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A Framework to Collect and Reuse Engineering Knowledge in the Context of Design for Additive Manufacturing

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Abstract

Design for AM (DfAM) requires the definition of Design Actions (DAs) to optimize AM manufacturing processes. However, AM understanding is still very blurred. Often designers are challenged by selecting the right design parameters. A method to list and collect DfAM DAs is currently missing. The paper aims at providing a framework to collect DfAM DAs according to a developed ontology to create databases (DBs). DBs were tested with two real case studies and geometric features to improve identified. Future developments aim at widening the database to provide all-around support for AM processes.

Keywords: *design for additive manufacturing (DfAM), ontology, knowledge-based engineering (KBE), computer-aided design (CAD)*

1. Introduction

Additive Manufacturing (AM) is a relatively new technology. It was developed in 1986 by Charles Hull with a process called stereolithography (SLA) (Ngo et al., 2018). Since then, AM increased the capability to handle different materials and production processes, such as powder bed fusion, fused deposition modelling (FDM), inkjet printing, contour crafting (CC), etc. The main advantage of the AM process concerns the overcome of design limitations associated with common manufacturing processes, such as the impossibility to machine internal volume of the closed body or the inability to create complex structure from a single piece (Gillespie, 2017). AM is being explored in several fields (e.g., biomedical (Bose et al., 2013; Wang et al., 2016); space (Garzaniti et al., 2019), etc.) and interesting reviews regarding AM technologies and their application have been proposed by Ngo et al., 2018 and Gao et al., 2015. To capture the opportunities given by AM technologies, it is necessary to consider their impact from the beginning of the product development process. On this aim, design methodologies such as the Design for Additive Manufacturing (DfAM) have been developed. DfAM belongs to the family of DfX methods which aim is to optimize the engineering design process in compliance with the adoption of AM technologies (Vaneker et al., 2020). The aim of DfAM techniques can be summarized as *"Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives."* (Chu et al, 2009). Since AM does not have many years of consolidation and practice in manufacturing as the traditional processes, the benefits introduced by AM processes and the limitations are often not clear for designers and engineers (Gibson et al, 2010). Several papers highlighted the need for design rules related to AM processes, capabilities, and materials (Liu, 2016; Hague et al., 2004). Knowledge formalization is the engineering branch that studies ways to capture and collect engineering knowledge, from simple approaches (i.e., documentation) to complex model based on ontology (Chandrasegaran et al., 2013). Currently in literature, several models focused on the formalization of AM knowledge were proposed (Lu et al., 2018; Eddy et al., 2015). However, to the best of author's knowledge, only preliminary works for collecting AM knowledge to avoid manufacturing issues have been provided. For instance, San Filippo et al., 2019 proposed an ontology which relies on both expert's knowledge and well-known modelling principles in order to collect AM knowledge, however it does not provide specific guidelines related to the geometrical features; Hagedorn et al., 2018 describes an ontology which is highly focused on innovative design, without tacking manufacturing aspects; while Favi et al., 2021 developed an ontology to assess manufacturing problems, however the provided DfAM rules are limited and do not consider printing directions. Printing direction plays a central role in AM processes, it influences several parameters such as product mechanical properties (material anisotropy, porosity, etc.) (Hanzl et al., 2015), the support type, the position, and the building time itself (Leary et al., 2014). Indeed, the less supports are used, the more efficiency the printing process will be since fewer finishing operations are required. The aim of this paper is to provide a framework to collect design actions for DfAM technologies based on a defined ontology to consider manufacturing issues together with printing directions. The main novelty recalls the possibility to link geometrical features of the product under development with the limitations of different AM technologies. The use of this limitation during the product development process allows predicting and avoiding possible geometrical features that cannot be realized by AM processes or required additional processes and costs. Ontologies are structures enabling to organize the knowledge, defining categories, properties, the relation among concepts and data relation (Chandrasekaran et al., 1999). The knowledge can be represented in several forms (e.g., hierarchical structure, graph, etc.). A well-designed ontology needs to follow five (5) criteria (Gruber, 1995): 1) *Clarity* - it should state objectively reasons to choose a specific class of objects; 2) *Coherence* - definitions and axioms obtained from the ontology must not contradict any other definition/axiom; 3) *Extendibility* - it should be able to incorporate future knowledge; 4) *Minimal encoding bias* - all information must be expressed at the knowledge level, meaning the knowledge correctness must not be affected by notation or implementation bias; 5) *Minimal ontological commitment* - it should make no claims about the world being modelled. The framework developed within this work uses a hierarchical ontology to collect AM rules and design practice into two databases (DBs): i) AM Designer DB, and ii) AM Machine Operator DB. The former is used by the designer during the product development to correctly design the component and its features, while the latter is used by the machine operator to choose the printing direction. The remainder of the paper is structured as follows. Section 2 (Ontology Derivation) presents the method used to create the ontology and to list AM rules. Section 3 (Case Study) presents the test and validation of the derived database, presenting two real case studies. Section 4 (Results and Discussion) discussed the obtained results. Finally, Section 5 (Conclusion and Future development) draws the conclusion and identifies avenues of future work.

2. Ontology Derivation

The framework used to derive the ontology and the subsequential AM design actions database is composed of three (3) steps (Figure 1).

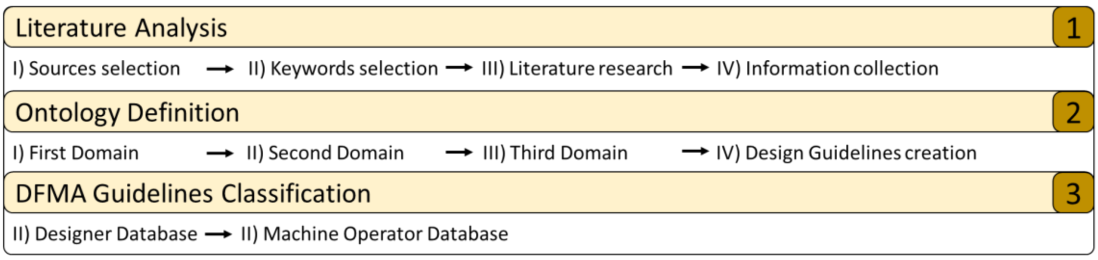

Figure 1. Ontology and database definition framework. Main steps are highlighted on the right whereas the task included in each step are described on the left.

Step 1 - Literature analysis. It consists in searching design issues associated to AM technologies. The goal of this step is to understand the main limitations of each AM technology according to the material selected, the technology used, and the features desired. The research was performed querying four

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different sources: i) books, ii) scientific databases (i.e., Google Scholar, Emerald, ScienceDirect, Scopus), iii) patent databases, and iv) company databases. The research was performed according to a keyword approach: once the source was selected (i.e., an article), a global search was performed using keywords such as "design rules", "design limitation", "design expertise", "drawback", "restriction", "performance". Also, plural and synonyms were considered. To further widen the research, meetings with experts in the field of AM technologies were arranged, in order to formalize their knowledge. The outcome of the literature analysis step was a list of unstructured information in the form of phrases (suggestions, good practice, etc.), features and parameters involved, and numbers (the threshold for given parameters, etc.). Most of the information collected is not based on a scientific foundation but is rather driven by experience (i.e., rules of thumb).

Step 2 - Ontology definition. It is based on three domains. Each domain classifies different product parameter**s**. *Domain I* describes the model geometry through the definition of model geometric features. A geometric feature is a 3D geometrical representation of elements such as slots, holes, fitting, etc. (Nasr and Kamrani, 2007). *Domain II* classifies AM technologies. The classification is done considering a funnel of four elements. *Domain III* catalogues the material used. Materials are classified as Plastics and Metals. An excerpt of the ontologies for features, technologies and materials are shown in Figure 2, Figure 3, and Figure 4 respectively. The identified domains are used to build DFAM design guidelines (DGs). DGs are expressed in two forms: i) language and ii) mathematical. The former is represented by a specific sentence made of an infinite verb + noun to which auxiliary information can be added, if necessary. The latter consists of the definition of a numerical threshold for the geometrical feature associated with the DG. Thresholds can be a single value or a range of values. To better guide the user through the error, a detailed explanation was added. Rules must be classified according to their importance. Classification is done with three different error types: i) Information - this error does not impact the manufacturing nor the cost of the component; ii) Warning - this error does not prevent the product manufacturability but increase the cost and the time of the process, and iii) Critical - this error prevents the product manufacturability. Finally, the source where the AM rule is obtained must be collected in the final section. In fact, the AM field is a constantly evolving area, it is necessary to keep track of AM design actions to check their validity in the future years.

Step 3 - DFAM design guidelines classification. It allows the creation of a cluster of DGs into two different databases, respectively the AM Designer DB and the AM Machine Operator DB. The AM Designer Database presents design rules that need to be considered during the product development phase. These guidelines aim at supporting the product design process, checking that the final product can be manufactured rightly, given the constraints of current AM technologies. The latter is meant to support the AM machine operator during the manufacturing process. The aim is to guide the operator through the choice of component orientation to accomplish the desired mechanical and aesthetic characteristics.

3. Case Study

The proposed framework was applied to research and collect AM design rules for plastic and metal. From the first step (Literature analysis) 157 AM design suggestions for plastic materials and 270 for metal materials were obtained. The sources used are summarized in Table 1.

Table 1. Design actions per material per source

Material	Source	Number of design hints found
Plastics	User Experience	51
	Books & Articles	95
	Industrial Databases	11
Metals	User Experience	89
	Books & Articles	91
	Industrial Databases	90

Then, all design suggestions were structured to be compliant with the developed ontology.

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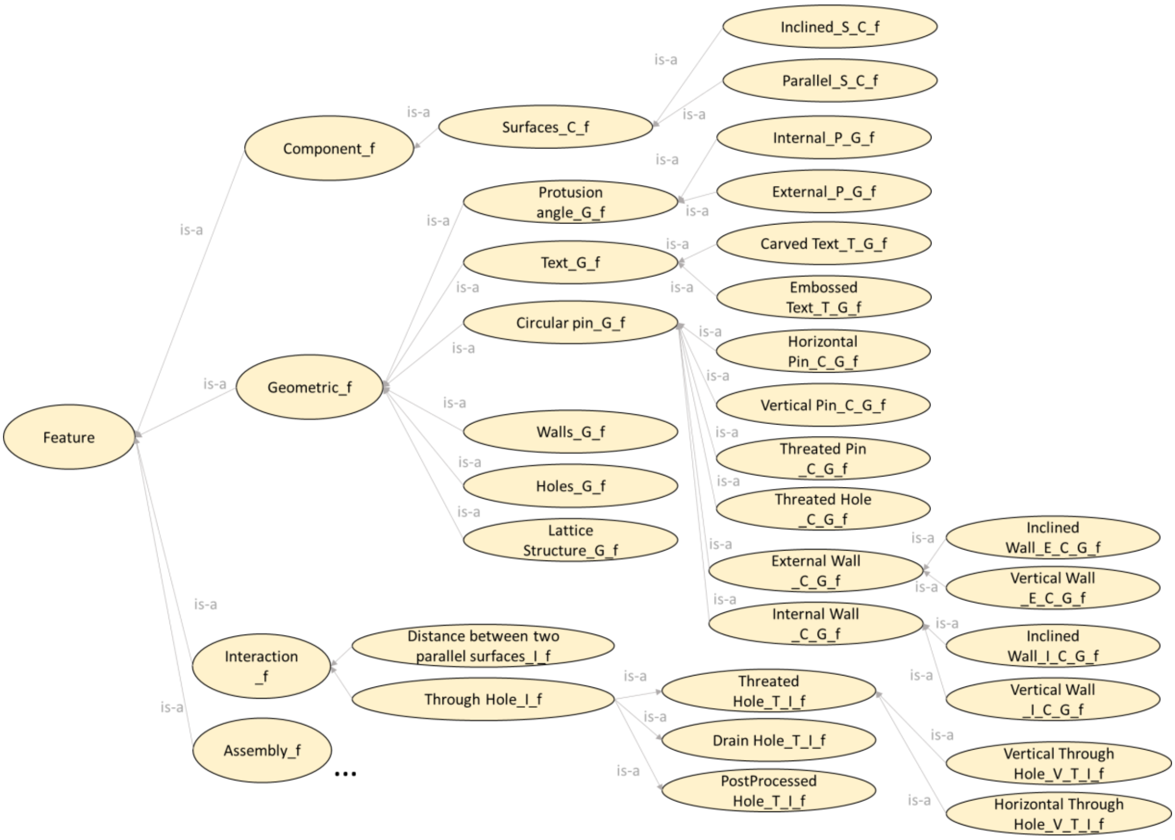

Figure 2. Domain I - Excerpt of feature ontology defined according to OWL

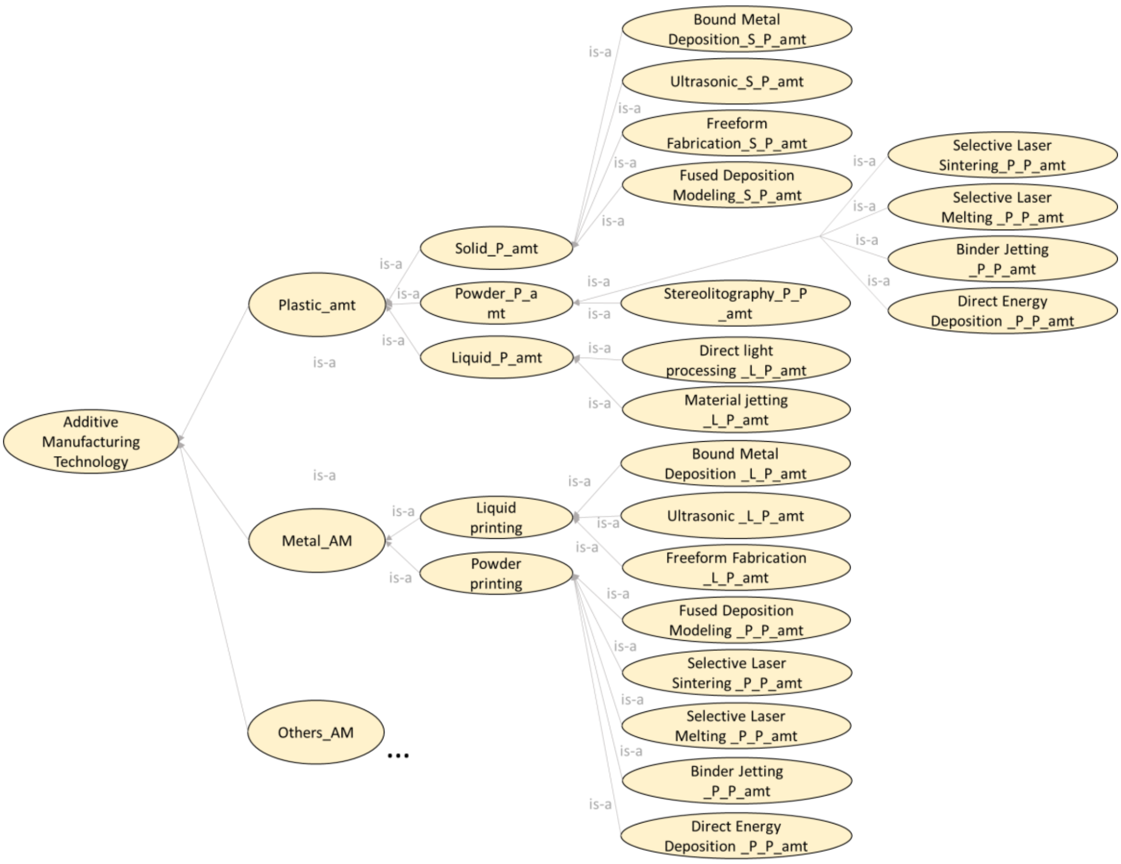

Figure 3. Domain II - Excerpt of technology Ontology defined according to OWL

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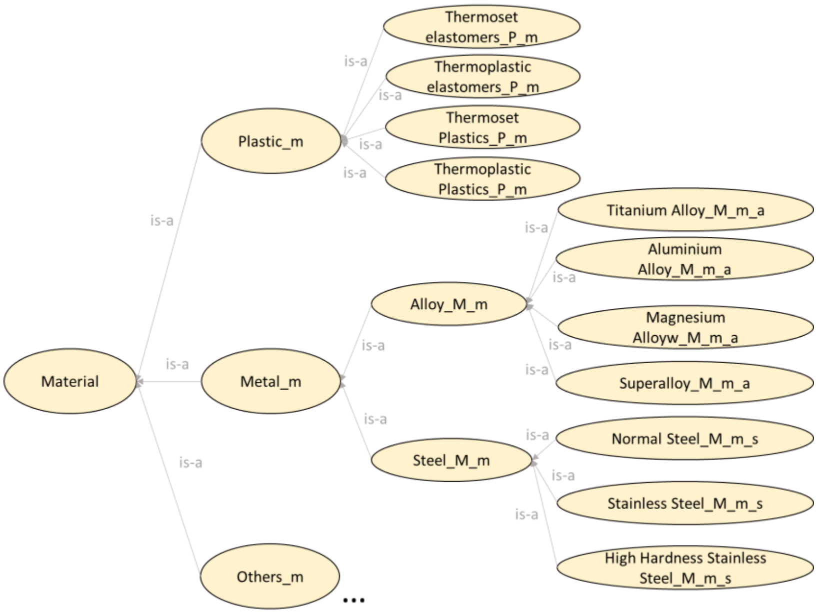


Figure 4. Domain III - Excerpt of material ontology defined according to OWL

Design suggestions were structured following the ontology defined. An example of a Design Guideline is presented in Figure 5. The colloquial form was kept and reported in the form of "infinite verb + noun" adding auxiliary information to create databases. The two databases were implemented into spreadsheets to make processes such as data input, error checking, etc. leaner. The aim is to provide a kernel composed of i) a feature recognition system, ii) DFAM guidelines databases that will be implemented into a software in future developments. The software will automatically recognize geometric features from CAD files and, making use of the databases, identify features which do not satisfy guidelines.

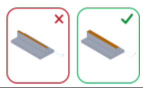
DFAM Design Guideline						
Threshold	**Design Guideline**	**Further detail**	**Design Guideline img**	**Warning type**	**Date**	**Source**
r = 0	To avoid sharp edges	To avoid stress concentration, avoid sharp edges. Make a fillet of 1/4 of the wall thickness close to it. Minimum fillet radius 1mm.		Information	28/11/2021	Book *A practical guide to additive manufacturing*
t < 1 mm	Avoid walls with a thickness lower than 1mm	The minimum thickness of the wall must consider the structural integrity during the sintering process. When a wall higher than 8mm is printed, the ratio between height and length must not exceed 8:1.		Critical	17/05/2021	Book *Desktop-Metal-BMD-Design-Guide*

Figure 5. DFAM Design Guideline

However, for the current case studies, CAD features were recognized manually based on the authors' experience with the aim to test the goodness of the developed ontology. For the sake of brevity, only two case studies are reported: one for a component made of plastic material (Poly1500) with Stereolithography (SLA) technology and another for a component made of metallic material (AISI 316L) with Selective Laser Melting (SLM) technology.

Case study I - Stereolithography (SLA)

The component analysed is the body of a toy car model (Jeep Willys) made of Poly1500. The component presents several geometrical features and details. The printing direction is not mandatory since no specific mechanical requirements are requested in a given direction. However, it is necessary to perform an analysis to understand which printing direction will guarantee the best feature manufacturing. Since the component is mainly used for aesthetic reasons, the main parameters to consider are the surface finish and the printing time. Using the Machine Operator DB, two DGs collected in Table 2 suggested that the best printing direction is the one shown in Figure 6.

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Table 2. Machine Operator DB - Design Guidelines used for connecting rod

Design Guideline	Description
AMM024 Operator	Minimize the number of required supports
AMM025 Operator	Minimize the roughness in areas in contact with supports

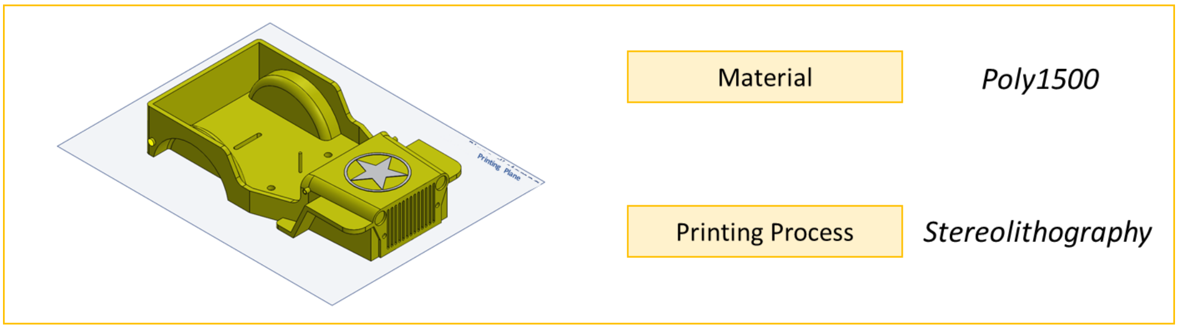

Figure 6. Case Study I - Jeep Willys

For the Stereolithography technology applied to Poly1500 materials, the Designer DB presents 29 DGs which are applicable. Among all features represented by the DGs, 52 features were identified as not satisfying the mentioned DGs. Violated DGs are summarized in Table 3.

Table 3. Violated DGs for the FDM calibrator

Design Guidelines	Description	Number of failing features	Error type
AMP107	Avoid holes with a diameter smaller than 0,5mm	1	Critical
AMP108	Avoid drain holes a diameter smaller than 4mm	1	Warning
AMP115	Avoid making horizontal protrusions longer than 2mm without supports	4	Critical
AMP119	Avoid embossed details with a height lower than 0,5mm	2	Warning
AMP157	Avoid sharp edges	44	Information

Due to space limitations, only a few examples are reported. The first one concerns the features highlighted in red in Figure 7 (embosses). Those features are not consistent with the design guideline *AMP119* (Warning), which suggests increasing the high of embossed details. Thus, keeping the requirements of design, the emboss feature of the logo was increased from 0.4 mm to 0.6 mm.

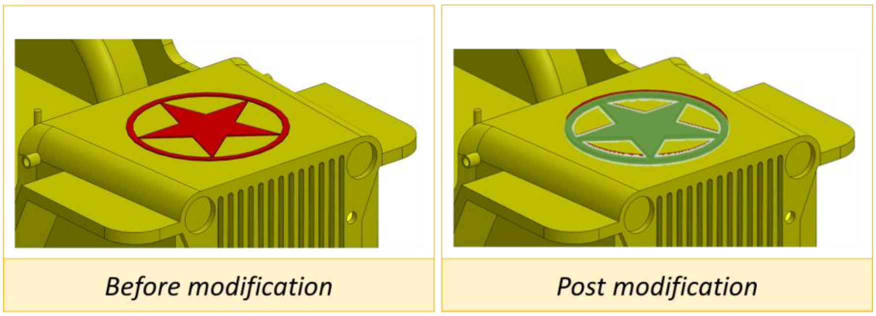

Figure 7. DG AMP119 identified error and implemented solution (post-modification)

The fenders highlighted in Figure 8 did not satisfied the DG *AMP115*, which is a Critical error. In fact, it is not possible to create horizontal protrusions longer than 2mm without supports, otherwise during the printing process, the material fused will sink, failing the creation of the desired feature. In this case, to keep the design constraints, the feature cannot be modified in geometry, size, and dimensions, and the use of supports is mandatory to realize the desired shape.

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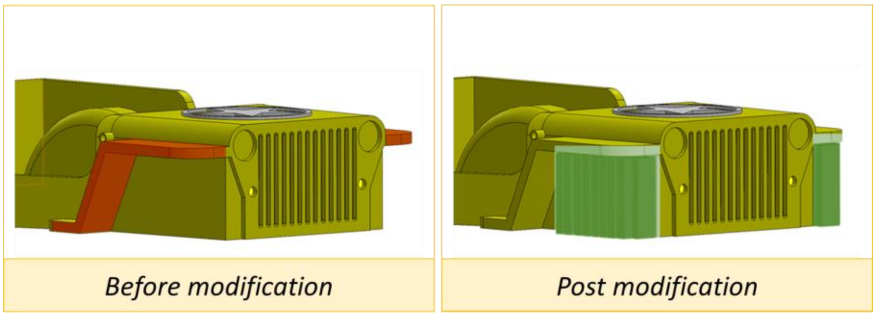

Figure 8. DG AMP115 identified error and implemented solution (post-modification)

Case Study II - Selective Laser Melting (SLM)

The component analysed is a connecting rod which is manufactured with Selective Laser Melting technique for metals. The material considered is AISI 316L. Since no mandatory printing direction is present, the optimum printing direction must be selected. The component must be used inside an engine; thus, mechanical performances are more important than printing time. Using the Machine Operator DB, two DGs, collected in Table 4, suggest that the best printing direction is the one identified in Figure 9, since it reduces the component anisotropy.

Table 4. Machine Operator DB - Design Guidelines used for connecting rod

Design Guideline	Description
AMM004 Operator	Minimize the number of zones without supports
AMM009 Operator	Consider forces in the Z loading direction

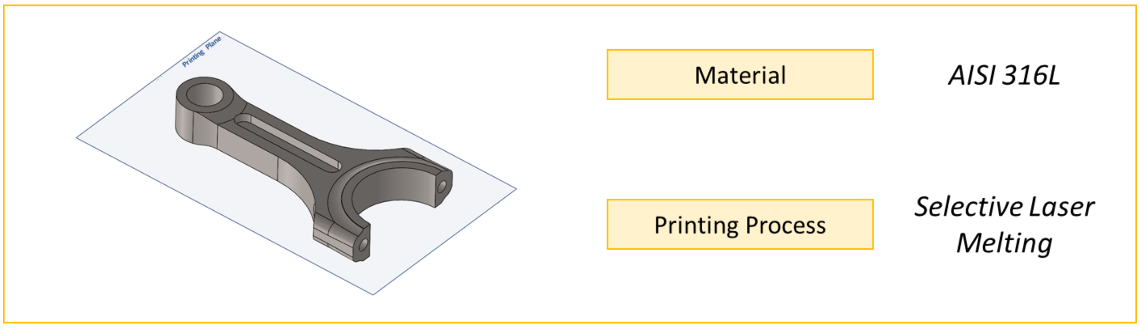

Figure 9. Case Study II - Connecting Rod

Once the printing direction were identified, the component was analysed with the Designer DB. The Designer DB presents 25 design guidelines for the Selective Laster Melting technology with AISI 316L material. Among all features presented in the model, 26 did not satisfied the identified DGs. Table 5 summarises the violated DGs.

Table 5. Violated DGs for the connecting rod

Design Guidelines	Description	Number of failing features	Error type
AMM001	Avoid sharp edges	18	Information
AMM119	Avoid making horizontal surfaces longer than 1mm without supports	2	Critical
AMM142	Avoid horizontal holes with a diameter greater than 6mm	2	Warning
AMM120	Avoid holes with horizontal axes with a diameter greater than 10mm	2	Warning
AMM140	Insert stock allowance with a thickness between 0.1mm and 0.5mm	2	Information

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Due to space limitation, only a few examples are made. 18 features presenting sharp edge are not compliant with DG *AMM001* (0). In fact, sharp edge should be eliminated with fittings of radius > 1 mm, where possible, to avoid stress concentration.

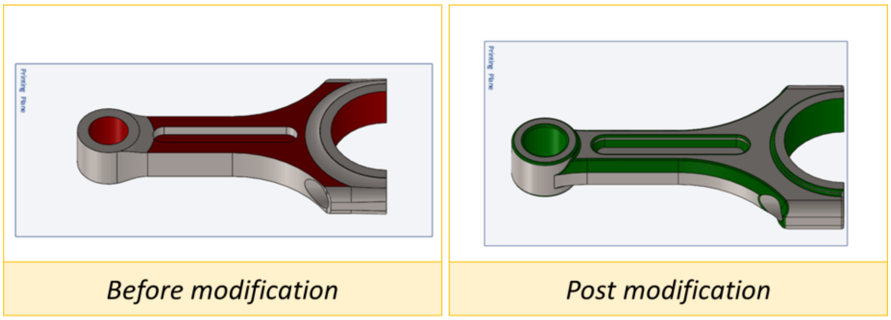

Figure 10. DG AMM001 identified error and implemented solution (post-modification)

Another feature which did not satisfied the DGs (i.e., the DG AMM120) is the horizontal hole presented in 0. Horizontal holes can be manufactured without supports only if the diameter is in the range of 0,5 - 6 mm. The DG is a warning; thus, it is still possible to manufacture the component, but post-printing finishing might be complex and increase the overall cost of the part. To avoid it, the hole dimension was reduced from the initial value of 6 mm to the value of 5 mm. (0). The modification was possible since it did not change the component functional requirements. Otherwise, it would have been necessary to machine the hole afterward increasing the cost of the part.

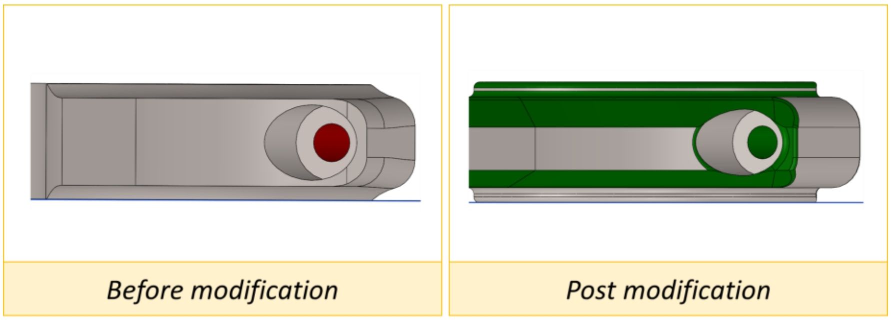

Figure 11. DG AMM120 identified error and implemented solution (post-modification)

4. Results and Discussion

The framework proposed allowed to formalize AM design knowledge according to a defined ontology. Two databases (i.e., Designer DB and Machine Operator DB) for collecting and presenting AM design rules were obtained. Table 6 summarizes the design rules identified for each manufacturing technology, according to the material selected for the Designer DB. Regarding the Designer DB, case studies showed three (3) parameters that, if not correctly designed, lead to product failure regardless of the material used: i) the presence of a sharp edge, ii) the ratio between filled and empty spaces, and iii) the component height. Then, according to the material selected, further parameters need to be studied to fulfil AM design guidelines. For instance, for the technology Direct Energy Deposition (Powder Based) parameters affecting the manufacturing process are component volume, holes, protrusion, roughness, walls thickness, and thread axes. In the same way, the Machine Operator DB aims at identifying the right AM process and the optimum orientation to manufacture the component. It focuses on parameters such as component anisotropy, support roughness, stair-stepping roughness, easy access for support removal, mating faces with the printing plane, and nesting optimization. Moreover, according to the selected AM process, further parameters can be analysed. For instance, the Powder Bed Fusion technique presents parameters such as the recoater orientation. Finally, it is interesting to notice that this database shares several design guidelines with the Designer DB (i.e., 41).

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Table 6. Number of Design Guidelines per Material, Status and Technology for Designer DB

Material	Material Status	Technology	Number of Design Guidelines
Metal	Solid-Liquid	Bound Metal Deposition	17
Plastic	N/A		N/A
Metal	Solid	Fused Deposition Modeling	12
Plastic	Powder		49
Metal	Powder	Binder Jetting	22
Plastic	Powder		12
Metal	Powder	Direct Energy Deposition	17
Plastic	Powder		N/A
Metal	Powder	Selective Laser Sintering	38
Plastic	Powder		44
Metal	Powder	Selective Laser Melting	25
Plastic	Powder		N/A
Metal	N/A	Stereolithography	N/A
Plastic	Powder		29
Metal	N/A	Material Jetting	N/A
Plastic	Liquid		29

Different from traditional manufacturing techniques where collaboration between manufacturing and design departments is sought for improving the overall product development process (i.e., concurrent engineering approaches), for AM technologies it is mandatory, otherwise, the final product cannot be manufactured. In fact, parts need to be designed considering both functional performances (e.g., use of connecting rod inside an engine) and manufacturing performances (e.g., reduce the number of post-printing furnishing) AM is a technology that is expanding quickly in the industrial world. Nowadays, the knowledge is mainly present in companies where it is acquired through trial-and-error approaches. The main drawback of the proposed approach lies in the generation of design guidelines. In fact, the scientific literature currently available is limited. Moreover, the available information changes quickly since the technology is evolving fast, requiring a continuous fine-tuning of design rules already identified. Finally, since printing properties and, hence, design guidelines, are strictly related to the material composition, a change in it might lead to a different threshold for a given design action. To date, this variation must be assessed manually, requiring a huge effort in terms of time.

5. Conclusion and Future development

AM technologies are gaining great importance in the industrial world. DfAM methods are used to design products optimized for AM technologies. To date, there are several DfAM techniques available in the literature that suggest design rules to improve products designed for AM technologies. However, a method to formalize DfAM knowledge is currently missing. In this paper, a framework to find, list and collect DfAM design guidelines was proposed according to an ontology developed *ad-hoc*. The framework allowed to create two databases: i) the Designer DB and ii) the Machine Operator DB. Databases have been developed to be linked with CAD software with the goal of spotting CAD features that do not fulfil the DGs collected. Databases were tested with two real case studies: i) the model of the body of a Jeep Willys made of Poly1500, and ii) a connection rod made of AISI 316L. Results showed the usefulness of the framework, helping designers to spot errors both from a manufacturing and designer points of view. The main drawback lies in the derivation of design guidelines. To date, AM manufacturing knowledge is still limited and continuously evolving, thus databases need to be updated often, leading to a great effort in terms of time. Future developments will focus on increasing the current database, by automatizing the definition of new design guidelines following the proposed ontology. In addition, an automatized system to retrieve CAD features from CAD models will allow to reduce the time for the DfAM analysis.

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