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KNOWLEDGE-DRIVEN DESIGN FOR ADDITIVE MANUFACTURING: A FRAMEWORK FOR DESIGN ADAPTATION

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ABSTRACT

Due to the high freedom of design, additive manufacturing (AM) is increasingly substituting conventional manufacturing technology in several sectors. However, the knowledge and the awareness for the suitable design of additively manufactured components or assemblies ensuring manufacturability and fully realizing its potential is still lacking. In recent years, approaches and tools have emerged that allow the incorporation of existing knowledge of Design for Additive Manufacturing (DfAM) into the design process. Nevertheless, these applications mostly do not consider the formalisation of both restrictive and opportunistic DfAM guidelines for their integration in design tools.

Therefore, the following article presents a framework for the knowledge-driven adaptation of existing designs in the context of DfAM within an expert system. The novelty of the presented approach lies in the interdisciplinarity between the formalization of design guidelines and their integration and consideration within computeraided design for the semi-automated adaptation of functional non-assembly mechanisms. The application of the presented framework to a case study manufactured via Fused Layer Modeling (FLM) illustrates the applicability and benefits.

Keywords: Additive Manufacturing, Knowledge-driven Design, Design for Additive Manufacturing (DfAM), Ontologies

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1 INTRODUCTION AND MOTIVATION

Despite the advantages of integrating additive manufacturing (AM) in the industrial workflow in recent years and its impressively proven maturity, there are still some challenges to face for its efficient and profitable use (Wohlers et al., 2020). A major concern is the current lack of domain-specific knowledge and tools for the efficient design of AM parts. This is particularly challenging for designers without in-depth process and **Design for Additive Manufacturing (DfAM)** knowledge. This shortcoming is one of the main reasons for the partially stagnating acceptance of this technology (Pradel et al., 2018; Laverne et al., 2015) and is seen as a major barrier for the extensive implementation of AM (Vaneker et al., 2020). Although there are several DfAM techniques emerging for improving product design for AM, a method for formalising this knowledge and making it available for designers is missing (Formentini et al., 2022). To overcome this deficiency, it is essential to gather and process sufficient and appropriate knowledge and, most importantly, to make it accessible in a practical context. Consequently, designers can be supported in designing AM-suitable parts, preventing iterative, time- and cost-intensive processes in order to achieve the vision of *print first time right* in the long term perspective. An efficient approach for realizing this vision would be the largely automated adaptation of the initial design within the framework of a comprehensive design expert system with respect to recent advances in the field of DfAM, taking into account process-specific design parameters. This leads to the question: How can existing design and process knowledge in the field of AM be formalised and integrated into computer-aided design (CAD) environments as a basis for the automated AM-suitable adaptation of existing models?

Motivated to find an answer to this research question and to form a basis for realizing the vision of *print first time right*, the following contribution presents a novel framework for formalising DfAM and process knowledge. The subsequent integration in design tools for the partially automated adaptation of existing models allows ensuring manufacturability, and ultimately exploiting the potential of AM. The paper is structured as follows. The current state of the art is presented in section 2. Section 3 introduces the general framework, which will subsequently be applied to an illustrative case study in section 4 to show the benefits of the framework. Finally, section 5 gives a conclusion and outlook on further need for action.

2 STATE OF THE ART AND RELATED WORK

The high potential of AM lies primarily in the freedom of design, often referred to as **shape complexity** (Sossou et al., 2018). However, its exploitation requires specific design methods, which are summarized under the term DfAM in analogy to the **Design for X (DfX)** approach. Thereby, a rough distinction can be made between three approaches, namely restrictive and opportunistic approaches and approaches combining both (Laverne et al., 2015; Kumke, 2018). Further research activities focus on the topics *design methods*, *AM technologies* and *DfAM guidelines* (Booth et al., 2017). Thompson et al. (2016) distinguishes between *design opportunities, benefits and freedoms of AM*, *constraints and quality considerations in design for AM* and *costs and benefits of AM products and processes*. The provision and development of DfAM knowledge, tools, rules, processes and methodologies is outlined as one of the most important technical challenges in the field of AM technology (Thompson et al., 2016). This knowledge can thereby be retrieved from use cases, publications, expert interviews, technical documentations and standards (Biedermann et al., 2022). For an efficient use of DfAM, these aforementioned sources need to be formalised, so that in-experienced designers can better explore the potentials and restrictions for designing AM-suitable components and assemblies as they are hardly aware of or do not understand DfAM knowledge and skills (Pradel et al., 2018).

Knowledge formalisation in an engineering context may thereby be described as ways to acquire and collect engineering knowledge and ranges from basic approaches (e.g. product documentation) to sophisticated models, for instance **ontologies**, which explicitly document the complex relationships in design (Štorga et al., 2010; Chandrasegaran et al., 2013; Formentini et al., 2022). Ontologies have already proven their applicability for the provision of knowledge in other areas like for the design of clinched and pin joints (Zirngibl et al., 2022) and for the representation of tolerancing and design knowledge for an automated tolerance specification of product concepts (Goetz and Schleich, 2020). The associated knowledge representation furthermore allows the verification of consistency via so-called

reasoning (Gruber, 1995). In addition, mechanisms of inference can derive new relations between existing knowledge representations. In this way, the ontology is capable of representing both explicit and inferred knowledge and thus derive, for example, new design knowledge in the context of DfAM.
In recent years, a number of researchers have been working on the development of AM-specific ontologies, with the current state of the art in this field being described in detail by Kim et al. (2019). In addition, a DfAM ontology is proposed which provides a holistic information structure that facilitates a manufacturability analysis of AM parts (Kim et al., 2019). With the help of design rules expressed as *Semantic Query-Enhanced Web Rule Language (SQWRL)*, manufacturing features, such as thin walls and overhang features requiring support structure were identified (Kim et al., 2019). As a result of the paper and the proposed case study, the authors claim that rules for redesigning AM parts with manufacturability issues can be formulated using *SQWRL* (Kim et al., 2019). In (Dinar and Rosen, 2017), three requirements for a DfAM-specific ontology were identified. First, it should include and represent domain, experiential, and also experimental knowledge, second it should facilitate reasoning connected with descriptive logic, and third it should be a basis for, or at least be easily integrated into, a CAD tool (Dinar and Rosen, 2017). Hagedorn et al. (2018) proposes an ontology for innovative design in AM, however, without specifically taking into account particular manufacturing aspects. Ko et al. (2021) proposed an approach for the automated, knowledge-based generation of AM design rules, combining data, machine learning approaches, and an ontology in specific combination with knowledge graphs. Within this study, a DfAM ontology (DfAMOnt) with integrated knowledge graphs was constructed for systematically capturing a-priori knowledge and newly derived knowledge based on a formal representation. Additionally, a knowledge inference structure was proposed for building new prescriptive (restrictive) design rules (Ko et al., 2021). A framework for using ontologies for formalising and storing DfAM knowledge and applicable AM concepts specific to applications of process planning is proposed in (Eddy et al., 2015). Therefore, a description logical link between product features and the associated process plan are implemented. In this context, a knowledge base management structure based on ontologies and *Semantic Web Rule Language (SWRL)* rules for capturing, communicating, reusing and logically inferring knowledge in the field of AM was created (Eddy et al., 2015). For the purpose of finding, listing, and collecting DfAM design guidelines a framework was developed in (Formentini et al., 2022) according to an ontology developed ad hoc. As a result, two databases were created, one for the designer and one for the machine operator which have been linked to CAD software for identifying features violating design guidelines (Formentini et al., 2022). For the analysis of manufacturability of parts produced via Lithography-based ceramic manufacturing, a knowledge-driven framework was proposed in (Mayerhofer et al., 2021) whereby an ontology is employed as a knowledge base for representing design guidelines for the respective manufacturing technology. As a result, the parts mesh is annotated and highlighted at the critical areas with the respective guideline (Mayerhofer et al., 2021).

Although there is a lot of research on the further development of DfAM tools and methods and the formalisation of engineering knowledge, there are only few approaches that deal with the intersection and the formalisation and structuring of precise DfAM guidelines, approaches and knowledge in general, with the objective of making them efficiently available to designers without specific knowledge in a conventional design environment, e.g. CAD tools. In recent work, the requirement of making this formalised knowledge applicable in CAD tools has not been fully achieved nor extensively explored since no suitable integration in a virtual designing environment has been proposed to the authors knowledge. Furthermore, the focus of DfAM is shifting from process-focused guidelines or restrictions to more sophisticated guidelines covering the interactions between process and design (Qi et al., 2018). Mostly restrictive DfAM guidelines are formalised for the purpose of manufacturability analyis, even though first efforts of formalising opportunistic guidelines have been conducted (Kim et al., 2019). In this context, a distinction can be made between restrictive rules to ensure manufacturability and functionality as a body of knowledge incorporating information about valid design actions (Jee and Witherell, 2017) and opportunistic guidelines for improving these. Another approach in this field is presented in (Biedermann et al., 2021, 2022). Here, the basic steps for the implementation of an automated design approach combining a knowledge-based approach and the **MOKA** framework (Methodology and tools Oriented to Knowledge-based engineering Applications) (Consortium, 2001). In conclusion, there is currently a shortcoming of suitable approaches for formalising DfAM guidelines in order to enhance the quality (e.g. performance, functionality, etc.) of AM products and especially non-assembly mechanisms hindering further exploitation of the potential of this application and of this manufacturing technology in general.

Considering the presented state of the art and related research in the context of DfAM and knowledge formalisation, the following research questions arise for this contribution.

1. How and to what extent can the adaptation of the initial design be automated making use of the direct linking of ontologies and CAD tools?
2. Is this combination of ontologies and CAD tool able to achieve simultaneous alignment of process parameters and design?

3 KNOWLEDGE-DRIVEN AND AM-SUITABLE DESIGN ADAPTATION

In order to assist designers without in-depth AM process and design knowledge in adjusting their design to ensure manufacturability and to enhance functionality through the provision of specific knowledge, a novel framework for an expert system is presented.

The following requirements are specified for the expert system. The application should allow an integrated representation of restrictive and opportunistic DfAM guidelines specific to non-assembly mechanisms and provide an assistance for the semi-automatic adaptation of the initial design. Finally, the proposed expert system shall allow an interoperability between the different commercial tools enabling them to be independently developed and updated. This is intended to achieve a modular and universal applicability of the system. In the following, section 3.1 presents the basic idea and the proposed framework while section 3.2 introduces the practical implementation of the framework in a commercial CAD software.

3.1 Basic idea and proposed framework

As already mentioned in section 2, the formalisation of AM-specific design knowledge can facilitate the functional and manufacturable design of additively manufactured components. Especially for the design of non-assembly mechanisms manufactured via **Fused Layer Modeling (FLM)** this is crucial as most designers are not aware of the associated design limits, restrictions and opportunities. The proposed framework for overcoming this shortcoming is depictured in figure 1.

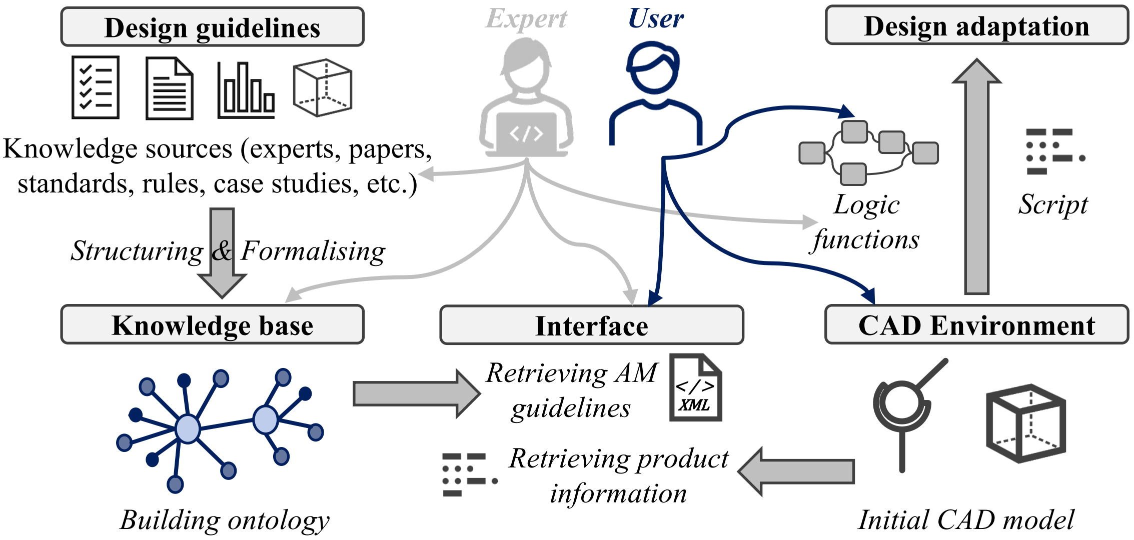


Figure 1. General framework of knowledge-based and DfAM-suitable design adaptation.

In a first step, the existing design and process knowledge concerning DfAM and FLM-manufactured non-assembly mechanisms and components in general must be systematically gathered, structured and processed in an interpretative manner. In doing so, it is possible to refer to already existing **design guidelines**, principles and restrictions (e.g. papers, standards, rules) and the derived findings from real case studies and experiments in a quantitative manner with respect to process variables and quality criteria. Numerous guidelines for the design of non-assembly mechanisms have already been identified, focusing on different quality criteria, also depending on FLM-relevant process variables (Lussenburg et al., 2021). However, it has to be mentioned that most existing FLM-specific design guidelines and recommendations are only intended as a guidance and may differ due to the variabilty of design and especially of manufacturing devices with different working principles and resolutions. This issue has to be considered while building the **knowledge base** in the next step.

For the acquisition of knowledge, the focus within this contribution is on specific papers (Schulz et al., 2017; Cuellar et al., 2018; Lussenburg et al., 2021), standards and own preliminary work and experiments (Schaechtl et al., 2021). In order to be able to efficiently use the gathered and structured knowledge, it has to be formalised within a knowledge base. In this contribution, an **ontology** is built up manually by the authors. This ontology facilitates the representation of knowledge of DfAM guidelines depending on geometric features, specific FLM process variables and their impact on relevant quality criteria (e.g. minimum achievable joint clearance as a function of layer height, build orientation and seam pattern with respect to a specific manufacturing device). The initial setup of a specific ontology means high effort, it nevertheless enables a consistency check as well as an inference of knowledge in addition to the strict formalisation of DfAM guidelines via SWRL rules. Once the knowledge base has been created in consultation with the respective experts (e.g. manufacturing and process experts), it can be extended by the FLM-specific dependencies and used by inexperienced designers.

In order to utilize and process the resulting and via SWRL formalised design guidelines within the **CAD environment**, a sophisticated **interface** is required to retrieve these formalised design guidelines from the ontology on the one hand and to provide information from the **CAD environment** on the other hand for specifying such a retrieval for the respective CAD model. This interface is essential to ensure simplified interoperability between commercial tools and thus to be able to ensure a streamlined exchange of information. In the first step in this interface, information about the mechanism can be retrieved for the query within the ontology by automatically parsing through the CAD model. In this process, it is possible to determine the type of mechanism by analysing the assembly constraints and the geometry features for determining the associated design guidelines by means of a keyword query in the ontology within the CAD environment. In addition, further information about geometrical features and part orientations can be retrieved and utilized for the query.

The last step of the proposed framework consists of the semi-automated adaptation of the initial CAD model according to the retrieved guidelines. Within this framework, this is accomplished by using individually defined CAD-inherent logic functions allowing a case-specific **design adaptation** using input from the knowledge base, especially for restrictive guidelines (e.g. thresholds for minimum clearance depending on process variables such as layer height and orientation, radii for generating self-supporting overhangs in order to avoid support structures, etc.). These are available as pre-defined templates for the respective design tasks and only require user input for the definition of the elements to be subsequently automatically adapted in the last step for the design adaptation, especially for opportunistic guidelines.

3.2 Implementation

The ontology for the knowledge-base and the structuring of the design guidelines are created in Protégé 5.5.0 (Musen, 2015). For building the ontology, the process according to Dinar and Rosen (2017) and Noy and McGuiness (2001) was followed, whereby the five criteria according to Gruber (1995) were considered. Particular focus was devoted on defining the dependence between geometrical features and FLM-specific variables which is supplemented by quantitative values for their relationships. The interface between the ontology and the CAD environment in *Siemens NX* was developed in Python using the specific library *owlready2* (Lamy, 2017) for the interpretation and retrieval of the formalised DfAM knowledge in the ontology and the passing of variables and design tasks. *owlready2* (Lamy, 2017) is applied as it provides the possibility to easily access, edit and add to ontologies and to link them to other applications, thus ensuring interoperability. In this particular case the downstream application is the CAD environment. Thereby, the in-built *logic editor* for *algorithmic modeling* is used for semi-automated design adaptation as it provides the possibility to automatically adjust existing geometry according to pre-defined rules, guidelines and user input resulting from the developed ontology.

With the help of this *logic editor* and specific pre-defined scripts for design adaptation tasks it is possible to build procedural design workflows as different logic blocks for the respective design tasks (e.g. blending edges and adding design features) can be created and connected using wires. For the demonstration of the proposed approach, various design tasks were defined for this contribution according to the specific DfAM guidelines and saved as templates within the logic editor. These can then be called automatically and customized by input in a graphical interface within the CAD environment. Consequently, by invoking them, a fast and semi-automated adaptation of the inital design can be performed according to defined DfAM guidelines, which can be managed either by user input or by values and variables directly retrieved from the ontology. The distinction which path is chosen is defined whether it is restrictive rules (e.g. minimum required joint clearance) which can be applied automatically with stored functions or whether it is opportunistic rules (e.g. adaptation of radii to create self-supporting overhangs). The application of these rules must first be verified by the user due to possible interference with competing requirements (e.g. functional geometry elements not suitable for adaptation).

4 APPLICATION

In the following, the framework presented in section 3.1 (see Figure 1) is exemplary applied to a case study. Subsequent to the presentation of the case study in section 4.1, the knowledge-based adaptation of the initial design is presented in section 4.2, whereby the results are discussed in section 4.3.

4.1 Presentation of the case study

As an academic case study an angular joint based on *DIN 71802* is chosen (see Figure 2) and serves as a starting point for the application of the developed framework in order to show the benefits of the implementation of the developed DfAM-ontology into the CAD environment. The main goal is to adjust its inital design to be suitable for additive manufacturing as a non-assembly mechanism for omitting a subsequent assembly step after production, thus exploiting the AM potential and achieving the vision of *print first time right*. Figure 2 presents the initial angular joint and the associated hurdels and guidelines for adapting the design to become suitable for FLM as a non-assembly mechanism.

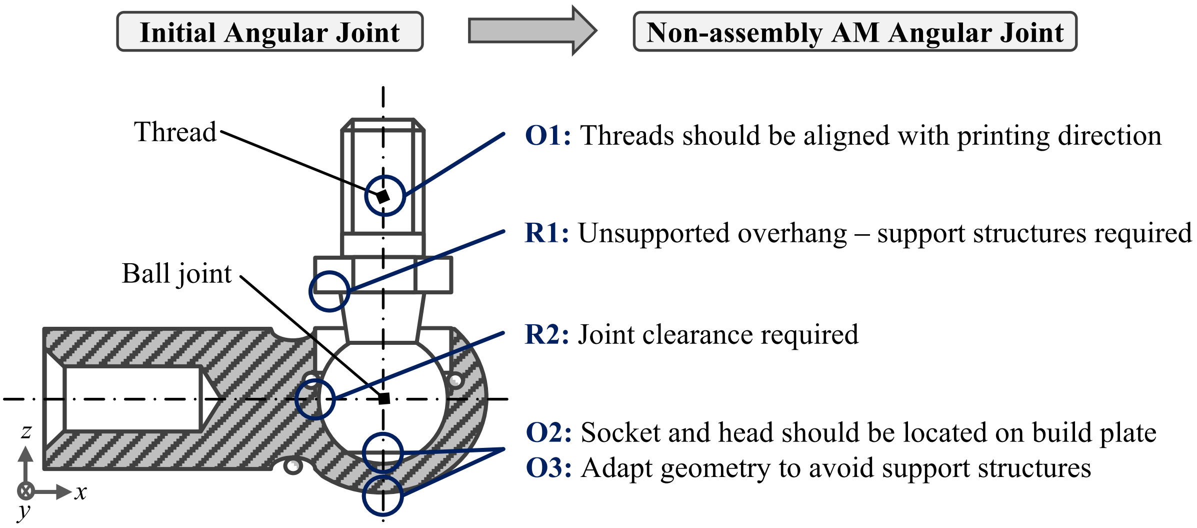
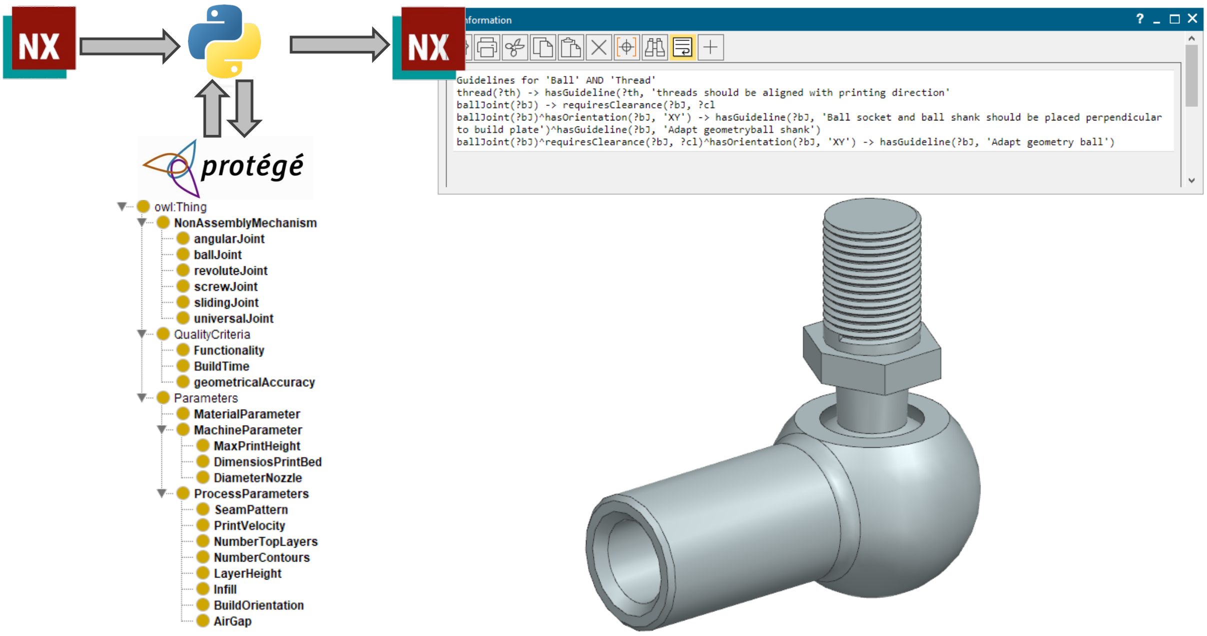


*Figure 2. Case study with restrictive (**R**) and opportunistic (**O**) DfAM guidelines for the adaptation of the design for manufacturing via FLM as non-assembly mechanism.*

4.2 Knowledge-driven adaptation of the initial design

As a first step for the knowledge-driven adaptation of the initial design, an automatic parsing through the CAD file is performed in order to retrieve information for the query in the ontology whereby significant keywords are extracted. For this case study the keyword *"Ball"* as the assembly constraint for the assembly and the keyword *"Thread"* as a geometry feature is retrieved in a first step. As a consequence, the ontology file is searched for these keywords using the interface within the CAD environment (see Section 3.2) and the associated design rules are retrieved in form of SWRL rules and displayed in order to raise awareness. In addition, the logic stored in the ontology allows to identify the assembly as an angular joint based on SWRL rules. Figure 3 illustrates the required steps whereby an excerpt of the ontology in Protégé is exemplary shown.



```
Guidelines for 'Ball' AND 'Thread'
thread(?th) -> hasGuideline(?th, 'threads should be aligned with printing direction'
ballJoint(?bJ) -> requiresClearance(?bJ, ?cl
ballJoint(?bJ)^hasOrientation(?bJ, 'XY') -> hasGuideline(?bJ, 'Ball socket and ball shank should be placed perpendicular
to build plate')^hasGuideline(?bJ, 'Adapt geometryball shank')
ballJoint(?bJ)^requiresClearance(?bJ, ?cl)^hasOrientation(?bJ, 'XY') -> hasGuideline(?bJ, 'Adapt geometry ball')
```

Figure 3. Display of DfAM guidelines retrieved from ontology within the CAD environment.

From the guidelines displayed in Figure 3 it can be derived that the geometry of the mechanism needs adaptation in order to become suitable for FLM. This is the starting point for the next step, the design adaptation based on in-built and individually adapted logic functions within the CAD tool. For each of the formalised guidelines for non-assembly mechanisms with respect to process variables, manufacturing constraints and quality criteria, different logic functions were predefined within the Siemens NX in-built algorithmic modeling or with simple rule-based functions. For this case study, the first guideline suggests that the thread should be aligned with the printing direction in the Z-axis (**O1**). This decision subsequently defines that the ball joint is located in the X-Y plane. In the next instance, this further restricts the guideline for the ball joint and results in the guideline that for a ball joint located in X-Y plane (**O2**), an adaptation of the geometry of both parts (ball socket and ball shank) is beneficial as both, internal and external support structures can be avoided, resulting in a better performance in terms of post-processing activities (**O3**). The adjustment of the geometry of the two elements is subsequently performed semi-automatically using pre-defined logic functions. The user is only required to define the part to be adjusted and to specify the coordinate system of the manufacturing device within the overall coordinate system. The next step for an AM suitable design is the adaptation of unsupported overhang (see Figure 2, **R1**). Areas needing support structure can be identified in Siemens NX with the *Design for Additive Manufacturing* plug-in by defining the maximum overhang angle, which can be retrieved from the FLM and DfAM-specific ontology via the interface. Since the unsupported overhangs are automatically identified, the respective design feature can be adjusted by calling a specific logic function by the user. By checking the maximum overhang, the design task can finally be verified and completed. Furthermore, with the help of the *Design for Additive Manufacturing* plug-in within Siemens NX, additional restrictive design guidelines such as wall thickness and the minimum radius as well as hardware restrictions such as the maximum build volume can be automatically checked. The specific input values required for this can be automatically retrieved from the knowledge base via the interface query and assist the designer in checking the final design. Finally, the joint clearance must be checked or adjusted to ensure functionality of the ball joint after production (**R2**). For checking and adjusting the joint clearance, a logic function can be called automatically, which first determines the distance between the contact partners via the assembly constraints and then adjusts the diameter of one of the two elements after determining the minimum achievable joint clearance from the ontology.

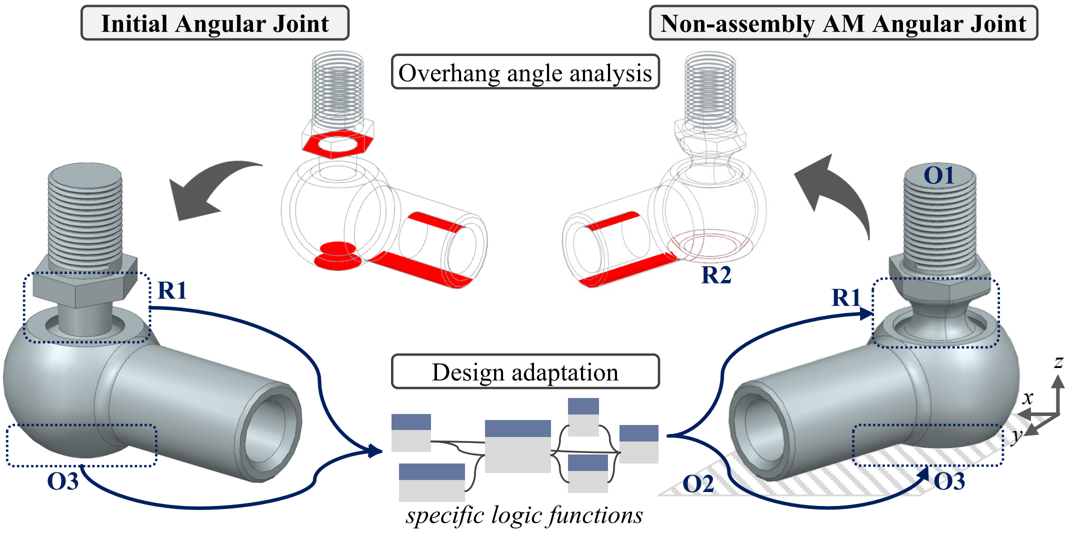


Figure 4. Adaptation of the initial design for FLM as non-assembly mechanism.

4.3 Results and Discussion

As a result of the application of the framework, the initial design of the angular joint is adjusted in order to ensure its manufacturability and enhance the functionality as a non-assembly mechanisms for 3D-printing (see Figure 4). The results demonstrate that the proposed framework works well for this case study and the realization of the associated restrictive and opportunistic guidelines. Furthermore, the integration of ontology-based DfAM knowledge into the CAD environment is achievable and can be employed profitably for the AM-specific design adaptation to become suitable for manufacturing as non-assembly mechanisms. The semi-automated application of logic functions supported by information retrieved from the ontology can additionally support AM-inexperienced designers and thus simplifies the design process for functional AM mechanisms. Furthermore, through the display and the subsequent application of design rules, awareness of the DfAM opportunities rises and deeper understanding is achieved. In this way, in addition to the implicit learning of the DfAM guidelines and the relationship to process-specific variables on explicit examples, a transparency of the design changes with regard to documentation and traceability can be achieved. However, it must be noted that a partial automation of DfAM guidelines by mapping logic functions with input from users and the ontology is possible, but are not universally applicable for all design tasks. Instead, DfAM guidelines and restrictions are highly specific to the certain AM technology and the used manufacturing device, which has to be considered while building, respectively updating the DfAM ontology. Therefore, user input is still required for defining the respective device and the process variables of interest. However, this can already be done in the knowledge base either directly by an expert or in consultation with one, and is thus to be evaluated separately from the proposed method. Thus, transferability to other AM technologies is feasible.

5 CONCLUSION AND OUTLOOK

Additive manufacturing has been partially integrated in several industrial sectors today, but their consequent use is often limited by the lacking DfAM knowledge and missing awareness of the designers. Additionally, there is currently a lack of suitable methods and tools for overcoming this issue thus exploiting the high freedom of design offered by AM, e.g. in the field of designing non-assembly mechanisms. A comprehensive and knowledge-driven expert system considering the relationship between geometry features and specific process variables could therefore remedy this shortcoming, reinforcing the awareness of constraints and possibilities of this technology. For this reason, this contribution introduced a novel framework for building an expert system in which restrictive and opportunistic design guidelines in combination with FLM-specific variables are formalised in a DfAM and FLM-specific ontology and subsequently integrated into a design environment for a partially automated design adaptation. Through its application to an illustrative case study, the benefits of the framework for adapting an initial CAD model was shown.

Future research will focus on the enhancement of the presented ontology in terms of the integration of more opportunistic guidelines depending on specific process variables thus enabling an optimization of both, the parameter design and the process design for the manufacturing of non-assembly mechanisms. This can be furthermore achieved by the coupling of a downstream pre-processing tool which is possible due to the systems interoperability. Currently, the design guidelines are applied in a defined order. To achieve a better degree of automation, it is necessary to define a prioritization of the guidelines in the case of competing guidelines (e.g. crossing axes of threads). Special focus will be devoted on extending the tools for design adaptation within the CAD environment in terms of usability and variability to allow a sophisticated adaptation and increase the degree of automation. Additionally, the interface for exchanging information between the knowledge base and the design tool needs improvement to achieve a higher level of automatisation for the design adaptation process.

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