Resources and their Description for Additive Manufacturing

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***Abstract*—For an enhanced automated usage of 3D-printers in case of multiple available 3D-printers, such as in Cloud Manufacturing or Cloud Printing services, the requirement arises to select and provision suitable resources for user provided model files. As Additive Manufacturing (AM) consists of a number of different technologies, ranging from fabrication using thermoplastic extrusion to electron beam based curing of metal powder, the necessity is evident to enable users to describe limitations, capabilities, interfaces and requirements for a these resources in a machine readable and processable format. This resource description enables the discovery and provisioning of appropriate resources within a service composition, where 3D-printing resources are regarded as manufacturing services themselves. In order to compose a service from these hardware resources, the comprehensive description of such resources must be provided. With this work, we provide an abstract and universal capability description framework of such 3D-printing resources. The framework consists of an ontology for the resources of the AM Domain, a flexible Extensible Markup Language (XML) schema and the implementation in a cloud-based 3D-printing system. With this resource description both hard- and software resources are universally defined. Applied to systems with multiple 3D-printers, a scheduling component is capable of resource discovery. This selection is based on the matching of described capabilities, status information and derived requirements from specific 3D-printing job definitions. This work provides a framework for the description of resources in the AM domain with an ontology, based on a collection of identified resource descriptors extracted from literature.**

Keywords*—*3D Printing; Additive Manufacturing; Resource Description; Capability Description; Service Selection; Service Discovery

I. INTRODUCTION

This work is an extension to Baumann et al. [1], presented at the ADASERC conference 2017.

For the efficient usage of 3D-printing resources in Cloud Manufacturing (CM) scenarios, it is necessary to identify and schedule the existing resources. This scheduling is in accordance with the requirements of the user and the relevant 3D-printing application or request. 3D-printing resources are mainly 3D-printers of various types, makes and models. These 3D-printers are characterised and differentiable by their capabilities, specifics and constraints for their usage. Similar usage of an abstracted description of resources is described in Grangel-González et al. [2], where industrial machinery is equipped with an “Administrative Shell”, which is used to interface with various devices. In a cloud printing environment, where these resources are considered part of a service, it is possible to compose them into new services to achieve tasks such the efficient execution of 3D-printing requests. This work offers a practical service composition framework and tool for the description required to establish service compositions within a 3D-printing service in the domain of Additive Manufacturing (AM). For this work, the applicability of the proposed resource description is analysed.

As 3D-printing is comprised of a number of different technologies, ranging from thermoplastic extrusion fabrication, over photopolymerisation to other methods, it is a prerequisite to understand these technologies and their specific parameters and differences. One thermoplastic extrusion based method is called Fused Deposition Modeling (FDM) (also Fused Filament Fabrication or Free Form Fabrication (FFF)). Fabrication on the basis of curing of photopolymers in a vat is called Stereolithography (SLA). Laser-based fabrication methods are either Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS). Other methods exist to create physical objects directly from digital models, such as Laminated Object Manufacturing (LOM). Besides the understanding of these technologies and methods, it is important to be able to describe them in a comprehensive and machine-understandable way. Furthermore, it is important to express the inherent and derived capabilities and restrictions of these technologies and machines. The different technologies do not only differ in the materials they are able to process but also in the quality that is achievable. They further differ in the geometric and structural features they can reproduce, in the cost they effect, and the means they are controlled by or programmed with. For the automated usage in a distributed service scenario, with a number of different 3D-printing resources involved, the service must be able to select an appropriate device or devices for any given user submitted task.

For the hardware providers, it is beneficial if their equipment is utilized to a high degree. This is required in order to amortise their assets on time and also to be ecologically sound [3]. For the users, such an automated and swift resource allocation is pertinent. This equates to a reduced turnaround time and also the promise of higher product quality due to optimum capability and requirements matching. For service operators, the automated resource allocation is an intrinsically motivated requirement for the operation of such a service.

With this work, a solution for the description of differing capabilities, restraints and requirements of various 3D-printing resources is provided. This solution provides an extensible, flexible, comprehensive and usable description format for the use in AM scenarios. The solution combines existing approaches for the description of resource capabilities and extends these for the usage in 3D-printing. The proposed solution is currently implemented in a prototype service to facilitate scheduling and selection of AM resources.

This work is motivated by the following five use cases:

3D-printer selection: The resource description, applied to a database of commercially available 3D-printers can serve as a purchasing guide for end-users/consumers or other potential buyers of 3D-printers [4], [5]. This will especially be the case if the information is readily available as a Web-service and supports pro-active user-questioning, e.g., a wizard.

Automated facility planning: In future modular factory designs, the dynamic reconfiguration of the shop floor [6] is becoming relevant. With a machine readable resource description, layouting and planning software can place the manufacturing resources at an appropriate location.

Scheduling in 3D-printing services: In this use case the resource description is the foundation for the scheduling algorithm that selects the most appropriate available 3D-printing resource for any given processing request, based on the constraints and preferences provided by the user and derived from the model data [7], [8].

Recommender systems for CAD development: Based on the resource description, a software system can support Computer Aided Design (CAD) designers with information and recommendations for geometrical and topological features within models that are manufacturable with 3D-printing resources available to a company.

Technological improvement: Through an extended understanding of the specific resources for different technologies, commonalities can be identified and improvements on specific technologies and implementations can be enabled.

This work is an extended version of [1] and structured as follows: Starting with related work in Section II, a review of existing publications is performed. In Section III, the approach for the resource description is described, its underlying concepts and sources as well as the implementation and evaluation. In Section IV, the implementation and its results are discussed and analysed. Lastly, Section V provides a summary of this work.

II. RELATED WORK

In the work by Pryor [9], the implementation of a 3D-printing service within an academic library is described. The system consists of two low-cost hobbyist 3D-printers and a 3D scanner. Of relevance to this work is the description of the workflow for the user handling. Pryor describes the processing workflow as purely manual with the data being deployed by the users either via a web form or email. The library staff performs sanity checking, pre-processing (i.e., positioning, slicing, machine code generation) and manual scheduling of the 3D-printer resource. The text does not provide an analysis of the time required for the staff to perform these tasks.

In the article by Vichare et al. [10], the authors propose a Unified Manufacturing Resource Model (UMRM) for the resource description of machines within the manufacturing domain. Specifically, the authors aim to describe Computer Numeric Control (CNC) machines and their associated tools in a unified way to represent the capabilities of these systems in their entirety. Their work provides a method to describe a CNC machine in an abstract sense for use in software, e.g., for simulations. As part of the collaborative peer-robot control system described in the work by Yao et al. [11], an ontology for a resource description is partially described, on which we build our work. This ontology distinguishes between hardware and software resources, as well as capability and status description. The authors provide an exemplary Extensible Markup Language (XML) schema definition for such a resource description, on which we extend upon. The *3D Printer Description File Format Specification* (3PP) by Adobe [12] is very relevant to this work, as it describes the 3D-printer's capabilities in XML format as deemed necessary by Adobe, presumably for the application within their software. This work contains an extensive listing of possible attributes relevant to a resource description, on which we base our work. The 3PP format is limited to FDM 3D-printers. The definition includes hardware and material description but only partially caters for software support. In the publication by Chen et al. [13], the authors provide another approach to the problem of model-fabrication resource mismatch by the introduction on an abstract intermediary specification format. The authors propose this reducer-tuner model to abstract design implementations for the application to a variety of 3D-printers whereas our work proposes a 3D-printer resource description that enables the matching of suitable machines to specific model files. In the work by Dong et al. [14], the problem of scheduling in AM is handled by a rule-based management of autonomous nodes, i.e., 3D-printers. This system is based on an ontology for 3D-printing of which some excerpts are presented in this work. From this example, our work is influenced and extends on missing attributes. Yadekar et al. [15] propose a taxonomy for CM systems that are closely related to AM. This taxonomy is focused on the concept of uncertainty and only briefly discusses the taxonomical components that define the manufacturing resources. The main distinction for the authors is the division into soft and hard resource groups. In the work by Mortara et al. [16], a classification scheme for direct writing technologies, i.e., AM, is proposed. The authors define the scheme for three dimensions, namely technology, application, and materials. The properties of specific materials are discussed exemplary in brief. A listing of potential properties for the varying technologies and materials is missing.

III. MATERIALS AND METHODS

From existing literature, software and expertise, we construct an ontology that is described in the following Section. This ontology is the basis for the extension of the properties proposed, that are relevant to the domain of AM. In this work, we exclude concepts like business process related capabilities, and knowledge and abstract ability related mapping, i.e., it is not possible to express certain abilities of people, teams or companies, e.g., the level of knowledge for the design of objects for AM. The properties are derived from literature, software and 3D-printer documentations. The following requirements are expressed to guide the generation of the ontology and properties list:

RQ1 The ontology and properties list must be flexible and extensible. Flexibility means that for specific application scenarios where only subsets of properties and relations are of interest, these must be expressible within the proposed ontology or resource description. Extensibility denotes the property to be able to incorporate future, currently unforeseen, properties of technology and materials.

RQ2 The resource description must be able to reflect temporal, local and other ranges of validity and restrictions. Conditional validity is to be reflected. With this requirement we reflect the necessity that certain properties, e.g., material strength, are only valid and guaranteed for a certain period.

RQ3 The resource description must be able to distinguish between general concepts of things, e.g., 3D-printers and materials, that form a class and its individual instantiation that might have differing properties and attributes.

In this work, the following separation of information description is performed for the resource description:

Materials: Encompasses all physical materials that are processed, or used during the digital fabrication. Also includes physical materials that are required for the digital fabrication process as indirect or auxiliary material.

Software: Encompasses all software and Information technology (IT) components that are involved in the model creation phase, the object fabrication phase or that are used for the control and management of digital fabrication equipment.

Processes: Encompasses all intangible processes, data and information that is generated, consumed, transformed or influenced by in any phase of the digital fabrication process. Business processes are part of this grouping.

Technology: Encompasses all hardware and machine equipment that is used for the object fabrication, as well as pre- and post-processing.

We exclude status information and status dependent properties from our resource description and ontology.

The resource description must be able to reflect required properties and information of all currently available 3D-printing technologies, regardless of the technology classification following any schema, such as the classification by Gibson et al. [17], the classification by Williams et al. [18] or the ISO/ASTM Standard 52900:2015 [19] classification. This work identifies common attributes between technologies and enables technology specific properties. As a guideline for the creation of the ontology and the resource description itself a distinction between object classes and their actual instances is followed. Given the example of a 3D-printer, the class is formed of all 3D-printers from a certain manufacturer and are of a certain make share a number of attributes like physical volume and number of printheads. Those general attributes might be extended by attributes pertaining to a certain 3D-printer that belongs to a user and is situated at a physical location. The general attributes might also be altered for a specific 3D-printer, as it might weight more than the original 3D-printer due to added extensions or modifications, or its build envelope is smaller than the original's due to a hardware defect.

A. Sources

Properties are extracted from datasheets from the following manufacturers and models:

3D Systems, Inc.: ProJet 7000 SD & HD, ProX 950, sPro 140, ProX DMP 200, ProX 800, ProX SLS 500, ProJet CJP 360, ProJet 1200, CubePro
Arcam AB: Arcam Q10 Plus, Arcam Q20 Plus, Arcam A2X
B9Creations LLC: B9Creator V1.2
CEL: CELRobox
Deltaprintr: Delta Go
EnvisionTEC GmbH: 3D-Bioplotter Starter Series, SLCOM1
EOS GmbH: EOS M 100, EOS M 290, FORMIGA P 110, EOS P 396, EOSINT P 800
ExOne GmbH: S-Max, S-Print, M-Flex Prototype 3D Printer
FlashForge Corp.: Creator Pro 3D
Formlabs Inc.: Form 2
LulzBot/Aleph Objects, Inc.: TAZ 6
Makerbot Industries, LLC: Replicator+, Replicator Z18
Mcor Technologies Ltd.: ARKe, IRIS HD
Optomec Inc.: LENS 450, Aerosol Jet 200
Renishaw plc.: RenAM 500M
RepRap: Prusa i3
SeeMeCNC: ROSTOCK MAX V3
SLM Solutions Group AG: SLM 125, SLM 280 2.0
Stratasys Ltd.: uPrint SE, Objet24, Dimension Elite, Fortus 380mc, Objet1000 Plus
Ultimaker B.V.: Ultimaker 3, Ultimaker 2+
UP3D/Beijing Tiertime Technology Co., Ltd.: UPBOX+
voxeljet AG: VX 200, VX 2000
WASP c/o CSP s.r.l.: DeltaWASP 20 40 Turbo

Furthermore, properties and capability attributes are extracted from publicly available slicing software (e.g., *Slic3r* [20], *Cura* [21], and *Netfabb* [22]) and acquired through experimentation. On the ontological concept itself, we refer to the work by Gruber [23] and the book by Fensel [24]. Following the distinction of ontologies by Ameri and Dutta [25], we classify our ontology as lightweight. For the construction of the ontology a list of key terms is compiled from existing glossaries and literature. The sources for the following list of key terms include:

- http://3dprintingforbeginners.com/glossary
- http://3dprinthq.com/3d-printing-glossary
- https://www.sculpteo.com/en/glossary
- https://ultimaker.com/en/resources/11720-terminology
- https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/445232/3D_Printing_Report.pdf

The key terms are the following:

1) Synonyms
    a) 3D Printer
    b) 3D Printing
    c) Additive Manufacturing
    d) Rapid Manufacturing
    e) Generative Manufacturing
    f) Digital Fabrication
    g) Additive Layer Manufacturing
2) Object
3) Model
4) File
5) File formats
    a) GCode
    b) STL
    c) AMF
    d) 3MF
    e) VRML
6) File types
    a) Log files
    b) Model files
    c) Configuration files
7) Software (types)
    a) Slicer
    b) CAD
    c) Modeller
    d) Control software
8) Technology
    a) FFF/FDM
    b) SLS
    c) SLM
    d) SLA
    e) EBM
    f) LOM
    g) Bioprinting
    h) Binder Jetting
    i) 3D Printing
    j) DMLS
    k) LENS
    l) MJS
9) Machine components
    a) Firmware
    b) Extruder
    c) Heat bed
    d) VAT
    e) Resin tank
    f) Nozzle
    g) Gantry
    h) Hot end
    i) Motor
        i) Nema 17
        ii) Stepper motor
    j) Belt
    k) Lens
    l) Electron source
    m) Vacuum chamber
    n) Build chamber
10) Material
    a) Support material
    b) Extrudate
    c) Binder
    d) acrylonitrile butadiene styrene (ABS)
    e) PLA
    f) PVA
11) Process related actions
    a) Post-processing
    b) Pre-processing
    c) Slicing
    d) Positioning
    e) File transformation
12) 3D Print
    a) Raft
    b) Object
    c) Shell
    d) Infill
        i) Infill percentage
        ii) Infill strategy
        iii) Infill geometry
    e) Overhang
13) Object features
    a) Wall
    b) Hole
    c) Surface
    d) Solid
14) Properties
    a) Machine properties
        i) Build volume
        ii) Build/Print speed
        iii) Extrusion speed
        iv) Travel speed
        v) Layer resolution
        vi) Positioning precision
    b) Material Properties
        i) Price per unit
        ii) Material form

A) Pellets
B) Filament
C) Resin
D) Powder

B. Properties

The following properties are identified from literature and technology documentation. These properties are listed in the appendix in order to avoid a disruption of the text flow. The provided listing is sufficient to describe relevant properties of AM machinery, i.e., 3D-printers, and the associated materials.

The properties can be further classified as either static, e.g., the serial number of a 3D-printer or its coordinate system, or dynamic, e.g., the owner or location of a 3D-printer. Dynamic properties are often dependent properties, which is a further classification applied to the properties. Dependent properties are influenced and depend upon a 3D-printer component, e.g., the nozzle and its diameter, the material, e.g., surface roughness achievable differs for materials processable or parameters selected during the 3D-printing process. This classification is not provided with this work due to brevity. The properties in the listing (see I) are for the hardware resources, i.e., the 3D-printer as well as its components and the material associated with the 3D-printer.

In the following table I, we list the an excerpt of the attributes, the category they belong to, the list of dependent factors, the unit the attribute is represented in, the source where the attribute is referenced from, possible restrictions based on printing mechanism, examples where appropriate and the respective classifications. The complete listing is presented in the appendix. In the listing the abbreviation **EXP** indicates attributes that are not referenced from literature but are either derivatives from literature referenced attributes, common knowledge or are derived from experiments. The unit **[String]** is an array of strings, meaning that the attribute is described by distinct texts. Furthermore, square brackets denote other types of arrays as indicated. The unit **Int** denotes an integer, **Bool** a boolean variable.

C. Implementation

In this Section, the implementation of both the ontology and the relevant core classes are described. Furthermore, information on a possible scheduling metric based on a cost estimation method and the resulting information flow in the implemented service is described.

The ontology is constructed using the protégé software version 5.1.0, see http://protege.stanford.edu/. The ontology is generated based on the properties brought forward in Section III-B. The guiding principle for the ontology is the flexibility of the properties that are applicable to 3D-printers, material and inherent constraints. The ontology is created based on the identified properties and derived concepts from literature and documentation.

The implementation in software to manage the specific properties of the resource description and to evaluate the applicability of the description is performed in the proposed 3D-printing cloud service by the authors [26], [27].

The implementation in the service is performed to enable provisional scheduling for 3D-printing resources based on availability, build volume and processable material type. In scheduling, some form of ordering metric must be provided. In this work, this metric is based on a proposed cost metric as described further in the text.

The cost metric is defined in [28] and serves as a prototypical implementation of cost estimation within AM.

The cost is calculated as (see Equation (1)) follows:

$$\begin{aligned}\text{Cost} = {} & (\text{Discount}(T,P,U) + \text{Profit}(U)) \\ & \times (\text{Machine} + \text{Material}(O,P,S,SO) \times \text{Factor B} \\ & + \text{Duration}(O,S,SO) \times \text{Factor U} + \text{Factor A} \\ & + \text{Factor C}(O,P))\end{aligned} \tag{1}$$

With the following abbreviations used in the equation: 1) T for team 2) P for 3D-printer 3) U for user 4) O for object 5) S for slicer and, 6) SO for slicing options The cost for a 3D-print is dependent upon the 3D-printer selected (base cost), the material that is consumed and the time required for 3D-printing. Within the service, these attributes are user selectable for each materialtype and 3D-printer that is under the control of the user.

The scheduling of resources is implemented to adhere to a user selected criterion, e.g., lowest cost possible or fastest execution available. These criteria are calculated based on the proposed resource description that finds suitable and available manufacturing resources first and then calculates the expected cost. The user and resource operator are queried for confirmation before the actual commitment to ensure legal agreement on the execution. The operator is able to forfeit the manual confirmation to enable automated operation.

From Baumann et al. [28] we use this explanation for the parts of the cost formula (see Equation (1)).

Material is a factor that adjusts the cost to the material chosen.

Factor A is a factor that compensates for required time associated with pre-heating of the AM resource and other preparatory tasks not dependent upon the build volume.

Factor B is a factor that compensates for required material used for raft and support structures.

Factor C is a factor that compensates for the required cooling time and the parts removal.

Factor U is an uncertainty factor associated with the 3D-printing time estimation that is generally unreliable to a certain extend for which this factor compensates.

Discount is a factor to address requirement of discounting for certain teams, members or machines.

Machine is a factor representing the base cost of usage of a certain 3D-printer.

Profit is a factor to address commercial interests of 3D-printer owners to offset the net-costs of a 3D-print for a profitable endeavor

Based on the cost metric, scheduling is implemented in the service as described below.

In Figure 1, the processing flow for the registration of a hardware resource with the 3D-printing service is depicted.

TABLE I: Properties in Additive Manufacturing – Excerpt

Name	Category	Unit	Source	Meaning	Only Applicable for	Example	Static	Dynamic	Independent	Dependent
Operating Temperature Min	Printer	°C	Delta Go	The lowest ambient temperature the 3D printer is specified for operation		15 °C	x		x	
Operating Temperature Max	Printer	°C	Delta Go	The highest ambient temperature the 3D printer is specified for operation		30 °C	x		x	
Operating Humidity Min	Printer	%	Delta Go	The lowest ambient humidity the 3D printer is specified for operation		10% RH	x		x	
Operating Humidity Max	Printer	%	Delta Go	The highest ambient humidity the 3D printer is specified for operation		90% RH	x		x	
Machine Weight	Printer	kg	TAZ 6	The gross weight of the 3D printer		10.6 kg	x		x	
Machine Length	Printer	mm	ProX DMP 200	The machine dimension (Length)		342 mm	x		x	
Machine Height	Printer	mm	ProX DMP 200	The machine dimension (Height)		380 mm	x		x	
Machine Depth	Printer	mm	ProX DMP 200	The machine dimension (Depth)		389 mm	x		x	

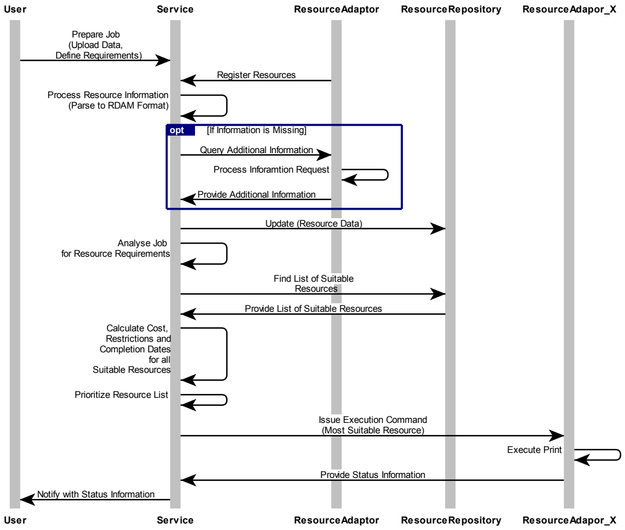

Fig. 1: Processing Flow for the Registration and Selection of a Hardware Resource

In this figure, the user dispatches a 3D-printing requirement (Job) with the service, for which a number of implicit and explicit requirements and restrictions are also deposited. A hardware resource registers its capabilities with the service, that is then stored with the resource registry. The service queries the resource registry for a suitable hardware resource for a job and issues the appropriate commands for a 3D-printing execution on this resource. On completion or failure, the user issuing the job is notified.

1) Core Classes: The core classes in the ontology are described in this Section. A visual representation of the ontology is depicted in Figure 2. In this figure, the classes are depicted as circles, with the relationships between them depicted as arrows with the relationship name as labels. This graph is created using the *WebVOWL* service [29].

MaterialGroup and **Material**, these classes denote the materials that are relevant for the description of the capabilities of the 3D-printing resource. The materials have an influence on a number of quality properties, e.g., the surface roughness. The materials a 3D-printing resource can process are relevant for the selection of the appropriate 3D-printing resource.

PrintingTechnology, **PrinterType**, and **Printer**, are classes to represent the underlying technology of a 3D-printing resource, e.g., a FDM based technology or a Electron Beam Melting (EBM) technology as well as the

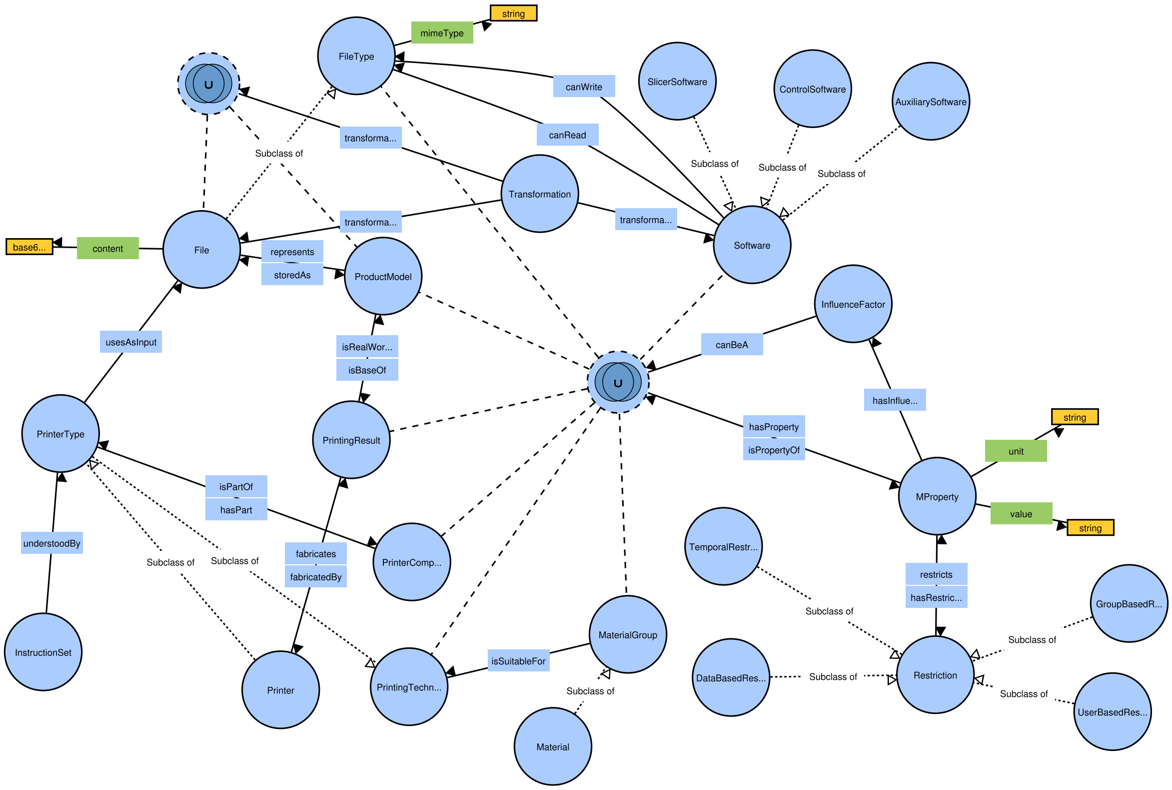

Fig. 2: 3D-printing Ontology

3D-printer class, which can be understood for example as a specific model line from a hardware manufacturer (e.g., the Replicator Series from Makerbot Industries). Hardware resources of a PrinterType have a number of common attributes that extend the PrintingTechnology. The Printer denotes the make of a specific PrinterType, e.g., the *MakerBot Replicator 2X* from Makerbot Industries. Instances of this Printer class have further common attributes extending the attributes of the PrinterType. Instances of the Printer class are actual 3D-printers that have further attributes like owner and a physical location.

PrinterComponent, is the class for the physical and immaterial components that are part of the specific 3D-printer. Every component can have a unbounded number of properties as described below. For example the printhead and its nozzles are components of a 3D-printer in the case of FDM technology and an electron source is a component of a EBM type 3D-printer.

Software, denotes all software that is used in the 3D-Printing Process (3D-PP). Software is used to control the 3D-printing resource, to convert files from one format into another, to prepare and process the files required for the control of the 3D-printer and to evaluate and monitor the 3D-print itself.

MProperty, this class is the generalisation of properties that are applicable to either the Material, Materialgroup, PrintingTechnology, PrinterType, Printer, PrinterComponent, Software, ProductModel or File. The guiding principle for the creation of this ontology is to enable flexibility and expandability, so this generalised property can hold all properties listed above (see Section III-B) and future properties.

Restriction, is a class that reflects the ability to enable restrictions on MProperties as the properties can be applicable only for a specified period of time or for a certain group of people. For example the property of filament quality might be linked to a certain expiration date.

InfluenceFactor, is a class that reflects the multi-dimensional influences on properties by a defined number of factors. For example the nozzle diameter can influence the extrusion rate in case of a FDM 3D-printer.

D. Resource Description Schema

From the ontological concept, an XML schema definition is constructed, which follows the principle of flexibility by encapsulation of properties in a flexible element. The property element is applicable to all relevant types of the schema, namely the PrintingTechnology, PrinterType, Printer, Printer-component, Materialtype, and Material.

All properties are extended to allow for restrictions based on user, group or temporal conditions. The properties can be influenced by any other class of the schema to reflect interdependent relations between components. The following example justifies this construction: In the 3D-printer, the property of the material deposition rate is dependent upon the technology in use, the material processed and, in case of the FDM technology, the nozzle diameter of the extruder installed in the 3D-printer. See the following excerpt from the schema definition on the components properties and the implementation on the influencing factors:

```
<xs:complexType name="influence">
<xs:sequence minOccurs="1" maxOccurs="1">
<xs:element name="id" type="xs:ID"
  minOccurs="1" maxOccurs="1" />

<xs:choice>
<xs:element ref="tdp:MaterialType" />
<xs:element ref="tdp:Material" />
<xs:element ref="tdp:PrinterType" />
<xs:element ref="tdp:Printer" />
<xs:element ref="tdp:PrinterComponent" />
<xs:element ref="tdp:PrintingTechnology" />
</xs:choice>

<xs:element name="influenceMethod"
  type="xs:string" />
</xs:sequence>
</xs:complexType>

<xs:complexType name="validity">
<xs:sequence>
<xs:element name="id" type="xs:ID"
  minOccurs="1" maxOccurs="1" />
<xs:element name="validityCondition"
  type="xs:string"
  minOccurs="1" maxOccurs="unbounded" />
</xs:sequence>
</xs:complexType>

<xs:complexType name="mproperty">
<xs:sequence>
<xs:element name="unit"
  type="xs:normalizedString"
  minOccurs="1" maxOccurs="1"/>
<xs:element name="description"
  type="xs:normalizedString"
  minOccurs="1" maxOccurs="1"/>
<xs:element name="value"
  type="xs:normalizedString"
  minOccurs="1" maxOccurs="1"/>
<xs:element name="name"
  type="xs:normalizedString"
  minOccurs="1" maxOccurs="1" />
<xs:element name="added"
  type="xs:dateTime"
  minOccurs="1" maxOccurs="1" />
<xs:element ref="tdp:influence"
  maxOccurs="unbounded" />
<xs:element ref="tdp:validity"
  maxOccurs="unbounded" />
</xs:sequence>
</xs:complexType>
```

IV. DISCUSSION

The proposed resource description offers the ability to the user to select the appropriate 3D-printing resource in a scenario where restrictions for the suitable 3D-printing resources can be derived, from either the users input or from the provided data files. Within a 3D-printing service, the user is enabled to state preferences and restrictions, such as the desired quality of the 3D-printed object or cost restrictions, based on which the service itself can query appropriate hardware resources for their availability and suggest them to the user. Furthermore, based on the provided models the service can exclude certain hardware resources if they are not fitting for the task to be executed. For example, if the model file is analysed and found to contain features under a certain threshold, the hardware that is not capable of manufacturing features of this dimension are to be excluded.

A perceived problem with the flexibility of the ontology and resource description is the requirement for contextual property checking within the service itself. As opposed to strict formalities possible with the XML Schema Definition (XSD) definition, this flexibility hinders such formality checking. The 3D-printing service must be equipped with a component that is capable of evaluating the provided properties and check them for completeness, applicability and correctness. The resource description also allows for the encapsulation of third-party 3D-printing services within the 3D-printing service itself, where the capabilities of these services are regarded as a resource and described as such.

V. CONCLUSION

This work provides an ontology of the AM domain with extensible and flexible constructs. The derived XSD provides flexibility for extensions, based on future developments of 3D-printing hardware. The flexibility also allows for user-centric extensions and use-cases. The use case for this work is the deployment in a 3D-printing service but other use cases are also provided, such as the use within a recommender system for the design and modelling phase, or purchase recommendation systems. The list of properties (Table II) can form a basis for further research and individual extension. The examples provided are intended to ease understanding of the list's compilation.

In future work, it is recommended to extend the ontology to include concepts that enable the expression of immaterial capabilities and abilities, such as the expertise in certain domains, e.g., Aerospace engineering, medical engineering or bioprinting, in AM. Furthermore, it is recommended to enable the expression of proficiency in areas related to the 3D-printing lifecycle or process itself, e.g., proficiency with the design process, with the software / IT components or with legal and business concepts for AM.

This schema will be fully implemented and evaluated in an upcoming project. In this project, the evaluation will be on the usefulness and usability of the ontology. This evaluation will utilise both expert and user surveys. Furthermore, the evaluation will compare this proposed method in respect of expressiveness and suitability.

ACKNOWLEDGMENT

The authors would like to thank Julia Holzschuh for her contributions to this work.

Appendix

TABLE II: Properties in Additive Manufacturing

Name	Category	Dependent Upon	Unit	Source	Meaning	Only Applicable for	Example	Static	Dynamic	Independent	Dependent
Operating Temperature Min	Printer		°C	Delta Go	The lowest ambient temperature the 3D printer is specified for operation		15 °C	x		x	
Operating Temperature Max	Printer		°C	Delta Go	The highest ambient temperature the 3D printer is specified for operation		30 °C	x		x	
Operating Humidity Min	Printer		%	Delta Go	The lowest ambient humidity the 3D printer is specified for operation		10% RH	x		x	
Operating Humidity Max	Printer		%	Delta Go	The highest ambient humidity the 3D printer is specified for operation		90% RH	x		x	
Machine Weight	Printer		kg	TAZ 6	The gross weight of the 3D printer		10.6 kg	x		x	
Machine Length	Printer		mm	ProX DMP 200	The machine dimension (Length)		342 mm	x		x	
Machine Height	Printer		mm	ProX DMP 200	The machine dimension (Height)		380 mm	x		x	
Machine Depth	Printer		mm	ProX DMP 200	The machine dimension (Depth)		389 mm	x		x	
Install Size Length	Printer		mm	SLM 125	The length required for the installation/-placement of the 3D printer		1200 mm	x		x	
Install Size Height	Printer		mm	SLM 125	The height required for the installation/-placement of the 3D printer		770 mm	x		x	
Install Size Depth	Printer		mm	SLM 125	The depth required for the installation/-placement of the 3D printer		1950 mm	x		x	
Build Envelope Height	Printer	No. Extruders	mm	SLM 125	The height of the build envelope		100 mm		x		x
Build Envelope Width	Printer	No. Extruders	mm	SLM 125	The width of the build envelope		100 mm		x		x
Build Envelope Depth	Printer	No. Extruders	mm	SLM 125	The depth of the build envelope		100 mm		x		x
Build Envelope Radius	Printer	No. Extruders	mm	Delta Go	The radius of the build envelope; for polar coordinate based systems		250 mm		x		x

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Machine Data Connection	Printer		[String]	ProX DMP 200	The connection from the 3D printer to a workstation or network		USB 2.0, SD-Card, TCP/IP	x		x	
Electrical Input Rating	Printer		V	ProX DMP 200	Description of the required electrical connection for the 3D printer		400 V	x		x	
Mimimum Possible Hole Diameter	Printer	Print Technology + Material	mm	Shapeways	Description of the minimum hole diameter possible to print		1 mm		x		x
Positioning Accuracy X	Printer		μm	Ultimaker 3	Description of the accuracy achievable by the machine in positioning in the X axis		50 μm	x		x	
Positioning Accuracy Y	Printer		μm	Ultimaker 3	Description of the accuracy achievable by the machine in positioning in the Y axis		50 μm	x		x	
Positioning Accuracy Z	Printer		μm	Ultimaker 3	Description of the accuracy achievable by the machine in positioning in the Z axis		50 μm	x		x	
Repeatability X	Printer		μm	ProX DMP 200	Capability of the 3D printer to produce repeatable results within a given margin, along the X axis		20 μm	x		x	
Repeatability Y	Printer		μm	ProX DMP 200	Capability of the 3D printer to produce repeatable results within a given margin, along the Y axis		20 μm	x		x	
Repeatability Z	Printer		μm	ProX DMP 200	Capability of the 3D printer to produce repeatable results within a given margin, along the Z axis		20 μm	x		x	
Print Accuracy X	Printer	Material	μm	Orion Delta	Description of the accuracy achievable by the machine in printing in the X axis		100 μm		x		x
Print Accuracy Y	Printer	Material	μm	Orion Delta	Description of the accuracy achievable by the machine in printing in the Y axis		100 μm		x		x

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Print Accuracy Z	Printer	Material	μm	Orion Delta	Description of the accuracy achievable by the machine in printing in the Z axis		150 μm		x		x
Number of Extruders	Printer	No. Extruders	Int	Replicator	The number of extruders installed in a 3D printer	FDM	2		x		x
Nozzle Diameter	PrinterComponent	Per Extruder	[mm]	Replicator+	The diameter of each extruder installed in a 3D printer	FDM	0.4 mm, 0.3 mm	x			x
Temperature Extruder Min	PrinterComponent	Per Extruder	[° C]	3D-Bioplotter	The minimum temperature a extruder can work with	FDM	30 °C, 70 °C		x		x
Temperature Extruder Max	PrinterComponent	Per Extruder	[°C]	TAZ 6	The maximum temperature a extruder can achieve	FDM	260 °C, 290 °C		x		x
Layer Thickness Min	Printer	Nozzle + Material	μm	Uitimaker 2+	The lowest layer size that the 3D printer is capable of printing		100 μm		x		x
Layer Thickness Max	Printer	Nozzle + Material	μm	Ultimaker 2+	The highest layer size that the 3D printer is capable of printing		400 μm		x		x
Movement Speed Min	Printer	Print Head	$\frac{mm}{s}$	Ultimaker 3	The minimum speed that the print head can be moved without any extrusion	FDM	200 $\frac{mm}{s}$		x		x
Movement Speed Max	Printer	Print Head	$\frac{mm}{s}$	DeltaWASP 20 40 Turbo	The maximum speed that the print head can be moved without any extrusion	FDM	900 $\frac{mm}{s}$		x		x
Extrusion (Movement) Speed Min	Printer-Component	Print Head + Nozzle	$\frac{mm}{s}$	EXP	The minimum speed that the print head can be moved while extruding	FDM	100 $\frac{mm}{s}$		x		x
Extrusion (Movement) Speed Max	Printer-Component	Print Head + Nozzle	$\frac{mm}{s}$	TAZ 6	The maximum speed that the print head can be moved while extruding	FDM	600 $\frac{mm}{s}$		x		x
Print Head Acceleration Max	Printer	Print Head	$\frac{mm}{s^2}$	Slic3r	The maximum acceleration that the print head is capable of	FDM	150 $\frac{mm}{s^2}$		x		x
Print Bed Speed X Min	Printer		$\frac{mm}{s}$	EXP	In case of a moveable print bed this denotes the minimum speed that the print bed can be moved in the X axis		10 $\frac{mm}{s}$	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Print Bed Speed X Max	Printer		$\frac{mm}{s}$	EXP	In case of a moveable print bed this denotes the maximum speed that the print bed can be moved in the X axis		100 $\frac{mm}{s}$	x		x	
Print Bed Speed Y Min	Printer		$\frac{mm}{s}$	EXP	In case of a moveable print bed this denotes the minimum speed that the print bed can be moved in the Y axis		10 $\frac{mm}{s}$	x		x	
Print Bed Speed Y Max	Printer		$\frac{mm}{s}$	EXP	In case of a moveable print bed this denotes the maximum speed that the print bed can be moved in the Y axis		100 $\frac{mm}{s}$	x		x	
Print Bed Speed Z Min	Printer		$\frac{mm}{s}$	EXP	In case of a moveable print bed this denotes the minimum speed that the print bed can be moved in the Z axis		10 $\frac{mm}{s}$	x		x	
Print Bed Speed Z Max	Printer		$\frac{mm}{s}$	EXP	In case of a moveable print bed this denotes the maximum speed that the print bed can be moved in the Z axis		100 $\frac{mm}{s}$	x		x	
Print Bed Acceleration X Min	Printer		$\frac{mm}{s^2}$	EXP	In case of moveable print bed this denotes the minimum acceleration of the print bed in the X axis		5 $\frac{mm}{s^2}$	x		x	
Print Bed Acceleration X Max	Printer		$\frac{mm}{s^2}$	Slic3r	In case of moveable print bed this denotes the maximum acceleration of the print bed in the X axis		50 $\frac{mm}{s^2}$	x		x	
Print Bed Acceleration Y Min	Printer		$\frac{mm}{s^2}$	EXP	In case of moveable print bed this denotes the minimum acceleration of the print bed in the Y axis		5 $\frac{mm}{s^2}$	x		x	
Print Bed Acceleration Y Max	Printer		$\frac{mm}{s^2}$	Slic3r	In case of moveable print bed this denotes the maximum acceleration of the print bed in the Y axis		50 $\frac{mm}{s^2}$	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Print Bed Acceleration Z Min	Printer		$\frac{mm}{s^2}$	EXP	In case of moveable print bed this denotes the minimum acceleration of the print bed in the Z axis		5 $\frac{mm}{s^2}$	x		x	
Print Bed Acceleration Z Max	Printer		$\frac{mm}{s^2}$	Slic3r	In case of moveable print bed this denotes the maximum acceleration of the print bed in the Z axis		50 $\frac{mm}{s^2}$	x		x	
Print Bed Temperature Max	Printer	Heating Cartridge	°C	TAZ 6	The maximum temperature the print bed can be set to		150 °C	x			x
Print Bed Temperature Min	Printer	Print Bed Cooling	°C	3D-Bioplotter	The minimum temperature the print bed can be set to; active cooling of print bed is uncommon		-30 °C		x		x
Binder Material	Material	Print Technology + Material	[String]	S-Print Furan	A list of materials that can be used as a binder for a 3D printer	Powder Based Technology	Furan		x		x
Processable Material	Printer	Extruder	[String]	TAZ 6	A list of materials that are processable by the 3D printer		ABS, PLA, Nylon		x		x
Processable Material Grain Size Min	Printer	Per Processable Material	μm	S-Print Furan	The minimum size of powder grains that the 3D printer can process	Powder Based Technology	2 μm	x		x	
Processable Material Grain Size Max	Printer	Per Processable Material	μm	S-Print Furan	The maximum size of powder grains that the 3D printer can process	Powder Based Technology	30 μm	x		x	
Max Object Weight	Printer		kg	ProJet 7000 SD & HD	Denotes the maximum weight, All objects of a build can have without skewing or damaging the build plate		9.6 kg	x		x	
Lead Time Influencing Factors	Printer		[String]	EXP	A list of factors influencing the lead time		Cleaning, Model Preparation		x		x
Lead Time Formula	Printer		String	EXP	A formula that can be used to estimate/calculate the lead time required for a print				x		x
Requires Personal Attendance During Print	Printer		Bool	EXP	Indicator that states if personal attendance during the printing process is required or not		Yes	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Requires Manual Interaction for Start	Printer		Bool	Fortus 380mc	Indicator that states if personal attendance during the preparatory process is required or not		No	x		x	
Requires Manual Interaction for End	Printer		Bool	Fortus 380mc	Indicator that states if personal attendance during the stopping process is required or not		Yes	x		x	
Resolution X Min	Printer	Material	mm	Ultimaker 3	Synonym to Print Accuracy X		600 dpi		x		x
Resolution Y Min	Printer	Material	mm	Ultimaker 3	Synonym to Print Accuracy Y		600 dpi		x		x
Resolution Z Min	Printer	Material	mm	Ultimaker 3	Synonym to Print Accuracy Z		800 dpi		x		x
Operation Allowed for User	Printer	Business Process	[String]	EXP	A list of all users allowed to work on or with the 3D printer		PrinterAdmin, JorgeS, PaulK		x		x
Operation Allowed for Group	Printer	Business Process	[String]	EXP	A list of all user-groups allowed to work on or with the 3D printer		ShopfloorC2, Shopfloor C3		x		x
Maximum Achievable Surface Roughness	Material	Printing Technology + Material	μm	ProX DMP 200	The maximum average achievable surface roughness for a 3D printer		4 μm		x		x
Systematic Shrinkage during Build	Material	Printing Technology + Material	Bool	EXP	Indicator that states if there is systematic shrinkage of the object during the printing process		Yes		x		x
Atmosphere Pressure	Printer		Bar	SLM 125	The required atmospheric pressure for the 3D printer build envelop		6 Bar	x		x	
Atmosphere Connection	Printer		String	SLM 125	The connection of the 3D printer for externally connected atmospheric supply systems		Self-storing connection	x		x	
Atmosphere Content	Printer		[String]	SLM 125	The required atmospheric makeup for the 3D printers build envelope		Argon, Nitrogen	x		x	
Consumables	Printer		[String]	SLM 125, Arcam Q10plus	A list of consumables required for the printing process		1 $\frac{l}{h}$ He	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Compressed Air Supply	Printer		String	Formiga P 110	Specification of the required compressed air connection to the 3D printer		min. 6 000 hPa (87 psi); 10 $\frac{m^3}{h}$ (13.08 m^3)	x		x	
Atmosphere Consumed	Printer		$\frac{l}{min}$	SLM 125	Specification of the amount of externally supplied atmosphere the 3D printer is consuming during a printing process		70 $\frac{l}{min}$	x		x	
Beam Focus Diameter	Printer-Component	Laser lens	μm	SLM 125	The diameter of the laser beam	Laser Based Systems	70 μm		x		x
Laser Energy	Printer-Component		W	SLM 125	The energy that is put out by the laser	Laser Based Systems	400 W	x		x	
Scanning Speed Min	Printer		$\frac{mm}{s}$	[30]	The lowest speed that the laser beam can scan across the build surface	Laser Based Systems	80 $\frac{mm}{s}$	x		x	
Scanning Speed Max	Printer		$\frac{mm}{s}$	[30]	The highest speed that the laser beam can scan across the build surface	Laser Based Systems	90 $\frac{mm}{s}$	x		x	
Laser Type	Printer		String	ProX DMP 200	A specification of the laser type		CO2	x		x	
Power Supply	Printer		A	FORMIGA P 110	The amperage of the power supply to the 3D printer		32 A	x		x	
Power Consumption	Printer		KW	FORMIGA P 110	The wattage of the power supply to the 3D printer		3 KW	x		x	
Power Phase Requirement	Printer		Int	ProX DMP 200	The phase requirement of the power supply to the 3D printer		1 Phase, 3 Phase	x		x	
Precision Optics	Printer-Component		String	EOS M 400	The specification of the laser optics in the 3D printer	Laser Based Systems	F-theta-lenses	x		x	
Legal Conformity Certificates	Printer		[String]	ZPrinter 150	A list of legal conformity certificates for the 3D printer		CE, NFPA	x		x	
Workstation Requirement Ram Min	Printer		MiB	ZPrinter 150	The minimum amount of RAM required for the workstation controlling the 3D printer		8192 MiB	x		x	
Workstation Requirement OS	Printer		[String]	ZPrinter 150	A list of possible operating systems required for the workstation controlling the 3D printer		current Windows operating system	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Workstation Requirement CPU Min	Printer		String	ZPrinter 150	The minimum CPU speed required for the workstation controlling the 3D printer		Intel I5 2.3 GhZ	x		x	
Workstation Requirement Net	Printer		String	ZPrinter 150	The specification for the network connection required for the workstation controlling the 3D printer		Ethernet 1 Gbps, RJ-45 Plug	x		x	
Resolution X	Printer	Material	dpi	ZPrinter 150	Synonym to Print Accuracy X		4000 dpi		x		x
Resolution Y	Printer	Material	dpi	ZPrinter 150	Synonym to Print Accuracy Y		4000 dpi		x		x
Resolution Z	Printer	Material	dpi	ZPrinter 150	Synonym to Print Accuracy Z		4000 dpi		x		x
Number of Jets	Printer		Int	ZPrinter 150	The number of jets in a 3D printer	MJM	304	x		x	
Accepted File Formats	Printer	Firmware	[String]	ZPrinter 850	A list of file formats that the 3D printer is capable of processing		STL, VRML, PLY, FBX, 3DS, ZPR		x		x
Number of Colors	Printer	Print Head	Int	ZPrinter 850	The number of colors that are printable by the 3D printer		390000		x		x
Color Model	Printer	Firmware	String	ProJet CJP 360	The color model used by the 3D printer		CMY, CMYK, Monochrome		x		x
Manufacturer	Printer		String	EOS M 400	The manufacturer of the 3D printer		Zcorp	x		x	
Model	Printer		String	EOS M 400	The model of the 3D printer		Zprinter 850	x		x	
Serial Numbers	Printer		[String]	EXP	To be distinguished between the manufacturer assigned serial number, And possibly a serial number within the institution that utilizes the 3D printer		Mfg: 83892-2883-233, Int: 3838-B	x		x	
Object Bounding Box X Min	Printer	Printing Technology + Material	mm	Shapeways	The minimum size (along the X axis) of any object to be printed		1 mm		x		x
Object Bounding Box X Max	Printer	Printing Technology + Material	mm	Shapeways	The maximum size (along the X axis) of any object to be printed		100 mm		x		x
Object Bounding Box Y Min	Printer	Printing Technology + Material	mm	Shapeways	The minimum size (along the Y axis) of any object to be printed		1 mm		x		x

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Object Bounding Box Y Max	Printer	Printing Technology + Material	mm	Shapeways	The maximum size (along the Y axis) of any object to be printed		200 mm		x		x
Object Bounding Box Z Min	Printer	Printing Technology + Material	mm	Shapeways	The minimum size (along the Z axis) of any object to be printed		1.5 mm		x		x
Object Bounding Box Z Max	Printer	Printing Technology + Material	mm	Shapeways	The maximum size (along the Z axis) of any object to be printed		80 mm		x		x
Min Supported Wall Thickness	Material	Printing Technology + Material	mm	Shapeways	Minimum thickness of any wall (that is supported) of an object that is to be printed		0.8 mm		x		x
Min Unsupported Wall Thickness	Material	Printing Technology + Material	mm	Shapeways	Minimum thickness of any wall (that is not supported) of an object that is to be printed		0.9 mm		x		x
Min Supported Wire	Material	Printing Technology + Material	mm	Shapeways	Minimum thickness of any wire (that is supported) of an object that is to be printed		1 mm		x		x
Min Unsupported Wire	Material	Printing Technology + Material	mm	Shapeways	Minimum thickness of any wire (that is not supported) of an object that is to be printed		1 mm		x		x
Min Emboss Detail Width	Material	Printing Technology + Material	mm	Shapeways	Minimum width of embossed detail on an object to be printed		0.45 mm		x		x
Min Emboss Detail Height	Material	Printing Technology + Material	mm	Shapeways	Minimum height of embossed detail on an object to be printed		0.45 mm		x		x
Min Engraved Detail Width	Material	Printing Technology + Material	mm	Shapeways	Minimum width of engraved detail on an object to be printed		0.5 mm		x		x
Min Engraved Detail Height	Material	Printing Technology + Material	mm	Shapeways	Minimum height of engraved detail on an object to be printed		0.5 mm		x		x

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Min Escape Holes	Material	Printing Technology + Material	String	Shapeways	Description of the type, placement and number of escape holes in an object		More than one hole at the objects lowest points and the top side		x		x
Clearance	Material	Printing Technology + Material	mm	Shapeways	Distance required between any parts of the object or between objects to avoid fusing		2 mm		x		x
Enable Interlocking Parts	Material	Printing Technology + Material	Bool	Shapeways	Indicator if the printing of interlocking parts is feasible		Yes		x		x
Maximum Angle for Unsupported Overhang	Material	Printing Technology + Material	°	EXP	The angle up to which slopes can be constructed without the requirement of supporting structures		45°		x		x
Available Infill Patterns	Software	Version	[String]	Slic3r	A list of available infill patterns for non solid printing		ZigZag, Honeycomb, Random		x		x
Active Cooling Extrudate	Printer-Component	Active Cooling Component	Bool	EXP	Indicator if the extrudate is actively cooled using a fan or not	FDM	Yes		x		x
Hot Pause Ability	Printer	Firmware	Bool	EXP	Ability to pause a print without cooling the extruders		Yes		x		x
Cold Pause Ability	Printer	Firmware	Bool	CELRobox	Ability to halt and resume a print for a longer period of time		Yes		x		x
Requires Support Structure	Printer	Printing Technology + Material	Bool	EOSINT P 800	Describes if the object to be printed requires a support structure or if it can be printed without		No		x		x
Cathode Type	Printer		String	Arcam Q10plus	Describes the cathode, i.e., the electron source, of the 3D printer	EBM	Single crystaline	x		x	
Vacuum Pressure	Printer		mbar	Arcam Q10plus	The pressure of the vacuum required for operation of the 3D printer	EBM	5×10^{-4} mbar	x		x	
Material Supply Format/-Packaging	Printer		String	ProJet 7000 HD & SD	Describes the format in which the material is provided to the 3D printer		Cartridge, Powder, Filament, Pellets	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Noise (Operation)	Printer		dBa	ProJet 7000 HD & SD	The amount of noise emitted by the 3D printer during operation		65 dBa	x		x	
Noise (Preparation)	Printer		dBa	EXP	The amount of noise emitted by the 3D printer during the preparation phase		55 dBa	x		x	
Noise (Idle)	Printer		dBa	EXP	The amount of noise emitted by the 3D printer while idle		40 dBa	x		x	
Laser Wave Length	Printer		nm	ProX DMP 200	Wavelength of the laser unit in the 3D printer	Laser Based Systems	1070 nm	x		x	
Material Deposition Mechanism	PrinterType		String	ProX DMP 200	Similar to the peel mechanism, describes the method with which the powder is spread for the next layer		Roller, Scraper	x		x	
Number of Print Heads	Printer		Int	ProJet CJP 360	The number of individual print heads in the 3D printer		4	x		x	
Filament Diameter	Material	Nozzle + Material	mm	Replicator+	Diameter of the filament usable with the 3D printer	FDM	1.75 mm		x		x
Stepper Motors	Printer-Component		[String]	Prusa i3	Description of Stepper Motors		Nema 17	x		x	
Build Plate Material	Printer-Component		String	Ultimaker 3	Description of the material of which the build plate/print bed is made of		Bor-Silicat glass	x		x	
Nozzle Heat Up Time	Printer	Heating Cartridge	s	Ultimaker 3	Time required for the extruder to heat up to operating temperature, most commonly about 240 °C		300 s		x		x
Build Plate Heat Up Time	Printer	Build Plate	s	Ultimaker 3	Time required for the build plate/print bed to heat up to operating temperature, most commonly about 120 °C		120 s		x		x
Build Speed	Printer	Nozzle + Material	$\frac{mm^3}{s}$	Ultimaker 2+	Indicates the maximum amount of material per second that is deposited during the print		16 $\frac{mm^3}{s}$		x		x

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Platform Leveling Mode	Printer		String	UPBOX+	Describes the mechanism that is used to level the build plate/print bed		Full automatic leveling with integrated leveling probe	x		x	
Laser Class	Printer		Int	Form 2	Classification for the laser system of the 3D printer	Laser Based Systems	Class 1	x		x	
Laser Certification	Printer		String	Form 2	Describes the certification for the laser unit in the 3D printer	Laser Based Systems	EN 60825-1:2007 certified	x		x	
Peel Mechanism	Printer		String	Form 2	Describes the mechanism that is used to peel, i.e., wet the top surface, of an object	SLA		x		x	
Resin Fill Mechanism	Printer		String	Form 2	Describes the mechanism that is used to fill the vat with resin	SLA	Automatic fill mechanism	x		x	
Extruder Heater Cartridge Wattage	Printer	Per Extruder	[W]	ROSTOCK MAX V3	Watts that the heating cartridge of the extruder consumes		40 W		x		x
Extruder Heater Cartridge Voltage	Printer	Per Extruder	[V]	EXP	Voltage with which the heating cartridge for the extruder is driven		24 V		x		x
Firmware Name	Printer		String	Creator Pro 3D	Describes the firmware that is installed on the 3D printer		Sailfish, Marlin		x	x	
Firmware Version	Printer		String	EXP	Firmware version indicator		5.0.1		x	x	
Deposition Rate	Printer	Material	$\frac{kg}{h}$	LENS 450	Rate of which material is deposited, i.e. At which rate an object is printed		0.5 $\frac{kg}{h}$		x		x
Special Facility Requirements	Printer		String	Objet24	Description of special requirements for installation of the 3D printer		None	x		x	
Network Connectivity	Printer		String	Dimension Elite	Describes the kind and speed of the network connectivity of the 3D printer		Ethernet TCP/IP 10/100Base-T	x		x	
Automatic Material Recognition	Printer		Bool	CELRobox	Indicator for the presence of any kind of automatic material recognition system in the 3D printer		Yes	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Internal Lighting	Printer	Lighting Component	String	CELRobox	Describes if and what kind of internal lighting is present in the 3D printer		Full RGB		x		x
Enclosed Build Envelope	Printer		Bool	CELRobox	Indictor for presence of an enclosed build envelope		No	x		x	
3rd Party Material Compatible	Printer		Bool	CELRobox	Indicator for the (allowed) use of compatible third party material		Yes	x		x	
Nozzle Offset X	Printer-Component	Nozzle	mm	EXP	For multi-nozzle systems the offset of each nozzle to the middle of the print head (X axis)		5 mm		x		x
Nozzle Offset Y	Printer-Component	Nozzle	mm	EXP	For multi-nozzle systems the offset of each nozzle to the middle of the print head (Y axis)		0 mm		x		x
Nozzle Offset Z	Printer-Component	Nozzle	mm	EXP	For multi-nozzle systems the offset of each nozzle to the middle of the print head (Z axis)		0 mm		x		x
Coordinate System	Printer		String	EXP	Cartesian, Polar, Spherical or other coordinate system that is used by the printer for movement and positioning		Cartesian coordinate system	x		x	
Printer Geometry	Printer		String	EXP	Cartesian, Polar or Spherical geometry of the printer. Also possible to denote robot based geometry		Polar geometry	x		x	
Coordinate System Origin	Printer		String	EXP	Denotes the origin of the 3D printer that is used for referencing		Origin is at top right corner of 3D build envelope				
Absolute Density	Material		$\frac{g}{cm^3}$	ProX DMP 200	Material property		4.51 $\frac{g}{cm^3}$	x		x	
Relative Density	Material		%	ProX DMP 200	Material property		100.00%	x		x	
Cytotoxicity (ISO 10993-5)	Material		Int	ProX DMP 200	Material property		Grade 0	x		x	
Melting Point	Material		°C	ProX DMP 200	Material property		1668 °C	x		x	
Magnetic Permeability	Material		$\frac{H}{m}$	ProX DMP 200	Material property		1.0008 $\frac{H}{m}$	x		x	

TABLE II: Properties in Additive Manufacturing – continued

Name	**Category**	**Dependent Upon**	**Unit**	**Source**	**Meaning**	**Only Applicable for**	**Example**	**Static**	**Dynamic**	**Independent**	**Dependent**
Electrical Resitivity	Material		nΩ×m	ProX DMP 200	Material property		740 nΩ×m	x		x	
Specific Heat Capacity	Material	Temperature-Range	$[\frac{J}{kg \times K}]$	ProX DMP 200	Material property		0–100 °C: 500 $\frac{J}{kg \times K}$		x		x
α/β Transus Temperature	Material		°C	ProX DMP 200	Material property		882 °C	x		x	
Micro Vickers Hardness	Material		Hv	ProX DMP 200	Material property		210 Hv	x		x	
Coefficient of Thermal Expansion	Material	Temperature-Range	$[\frac{1}{°C}]$	ProX DMP 200	Material property		20–100 °C: 7.71 $\times 10^{-}6$ / °C, 20–300 °C: 9.4 $\times 10^{-}6$ / °C		x		x
Macro Rockwell C Hardness	Material		HRC	ProX DMP 200	Material property		30 HRC	x		x	
Thermal Conductivity	Material	Temperature	$[\frac{W}{m \times K}]$	ProX DMP 200	Material property		50 °C: 16 $\frac{W}{m \times K}$		x		x
Flexural Modulus	Material		MPa	ProX 800	Material property		1660 MPa	x		x	
Flexural Strength	Material		MPa	ProX 800	Material property		55 MPa	x		x	
Tensile Modulus	Material		MPa	ProX 800	Material property		1590 MPa	x		x	
Tensile Strength	Material		MPa	ProX 800	Material property		38 MPa	x		x	
Elongation at Break	Material		%	ProX 800	Material property		13.00%	x		x	
Impact Strength	Material		$\frac{J}{m}$	ProX 800	Material property		19 $\frac{J}{m}$	x		x	
Heat Deflection Temp	Material	Pressure	[°C]	ProX 800	Material property		60 psi: 58 °C, 264 psi: 51 °C		x		x
Viscosity	Material	Temperature	[cps]	ProX 800	Material property		30 °C:25, 50 °C:20		x		x
Shore Hardness	Material		D	ProX SLS 500	Material property		73 D	x		x	
Dielectric Constant	Material	Frequency	[Int]	ProX SLS 500	Material property		3.31		x		x
Dielectric Strength	Material		$\frac{kV}{mm}$	ProX SLS 500	Material property		18.1 $\frac{kV}{mm}$	x		x	
Volume Resistivity	Material		Ω×cm	ProX SLS 500	Material property		7.2 $\times 10^{1}4\Omega\times$cm	x		x	
Flammability	Material	Length	[String]	ProX SLS 500	Material property		HB		x		x
Young's Modulus	Material		GPa	ProX DMP 200	Material property		105 GPa	x		x	
Yield Strength	Material		MPa	ProX DMP 200	Material property		320 MPa	x		x	
Ultimate Tensile Strength	Material		MPa	ProX DMP 200	Material property		450 MPa	x		x	

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