geometric data translation process was not free of problems (Lachance, James and Elenbogen, 1987).

Table 17: Summary of AM file formats and their limitations, provides a summary of the file formats used within the AM ecosystem. Voxel-based and trivariate spline methods, which were developed to support the definition of the areas in a part that have different materials and proprietary formats, are currently not included in the table.

At that time, 3D Systems decided to use a geometric approximation technique based on the creation of triangular facets to represent the part surfaces (tessellated geometry) to import a part geometric model into the AM process plan application. The result was the STL (STereoLithography) file format (Kai et al., 1997). The limitations of the format with regard to the resulting model accuracy, redundant data, geometric quality issues and lack of material information have been widely acknowledged in the relevant literature, e.g. (Kai et al., 1997; Jurrrens, 1999; H allgren et al., 2016; Altenhofen et al., 2018; Qin et al., 2019). Nevertheless, STL was adopted as the de facto standard within the rapid prototyping (RP) and AM community and remains so. Alternatives to the exchange of 3D approximated geometry

have been developed over the years for purposes other than AM, but they have been also used in the AM context (e.g. OBJ, X3D, PLY, etc.). Two other approaches that originated in the AM context are currently available: AMF (ISO/TC 261, 2020) and 3MF (3MF, 2020).

Since most AM processes are executed in slices or layers, an alternative was to exchange slice data rather than 3D faceted geometry (STL file format). The CAD system is used to slice the original exact model and the resulting slice data is exchanged via a slice format. This approach led to the development of several formats (e.g. CLI and SLC) (Kai et al., 1997; Qin et al., 2019). However, most of those formats support only polyline entities (segments of straight lines) for defining contours, which does not bring any advantage over STL in terms of accuracy. A summary is provided Table 17: Summary of AM file formats and their limitations.

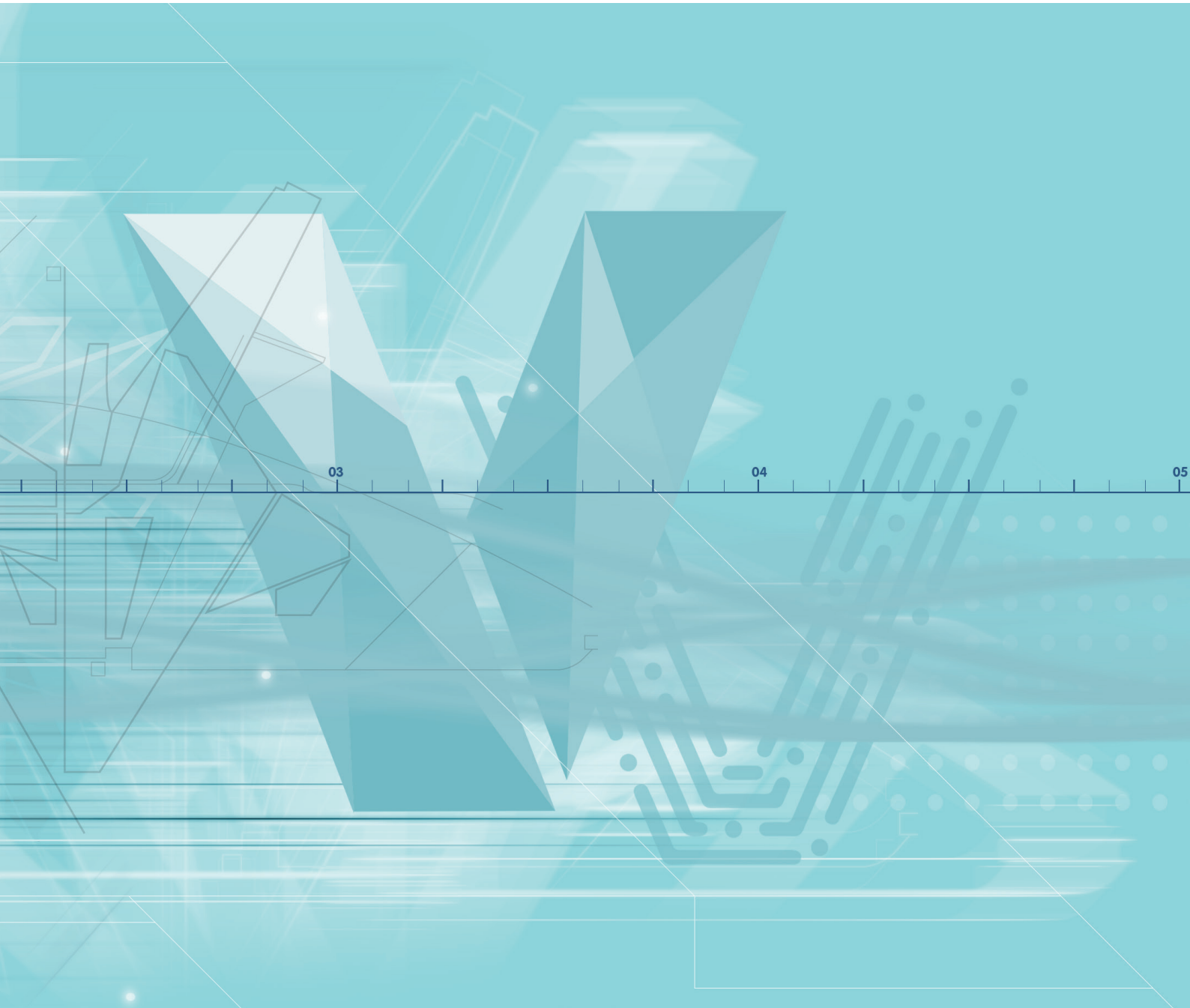
	Acronym	The Acronym stands for	Standard?	Developed by and/or Standard number	Developed for	Based on eXtensible Markup Language?	Level of implementation within the AM ecosystem	Design?	Material?	Manufacturing?	
Formats	Approximated geometry	STL		3D Systems	AM Geometry		"de facto" standard	x			
		AMF	x	ISO/ASTM 52915	AM	XML	medium	x	x		
		3MF		3MF consortium	AM	XML	very high	x	x		
		OBJ +			3D rendering		medium	x	x		
		MTL									
		VRML	x	ISO/IEC 14772	3D rendering		medium	x			
		X3D			3D rendering	XML	low	x			
		COLLADA	x	ISO/PAS 17506 Khronos consortium	3D visualization	XML	high	x			
		JT	x	ISO 14306	3D visualization		medium	x	x		
		RPI		Rensselaer DRC	AM Geometry		none	x			
		STH		Brock Rooney & Ass.	AM Geometry		none	x			
		CFL		Cubital	AM Geometry		none	x			
		SIF1		McMains	AM Geometry		none	x			
		SPF		Univ. of Cincinnati	AM Geometry		none	x	x		
	PLY		Stanford Graphics Lab	3D scanned data		low	x	x			
	SLICES	LEAF		Helsinki U. of Tech.	AM		none	x			
		SLC		3D Systems Stratasys	AM		medium	x			
		CLI		EU Project	AM /Scanned data		high	x			
		HP-GL		HP			?	x			
		MAMF		PennState Univ.	AM	CLI based	none	x	x		
	Prop.	DXF		Autodesk	2D-3D geometry		?	x			
		3DS		Autodesk	3D animation & rendering		?	x			
		SAT		Spatial (DS)	3D geometry		?	x			
	B-Rep	STEP	x	ISO 10303-242	Product model Data	Part 21, XML	low	x	x		
		JT	x	ISO 14306	3D visualization			x	x		
		STEP-NC	x	ISO 14649-17 ISO 10303-238	Numerical Control Programming	Part 21, XML	none	x	x	x	
	CNC		x	ISO 6983	Numerical Control Programming		low (specific kind of G-code from each manufacturer)			x	

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