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Development of a Methodology for the Digital Representation of Manufacturing Technology Capabilities

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Abstract

The demand for efficient and digital systems for supporting the decision making during the design of a product is a key issue in manufacturing companies. Decisions made during the development and design of a product have a strong impact on the costs and delivery times of a product. Hence, a digital system which supports the engineer during and after the development process with information about the manufacturability of the product can reduce the production costs and times. In order to be able to evaluate the manufacturing capabilities at manufacturing process and machine level, there is a need to represent them in a digital way. Digital knowledge bases like taxonomies and ontologies provide the possibility for a representation of manufacturing resources. The state of the art shows different approaches for the use of ontologies in the domain of subtractive manufacturing processes as well as additive manufacturing (AM) processes. The goal of this work is the semantical representation of manufacturing technology capabilities with focus on AM-machines and processes. In this paper we introduce taxonomies of Manufacturing Features and Manufacturing Restrictions which were developed in accordance with current standards. To enrich the taxonomies with information, it was enhanced by relations between different manufacturing related entities in a knowledge graph. If manufacturing processes and machines can be digitally mapped, described and linked to the geometric information of a product together with information on the current performance of the company/network, bottlenecks and delivery delays during the manufacturing of parts can be avoided.

Keywords

Knowledge Representation; Taxonomy; Knowledge Graph; Ontology; Additive Manufacturing

1. Introduction

The ongoing demand on companies to reduce manufacturing costs and delivery times of products requires the development of new approaches and methods [1], [2], [3]. Decisions made during the design process of products have significant impact on costs as well as production and delivery times [4]. Incomplete information about the availability and capabilities of manufacturing technology resources in the factory can lead to design changes which can then cause delayed delivery times and increased cost [5], [6]. The use of information on available resources and capabilities in the company during the design phase of a product can prevent these problems [7]. Especially for the development of components with batch size one (engineer-to-order products), the development costs play a significant role. For small batch sizes innovative manufacturing processes such as additive manufacturing (AM) play an increasingly important role. In order to be able to evaluate the manufacturing possibilities of a factory automatically at the process and machine level, it is necessary to digitally represent the capabilities of manufacturing processes and manufacturing machines. Hence, these properties and capabilities must be described semantically and in a machine-readable manner. Furthermore, in addition to the requirements mentioned above, such a system must also be easy to

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extend, be used for the description of as many manufacturing processes as possible, and be used specifically for the description of component properties as well as machine capabilities. In this work, we represent the knowledge and information about the properties of a certain manufacturing process or the capabilities of a certain manufacturing machine digitally and semantically in an ontology.

There are various methods described in the literature for semantically representing knowledge [8], [9], [10], [11]. Those methods differ in quantity of richness of information and relationships. The semantic staircase model compares and sorts these models depending on their semantic richness [8]. In ascending order, the following models are on the semantic staircase: glossaries, taxonomies, thesauruses, topic maps, and ontologies. According to Blumauer and Pellegrini, ontologies are considered to be the richest. [8]

Gruber describes ontologies as follows: „An ontology is a formal, explicit specification of a shared conceptualization" [12]. This means that an ontology is used to describe the common understanding of reality. Furthermore, an ontology can be defined as the explicit formal definition of concepts in a particular setting and the relationships between them [13]. This formality allows knowledge to be represented in machine-readable form. [14], [15], [16]

Ontologies in manufacturing engineering exist for both the subtractive and additive manufacturing domains. The current state of the art shows, that most approaches are aiming at automated process step planning. For example, in the domain of subtractive manufacturing processes, Ma et al. [11] represent in their work the fundamental Manufacturing Features for the turning process in a taxonomy in order to be able to use them subsequently for manufacturing planning. In the area of additive manufacturing, Sanfilippo et al. [17] present an ontology that contains the fundamental principles of additive manufacturing. In addition to domain-specific ontologies, cross-domain knowledge representations for manufacturing processes are also presented by some authors (e.g. MASON [18] or MDSL [19]). Summarized the state of the art shows some gaps in the area of automated feasibility checks depending on capabilities of available additive manufacturing machines. The goal of this work is therefore to semantically describe additive manufacturing processes and the capabilities of manufacturing machines in an ontology in order to subsequently make a statement about the manufacturability of a component. A digital and semantic representation of manufacturing technologies and conditions in combination with evaluation algorithms, can be used to automatically evaluate a designed 3D model according to specifications of manufacturability and cost requirements. This approach is based on the idea that specific statements about the manufacturability on a certain machine can be made, by the combination of taxonomies for Manufacturing Features (MF) and Manufacturing Restrictions (MR) in an ontology. In future works, we will present a reasoner, which access the information represented in the ontology.

2. Literature review

The state of the art shows different existing approaches for this purpose, which will be reviewed in detail in the following sections. Current research can be divided into the broad domains of subtractive and additive manufacturing technologies. Furthermore, different goals can be pursued with the presented ontologies, for example, they can be used for process step planning, for the analysis of manufacturability or for the assignment of components with the corresponding manufacturing processes and/ or machines.

The following publications can be attributed to the field of process step planning of subtractive manufacturing processes. In 2015, Rehage and Gausemeier [20] presented the ontology *InVor*. In this ontology, tools of CNC machines are represented and the possible NC functions are assigned to them. The authors also follow the approach of determining alternative CNC machines based on the NC codes of a component mapped in the ontology. A similar approach for process step planning for milled parts is pursued by the authors Eum et al. [21]. The content of their publication is a system based on ontologies, in order to determine and assign the process steps of the manufacturing of a component. For this purpose, selected features for the milling process and their description by logical rules are explained in their paper. A publication on process planning of prismatic parts using a process model based on ontologies is presented by the authors Kang et al. [22] In this work, part features and manufacturing process steps which can be performed with a milling machine are described and then linked by appropriate rules.

In order to represent the properties of manufacturing technologies in an ontology, a taxonomy of possible MFs can be created, which contains geometries that can be manufactured by using individual technologies. This approach is pursued by Ma et al. [11] in the field of rotation-symmetric components. In their work, they represent the basic MFs for the turning process in a taxonomy in order to subsequently enable the planning of manufacturing. Besides subtractive manufacturing processes, ontologies for process step planning of additive manufacturing are also part of recent scientific research. For example, Liang [23] presents in his paper a methodology for representing additive manufacturing using a knowledge base. The result of the presented research is an ontology (*AM-OntoProc*) which aims at supporting process planning of additive manufacturing. Another part of current research is the automated assignment of components to processes and machines that can produce this component. Publications exist here in the area of both subtractive and additive manufacturing processes. Mesmer and Olewnik [24] published in their work a methodology based on an ontology model for the assignment of components and the corresponding subtractive manufacturing processes. The concept of the methodology relies on the fact that a manufacturing process can be determined based on features and attributes of a product. The objective of the publication by Ming et al. [25] is to automate and thus facilitate the selection of tools in CNC milling machines. In their paper, a taxonomy is presented, which is extended by relations and properties. The authors Sarkara and Šormaz [26] present in their work an ontology that describes the properties of manufacturing processes and matches them with the capabilities/boundaries of manufacturing resources. In their work, subtractive manufacturing processes are considered and represented. Part features are assigned to the corresponding subtractive manufacturing processes, and then the part features and manufacturing process steps are linked to the corresponding machines using logical rules to enable step-by-step process planning. In 2015, the authors Eddy et al. [27] presented an ontology that works in combination with a rule base. The use of the rule base allows, on the one hand, support for decision making in process planning in additive manufacturing and, on the other hand, determination of the appropriate manufacturing processes for a component. Furthermore, Kim, Rosen et al. [28] present the structure of an ontology in their 2019 publication and show how rules for creating AM components can be digitally described. In this ontology, MFs are introduced, which allow the representation of design features and their restrictions caused by the respective AM process and thereby achieve a manufacturability check with the help of these features. Ko et al. [29] present the extension of this work in 2021. The authors present a knowledge graph that supports engineers in the design of AM components.

The described studies show that there is a huge interest in the topic of knowledge representation for manufacturing technologies. For the more specific approach of assigning capable manufacturing machines, some authors describe the capability of machines and processes by means of MFs and restriction properties of a part. For those studies, some research gaps can be outlined. First, a manufacturability analysis, as well as an analysis of machine resolution and accuracy restrictions of additive manufacturing parts in order to assign a part to a certain machine individual is not considered. Second, the taxonomies of MFs were not compiled according to current standards of manufacturing technology, in order to be able to guarantee a reliable assignment of the features to the machines. Third, the Manufacturing Restrictions, which describe the capabilities of a machine and define the properties of the MFs were also not selected based on current standards for additive manufacturing. Furthermore, those restrictions were not introduced in a taxonomy model to provide a framework for ensuring an easy expandability.

3. Methodology

For the semantic description of knowledge of the capabilities of manufacturing processes and machines, a knowledge base is developed and presented in this paper. The capabilities of manufacturing processes are described by a semantic representation of manufacturable part geometries. These part geometries are further referred to as Manufacturing Features. In the presented method, the MFs are defined based on current manufacturing technology standards and then semantically represented in a taxonomy. The challenge here is to model the MFs in a way they represent a wide range of manufacturing processes. To describe the capabilities of a manufacturing process, the MFs are assigned to them in an ontology. For example, a turning process can only produce rotation-symmetric parts/features, whereas a milling process or an additive manufacturing process can also produce asymmetric features. Thus, a semantic description of manufacturable geometries of a process is provided. However, in order to be able to represent the capabilities of manufacturing machines in the same manner, it is not sufficient to assign only MFs. In reality, different machine individuals are able to execute the same manufacturing processes, but are not necessarily able to produce the same individuals of particular MFs. It is therefore necessary to define a set of restrictions that characterize both the capabilities of a machine and the geometric details of the MFs. These restrictions are called Manufacturing Restrictions (MR) in the following and are also defined according to current standards of manufacturing technology and represented in a taxonomy. In the section below, the structure of the ontology as well as the MFs and MRs are further described.

3.1 Knowledge Base

An ontology is used as the preferred knowledge base in this work, since this form of knowledge representation contains the most information. Furthermore, it is easily possible to extend the knowledge base e.g. with further MFs and MRs. The structure of the developed ontology is divided into two parts. The concepts of the manufacturing domain are represented in the Terminology Box (TBox). Here, the blueprints of the five main classes *ManufacturingFeature*, *ManufacturingRestriction*, *ManufacturingProcess, ManufacturingMachine* and *Part* are described with their corresponding subclasses and properties. The individuals of the classes are mapped in the Assertion Box (ABox). In addition to the part properties defined by the MFs and -Restrictions, the knowledge about the capabilities and limitations of particular machine individuals is also described here.

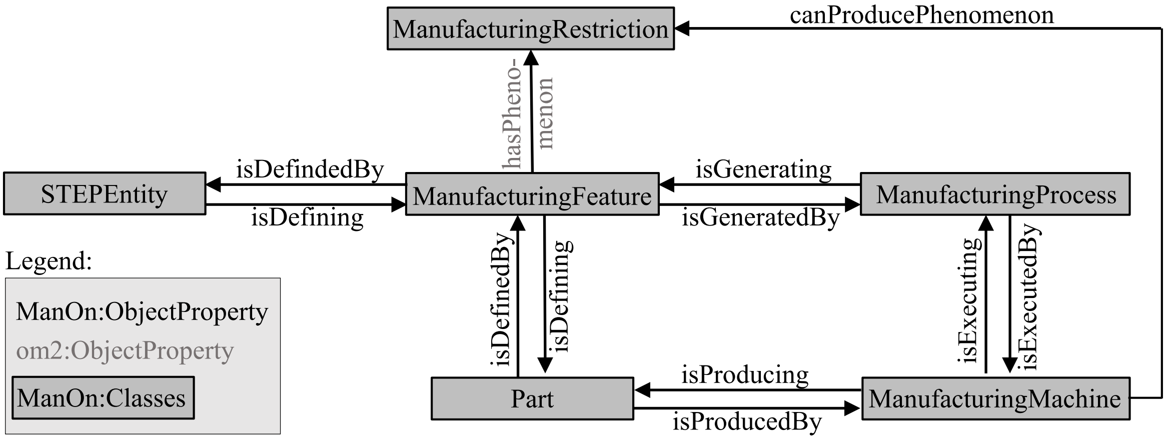

Figure 1: Structure of the presented ontology for providing manufacturability analyses

Figure 1 shows the TBox of the ontology. The shown structure of the ontology contains elements from the Ontology of units of Measure (om2) [30] in addition to self-defined classes and properties. At the center of the presented ontology is the class *ManufacturingFeature*, this class defines the class Part and is defined by class *STEPEntity*. *STEPEntity* describes the entities of the STEP-schema [31], which provides a standard for the exchange of product manufacturing data. Furthermore, the class *ManufacturingProcess* is described in the ontology. This class can generate a *ManufacturingFeature* and is executed by the class *ManufacturingMachine*. In order to be able to make a statement about the manufacturability of a *Part* in terms of accuracy requirements, geometric requirements and surface quality requirements, the *ManufacturingRestriction* class is linked to both *ManufacturingFeature* (by the ObjectProperty *om2:hasPhenomenon*) and *ManufacturingMachine* (by the ObjectProperty *canProducePhenomenon*). In the ontology it is defined which *ManufacturingFeature* has which *ManufacturingRestriction*. The properties associated with the *ManufacturingRestrictions* of features and machines can be compared, by the use of a reasoner, to achieve an assignment of MFs and Machines. The manufacturing technology aspect behind the *ManufacturingFeature* and *ManufacturingRestriction* classes is described in the next two sections.

3.2 Manufacturing Features

Before taking the step of semantically representing various manufacturing processes, the capabilities of those processes must first be analyzed and defined in more detail. A wide range of standards [32], [33], [34], [35] were consulted for this purpose in order to achieve a unified model of manufacturing process representation. Moreover, the Manufacturing Features, defined according to current manufacturing technology standards, are then used to build up a taxonomy (see Figure 2). The represented information about manufacturable geometries can be used for describing the manufacturing process capabilities.

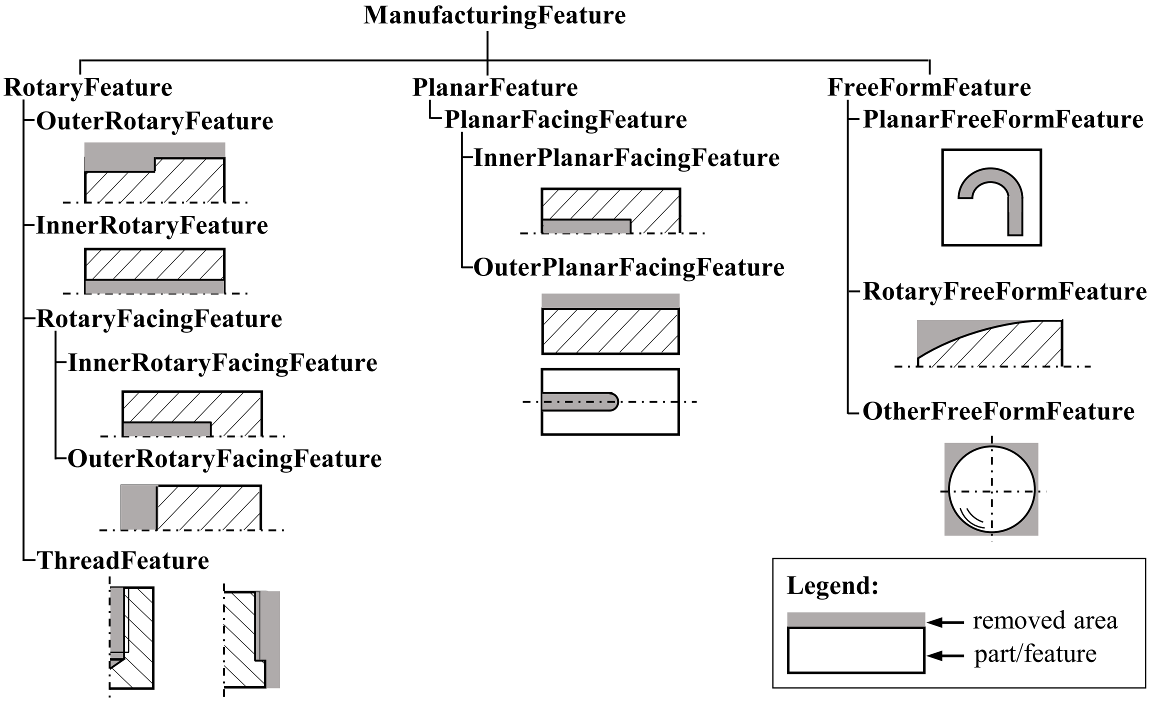

Figure 2: Representation of the taxonomy for Manufacturing Features with selected illustrated geometries

Based on the standard DIN 8589 [36], the MFs are defined in the following sections and specified in a taxonomy (see Figure 2). Since it is possible to produce almost all geometric shapes with additive manufacturing processes, subtractive manufacturing standards were used for modeling the MF taxonomy in order to obtain a more detailed description. The taxonomy of MFs can be used to define both, subtractive and additive manufacturing processes, by combining the MFs with the MRs that have been modelled on the basis of current additive manufacturing standards (see chapter 3.3).

In the presented taxonomy, a MF is divided into the three areas of geometric shapes: rotation-symmetric features (*RotaryFeature*), planar features (*PlanarFeature*) and other features (*FreeFormFeature*). The *FreeFormFeatures* here represent both rotation-symmetric features and planar features with a freely designed shape. This classification relies on the capabilities of different manufacturing processes. For example, all subclasses of *RotaryFeature* can be produced by a turning process.

These features are further divided by a classification based on the location of the machining area. The subclasses of *RotaryFeature* are divided into inner (*InnerRotaryFeature*) and outer machining (*OuterRotaryFeature*), as well as thread machining (*ThreadFeature*) and face machining (inner and outer machining) (*RotaryFacingFeature*). *PlanarFeature* is also divided into inner and outer machining. An *InnerPlanarFacingFeature* can be defined by the base area of a rotation-symmetric hole, a pocket or a slot. *OuterPlanarFacingFeature* refers to all geometric elements that are located on the outer surface of a component. This feature can represent geometries such as walls and other planar contours. Since the *FreeFormFeature* class describes a mixture of planar free form contours (*PlanarFreeFormFeature*), rotation-symmetric free form contours (*RotaryFreeFormFeature*) and other free form contours (*OtherFreeFormFeature*), all geometric elements that embody complex geometries are covered in this class.

3.3 Manufacturing Restrictions

The layered build-up of parts by additive manufacturing processes makes it possible to produce almost any geometric shape. Hence, a semantic process description only using MFs is not possible. In addition to the geometric description of the MFs, the limitations of manufacturing machines must also be described semantically and represented in a taxonomy. Those limitations are called Manufacturing Restrictions in this work. For example, it depends on the process type whether and to what extent unsupported or overhanging structures can be manufactured. Furthermore, restrictions in the area of tolerances and surface qualities have to be included.

Figure 3 shows the taxonomy of MRs. This taxonomy was developed by including standardized test characteristics for restricting geometrical properties as well as standardized technical aspects for the selection of suitable additive manufacturing processes. These were developed based on the guideline VDI 3405 sheet Nr. 3.2 [35], the standard DIN EN ISO/ASTM 52902 [33] and the standard DIN EN ISO/ASTM 52910 [34]. Furthermore, the elements of geometric tolerancing according to DIN EN ISO 1101 [32] were included in the taxonomy and described semantically. MRs can be different, with the same process, depending on the type of machine. In the presented taxonomy, the class of MRs is divided into the subclasses *Accuracy*, *Resolution*, *Manufacturability* and *SurfaceStructure*. The subclasses of these classes are described in Figure 3 with example drawings. In the following section, these subclasses will be further explained.

The accuracy with which a machine can produce a MF can be a decisive limitation for the selection of the machine. These limitations are represented in the *Accuracy* class, which is divided into *SizeTolerance*, *GeometricTolerancing* and *GeometricDimensioning*. The last two subclasses are described in accordance with DIN EN ISO 1101 [32]. According to this standard, *GeometricTolerancing* describes, for example, the roundness of a cylinder or the flatness of a surface. Examples of *GeometricDimensioning* are the parallelism between two planes or the concentricity of two cylinders. Another point in the area of restriction *Accuracy* is *SizeTolerance*. This restriction describes how precisely a machine can reproduce a digital model or drawing, or how strong the deviations from the model or drawing are.

The minimal manufacturable geometric structures are described by the MR of the maximum *Resolution* of a machine. Depending on the process and machine type, there is a minimum size of a feature, which can be created by the size of the tool or by the minimum layer width. Walls defined by a minimum *WallThickness* and pins defined by a minimum cylindrical *PinDiameter* can be assigned to the positive volume range of a part. In turn, the restrictions minimum *HoleDiameter* and minimum *GapWidth* are assigned to the area of negative volume. The minimum *EdgeRadius* describes the minimum manufacturable radius of an inner or outer edge.

The *Manufacturability* restrictions presented are mainly related to additive manufacturing, since this paper focuses on the semantic representation of AM-technologies. Some additive manufacturing processes make it possible to create cantilevered structures and overhangs by building removeable support structures. The restriction of the maximum overhang is described in the taxonomy by the class *UnsupportedStructure*. The minimum *TiltAngle* describes the minimum angle at which a structure can be situated in relation to the base plane. Above a certain tilt angle, a support structure is necessary in additive manufacturing to be able to produce a MF. Furthermore, the *HorizontalHoleDiameter* class describes the minimum producible diameter of a hole that is horizontal to the base surface.

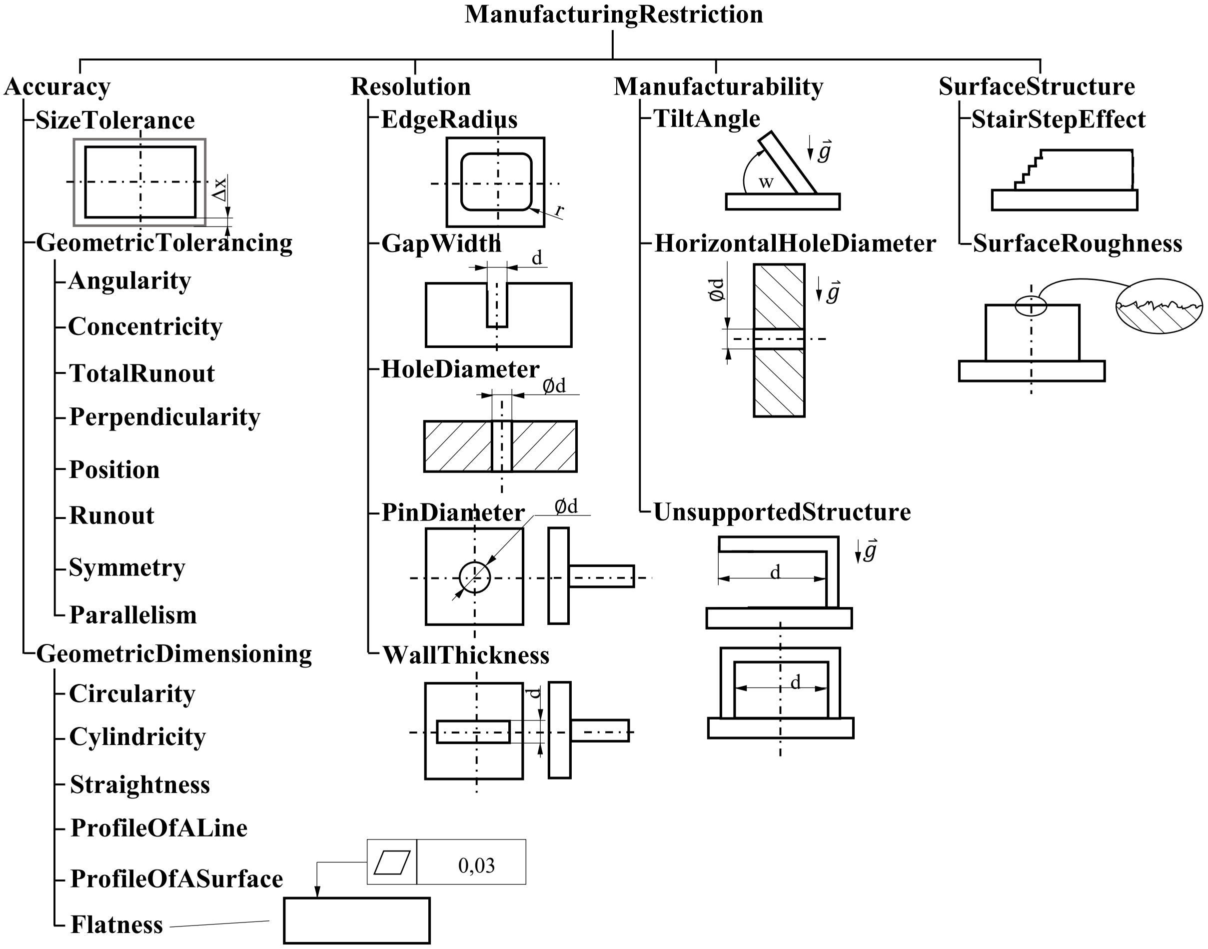

Figure 3: Representation of the taxonomy for Manufacturing Restrictions with selected illustrated geometries

Depending on the manufacturing process and the machine used, different qualities of surface structure can be generated. Those restrictions are represented in the class *SurfaceStructure*. The *SurfaceRoughness* applies as a restriction for both subtractive and additive manufactured components. If a function is assigned to a certain surface, then a maximum tolerated surface roughness must be defined. However, if a machine cannot achieve this quality, this has a limiting effect on component production. In addition to *SurfaceRoughness*, there is a further restriction in the area of surface structure. Due to the layered structure of a component in additive manufacturing, a step effect occurs horizontally to the build direction. This effect depends on the minimum layer height of a manufacturing process and the tilt angle of a feature. For example, a powder-bed laser process has a lower minimal layer height than a wire-based process. In the taxonomy this restriction is represented in the class *StairStepEffect*.

4. Conclusion

In this work we present a method to digitally and semantically represent geometric properties of components as well as the capabilities of additive manufacturing processes and machines. The basis of this method is an ontology that provides the structure for matching the required properties of components with the existing capabilities of machines. The representation of parts is done by geometric MFs in combination with limiting MRs. The described MFs combined with the MRs completely define and represent a part on an abstract level to achieve the goal of semantically modeling manufacturing processes. MRs are also used to describe the capabilities of manufacturing machines. The taxonomies presented in this paper contain the geometrical description of components (MFs) as well as machine and geometry dependent restrictions (Manufacturing Restrictions). The MF taxonomy is categorized according to the criteria of geometric shape (rotation-symmetric, planar and other contoured). This taxonomy can be applied to represent additive as well as subtractive manufacturing processes. With the MR taxonomy, we present a taxonomy for the limiting restrictions for additive manufacturing. In future works, we will extend and apply the MR taxonomy to subtractive manufacturing. In addition to the expansion of new process types and machine types, changes due to innovations in the field of manufacturing technology result in new Manufacturing Features and -Restrictions. Due to the structure of the taxonomies and the ontology, new restrictions and features can easily be added and extended. In the coming future the results of this paper are used to build a knowledge graph, which is used to plan the capacity utilization of a factory automatically, by assigning parts to a capable machine. Those automated assignments result from a comparison of the required MRs of a part and the existing restrictions of the machines in a factory. Furthermore, we will validate and evaluate the presented methodology with real world data.

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Biography

Tobias Köhler studied mechanical engineering at the Technische Universität Ilmenau, Germany. Since 2017, he has been a PhD candidate and research associate in the Production Technology Group (IFt) at the Technische Universität Ilmenau. Since 2019, he has been working for a scientific cooperation between IFt and the German Aerospace Center (DLR). His research topics are solid state welding processes and the digitization in production technologies.

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Philipp Matthias Schäfer studied Mathematics at the Technical University of Ilmenau, the University of Cambridge, and at Ulm University, receiving his PhD in 2012. He worked for 6 years as a Software Developer. Since 2017 he is a research associate at the Institute for Data Science in the German Aerospace Center (DLR) working on ontologies for robotics.

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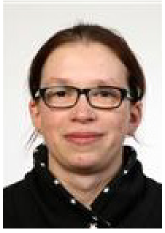

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