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A knowledge-driven, integrated design support tool for additive manufacturing

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Abstract

Increasing adoption of additive manufacturing (AM) makes software support for design for additive manufacturing (DfAM) more relevant. This paper presents a novel, knowledge-driven design support tool for AM that leverages a central knowledge base to provide extensible and powerful DfAM support early in the development process. The approach was implemented using Python for the knowledge base and as a plugin for Siemens NX. It offers automated design checks, optimizations, and further information through an integrated Wiki. Evaluation confirms the feasibility and benefits of the approach.

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

1. Introduction

Additive manufacturing (AM) has gained increasing adoption over time. The generative manufacturing process offers new potentials for product design. However, it is subject to various process specific restrictions. These characteristics require special awareness and skills from designers when creating parts for AM. (Gibson *et al.*, 2021; Kumar, 2020; Thompson *et al.*, 2016; Schmidt *et al.*, 2017)

To address this issue, various works have been done in the field of specific design for additive manufacturing (DfAM) guidelines (Adam and Zimmer, 2015; Booth *et al.*, 2017; Gibson *et al.*, 2021; Diegel *et al.*, 2019; Thomas, 2009; Kranz *et al.*, 2015; Adam and Zimmer, 2014; Teitelbaum *et al.*, 2010; Vayre *et al.*, 2013; Thompson *et al.*, 2016; Vaneker *et al.*, 2020).

An example of such guidelines can be seen in Figure 1. It illustrates various (horizontal) hole geometries that can be manufactured in metal AM, up to a specific dimension, without the need for support structures. For instance, a typical round hole can be printed without support structure up to a diameter of 8 mm. However, above that, support structures are typically required, which can cause problems during removal, especially for longer holes. In such cases, other geometries like ellipses, teardrops, or diamonds might be better alternatives. (Diegel *et al.*, 2019)

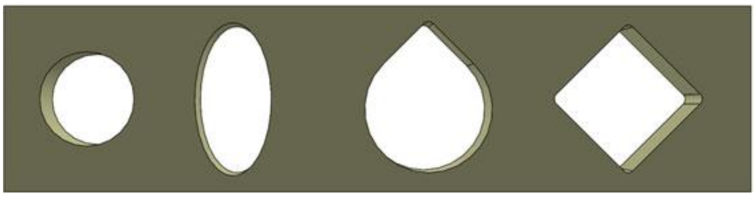


Figure 1. Different hole shapes that can be printed without the need of support structure (depending on their dimensions) (Diegel *et al.*, 2019)

In general, these guidelines and frameworks often consist of empirical knowledge and specific advice or constraints. Therefore, their guidance for designers can be complex, especially when detailed design support is needed. To overcome this problem, software tools can be used to accompany the existing DfAM guidelines. This allows them to be applied in a more interactive and context-sensitive way, as partly described by Goguelin et al. (Goguelin *et al.*, 2016).

In a previous publication, the available functionality of DfAM software support tools has been analyzed (in scientific literature, as well as in commercial software). Additionally, interviews were conducted to assess specific design workflows and problems in the current design process, especially those related to software. (Ellsel *et al.*, 2021)

The analysis showed that there are several existing approaches, applicable for different stages of the product design process, based on different file formats. However, while all major software vendors incorporate DfAM functionality into their CAD systems, no fully integrated, holistic support framework from CAD to manufacturing exists yet. In particular, there is no approach connecting a central knowledge base (KB) with a CAD-based DfAM framework. Central KBs can already be used for mesh-based part analysis systems (Tominski *et al.*, 2018; Mayerhofer *et al.*, 2019; Mayerhofer *et al.*, 2021). Existing related approaches with CAD integration (Han and Schaefer, 2019; Winkler *et al.*, 2021a; Winkler *et al.*, 2021b) are either rather abstract or have practical limitations. (Ellsel *et al.*, 2021)

Two newer publications describe frameworks for knowledge-driven DfAM. While being very powerful for selected use cases, they remain limited and require an extensive pre-setup of suitable parts/templates in the CAD system. Additionally, the specific linkage of the KB with the CAD system remains unclear and there is no focus on traditional, manual, CAD-integrated design workflows. (Schaechtl *et al.*, 2023; Wiberg *et al.*, 2023)

The conducted interviews show a demand to reduce the complexity within the toolchain as well as to increase the availability of knowledge during the design process. Therefore, a novel framework for an integrated design support toolchain that connects a KB to a design support tool within a CAD environment was proposed. It aims to address the shortcomings of the existing solutions by combining their well working solution elements. (Ellsel *et al.*, 2021)

This publication covers the description, implementation, and evaluation of such an integrated approach based on the previously proposed framework.

2. Description of the approach

The previously proposed integrated architectural framework (Ellsel *et al.*, 2021), that the approach is based on, is shown in Figure 2.

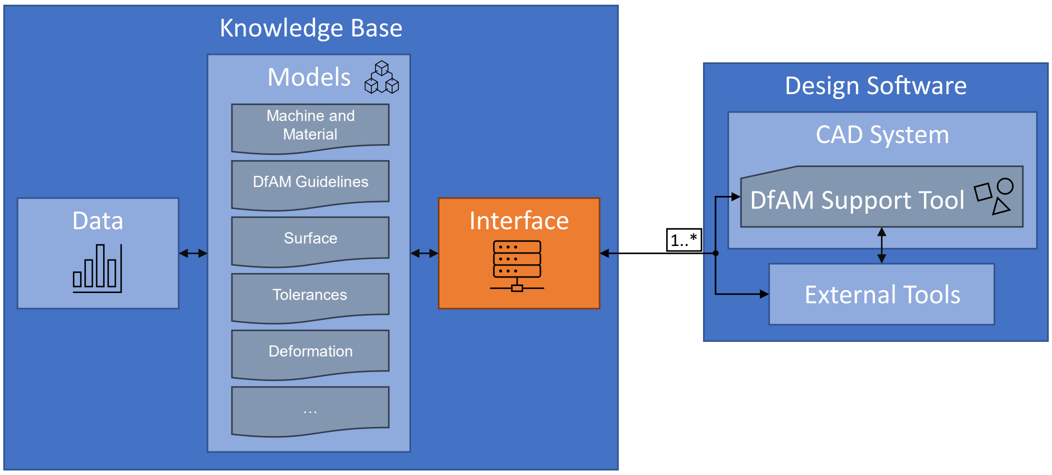


Figure 2. Schematic of the proposed integrated architectural framework (Ellsel *et al.*, 2021)

It consists of two main elements: a knowledge base (left) and the actual design software (right). Both are connected through a generalized interface (orange), which is provided by the knowledge base.

The knowledge base (KB) is the central element in the proposed approach. It is setup in a flexible and extensible way and holds relevant, DfAM specific knowledge. This knowledge is abstracted into so-called "models" which describe general categories and structure of the data (left in Figure 2). The description can for example be organized similarly to an ontology (e.g., in case of machine and material properties or general DfAM guidelines). More complex, possibly proprietary models can be used, when it comes to surface quality or deformation prediction. This includes machine learning models or other simulation algorithms. Oftentimes, these models at the core of the knowledge base serve as a blueprint for how the data is organized. Thus, to use this framework, the knowledge base needs to be instantiated (filled) with actual data (like specific critical thresholds for hole diameters based on machine and material).

The central knowledge management offers several benefits compared to a solution where everything is managed on the client (design software) side. This provides increased flexibility for implementation and maintenance. The knowledge management is not bound to specific client-side programming languages or other software limitations. The ability to access the KB through multiple clients ensures ease of maintenance and consistency. In case a new machine is added, or parameters change, all clients will have access to it. Additionally, many knowledge management tasks do not need to be performed on the client side, allowing possible performance gains. The centralization of the knowledge base also allows the use of more complex models like for machine learning.

To make the KB accessible, a generalized interface is provided (more details can be found in section 3). This allows the interaction of the design software with the KB.

The design software comprises a DfAM support tool, which is a plugin inside a CAD system. This allows direct, highly accessible knowledge integration into the design process which also leads to fewer workflow disruptions. The plugin provides the necessary software functionality needed by the designer based on data stored in the KB. The plugin can also be connected to external tools for extended functionality. Offered functionality includes automated design checks, adjustments of part geometry to fit for AM, and the offering of further design information, e.g., through a Wiki system.

The specific implementation of the approach is described in the next section.

3. Implementation of the approach

For the implementation of the approach, several choices were made regarding the specification of the general approach.

3.1. Detailing the general approach

The knowledge base (KB) was implemented in Python (Python Software Foundation, 2023). This allows easy setup, management of models, including powerful machine learning libraries, and good options to implement the interface (Raschka and Mirjalili, 2020).

To realize the interface, a REST API (Richardson and Amundsen, 2013) using the Flask framework (The Pallets Projects, 2023) has been chosen due to its flexibility and implementation capabilities in Python. Additionally, this allows easy access from multiple design software clients.

To facilitate the plugin integration into a CAD system, *Siemens NX* (Siemens Digital Industries Software, 2023b) has been chosen (specifically the 2007 Series, but compatibility should be given for a broader version range) as it is widespread for various product design use cases (Siemens Digital Industries Software, 2022). *NX* also offers some integrated design checks for AM (Siemens Digital Industries Software, 2023a) (also see section 3.3.1). These existing functions are rather performant. However, they are not covering all relevant geometrical features and require manual inputs of critical values (like minimum wall thicknesses). Thus, they are ideal to be integrated into the plugin for direct access and linkage with the KB, where such critical values can be automatically retrieved from.

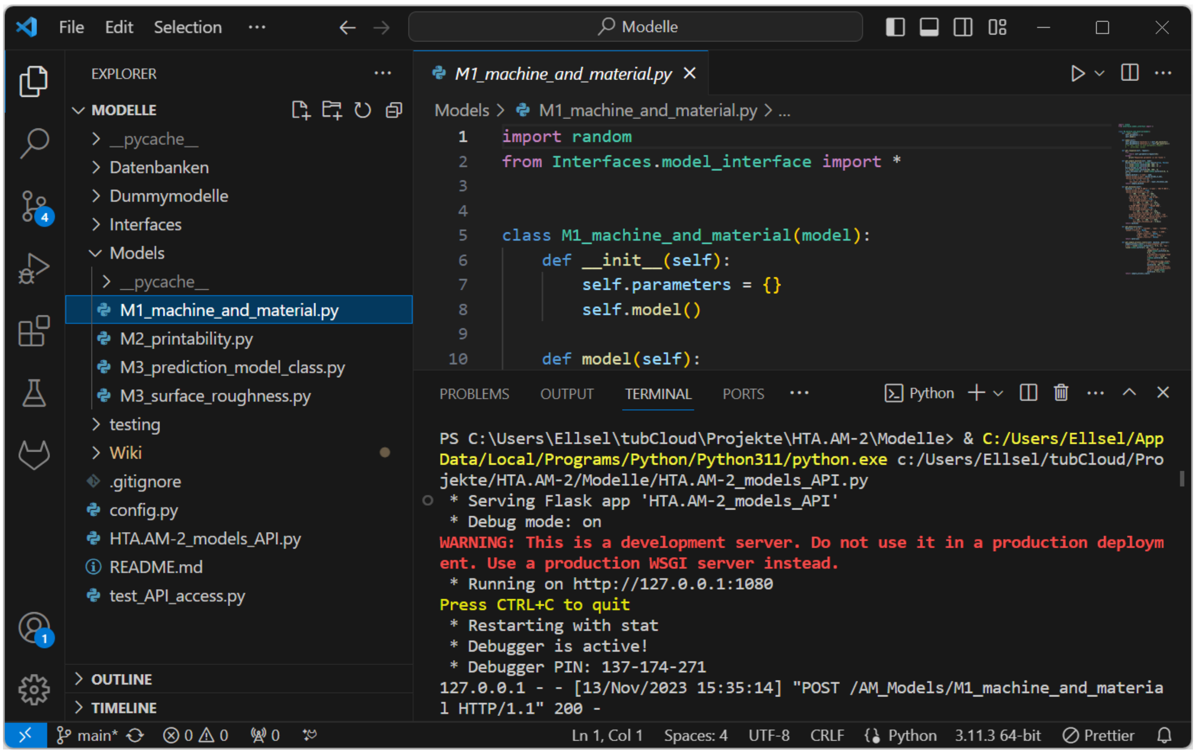
Additionally, *NX* provides access to their software through the NX Open APIs, allowing plugin creation, including integration into the *NX* menu (Siemens Product Lifecycle Management Software Inc., 2017). For implementation, the .NET framework (Microsoft Corporation, 2023a) has been chosen due to the vastly available documentation and versatility. C# (Microsoft Corporation, 2023b) was used as programming language as its syntax is more professional compared to Visual Basic (Microsoft Corporation, 2023c).

Further functionality is offered by the third party software *CAESES* (FRIENDSHIP SYSTEMS AG, 2023). For example, it allows shape morphing, which can be used for compensation of AM-induced part warpage.

3.2. Description of the knowledge base implementation

After establishing the general choices for implementation, the KB is described in detail. Figure 3 shows a screenshot of the running KB in Python.

The file tree on the left consists of separate folders for specific databases, general definitions of programming structure, test and real models, and code testing. Additionally, a Wiki (DokuWiki, 2023) is integrated, allowing access to further information regarding DfAM guidelines as outlined in section 2. The implemented models include one which contains information about AM machines and materials and one for DfAM guidelines. Additionally, there is a model for predicting surface quality. It uses a machine learning model with the Python library scikit-learn (scikit-learn developers, 2023) to make predictions for the surface quality at a given location with a given surface angle based on a measurement dataset.



```python
import random
from Interfaces.model_interface import *


class M1_machine_and_material(model):
    def __init__(self):
        self.parameters = {}
        self.model()

    def model(self):
```

```
PS C:\Users\Ellsel\tubCloud\Projekte\HTA.AM-2\Modelle> & C:/Users/Ellsel/App
Data/Local/Programs/Python/Python311/python.exe c:/Users/Ellsel/tubCloud/Pro
jekte/HTA.AM-2/Modelle/HTA.AM-2_models_API.py
 * Serving Flask app 'HTA.AM-2_models_API'
 * Debug mode: on
WARNING: This is a development server. Do not use it in a production deploym
ent. Use a production WSGI server instead.
 * Running on http://127.0.0.1:1080
Press CTRL+C to quit
 * Restarting with stat
 * Debugger is active!
 * Debugger PIN: 137-174-271
127.0.0.1 - - [13/Nov/2023 15:35:14] "POST /AM_Models/M1_machine_and_materia
l HTTP/1.1" 200 -
```

Figure 3. Knowledge base implementation in Python

The top right of the window shows an excerpt of the opened model for machines and materials. The project is set up in a way that there is a generalized model definition which each specific model needs to adhere to. This allows high modularity and ease of extension with further models.

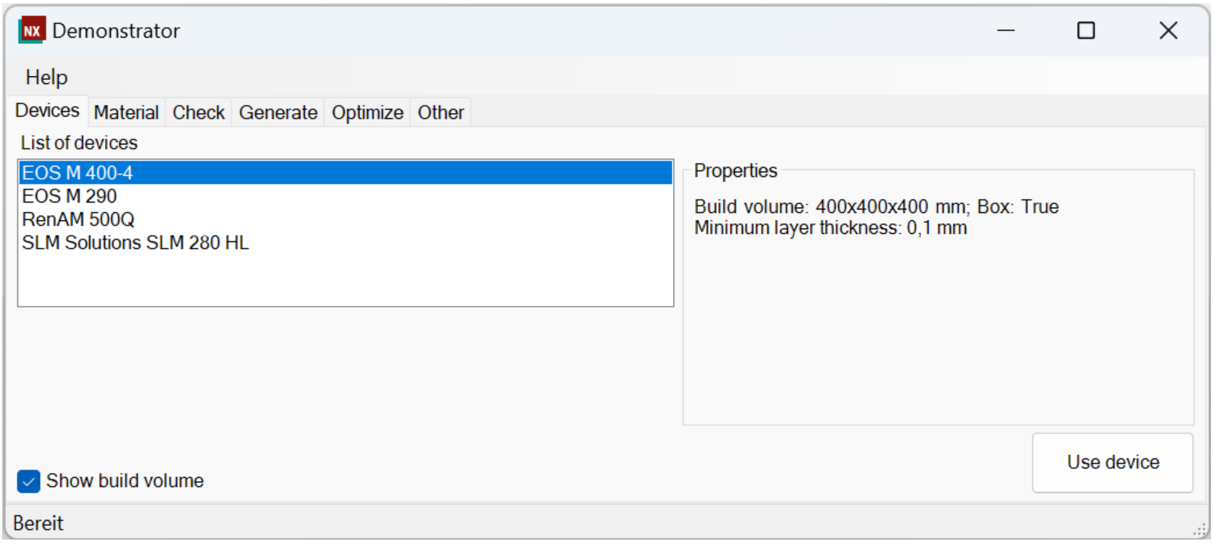
The bottom right of the window shows the current output of the running KB. In this case, it is running in development mode, creating the REST API on the same machine as the design software client. For real-world usage, the KB can be run on a separate server. At the bottom of the terminal, a request from the design software client in *Siemens NX* to the REST API can be seen.

3.3. Description of the design software implementation

This section describes the implementation of the design software side (DfAM support tool as a prototype CAD plugin). It consists of a main interface, integrated into the *NX* menu as shown in Figure 4. This menu allows easy invocation of specific functions like machine selection.

Figure 4. GUI of the support tool in Siemens NX

In addition to the menu integration in *NX*, the design support tool has an own main window, shown in Figure 5. The functions are grouped into different tabs. Often, data that directly comes from the KB is made accessible. This can be seen in the current view, where machines from the KB are shown including their properties. After selecting a machine, the build volume can be displayed in *NX*. After selecting a material, critical threshold values and other model parameters are retrieved from the KB. In a next step, several actions, such as design checks can be selected and executed (also see section 3.3.1).



List of devices

EOS M 400-4
EOS M 290
RenAM 500Q
SLM Solutions SLM 280 HL

Properties

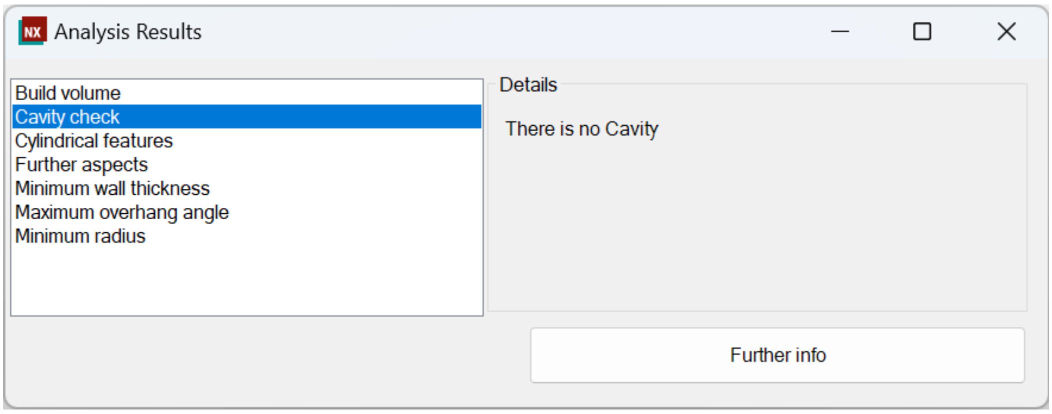
Build volume: 400x400x400 mm; Box: True
Minimum layer thickness: 0,1 mm

☑ Show build volume

Bereit

Figure 5. Main window of the support tool

A result window of a design analysis (consisting of several individual checks) can be seen in Figure 6. The individual checks that were conducted can be selected, and the results are displayed. The button "Further info" leads to the integrated Wiki in the KB (see section 3.2), explaining the corresponding design guideline and providing more details. Relevant information is made available directly via the current design step.



Build volume
Cavity check
Cylindrical features
Further aspects
Minimum wall thickness
Maximum overhang angle
Minimum radius

Details

There is no Cavity

Figure 6. Analysis results of the support tool

Depending on the results, further actions can be executed. In case of critical (horizontal) holes, a different shape can be applied in order to ensure the printability of the hole without support structure. Such automatically identified critical holes can be selected through a graphical user interface, and the shape modification is done automatically. The manual selection of holes to be converted is critical, as not all holes are suitable to be converted from a functional perspective. The conversion might also affect the ability to change the geometry later. Figure 7 shows an example of such an automated conversion of a round hole into a teardrop shaped hole (as seen before as an alternative hole shape in Figure 1).

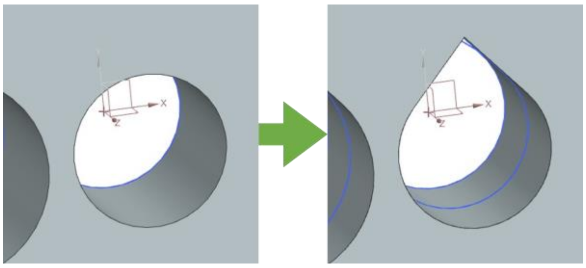


Figure 7. Automatic shape modification of a hole (Stark and Ellsel, 2022)

As of now, only the modification into a teardrop shape is implemented, but other shapes have been investigated and can be added with low effort to the existing approach.

3.3.1. List of implemented functions

The following list gives an overview of the functions that are currently implemented in the design support tool prototype:

- Check of AM design guidelines
    - Check whether the part fits into the build volume (currently implemented for cuboid build volumes)
    - Check whether the part height is a multiple of the layer thickness
    - Check for critical cylindrical features (holes and cylinders)
    - Check for islands
    - Check for cavities (possibility of powder removal)
    - Integration of internal checks from *Siemens NX*
        - Check for minimum wall thickness
        - Check for maximum overhang angles
        - Check for minimum radii
- Modification of identified critical geometries
    - Automated modification of critical horizontal holes for manufacturing without support structure
- Built on machine learning model
    - Prediction of surface quality
- Functionality using the external tool *CAESES*
    - Warpage compensation
- Additional functions
    - Highlighting of (especially identified critical) part sections
    - Displaying of the build volume from a selected AM machine inside *Siemens NX*
    - Linkage to a Wiki with further information for found critical features

As of now, all implemented functions require a single 3D part model to be loaded in the CAD software. The checks are aimed to be executable at all stages of such a model in the design process.

After covering the approach details and its specific implementation, it is evaluated and discussed in the next section.

4. Evaluation and discussion

The approach is evaluated using a test part that aims to cover all relevant geometrical features to be analyzed. The results and general approach are then discussed.

To evaluate the approach, a suitable test part is used that covers all relevant features that the tool will check and modify. Existing test parts are often focused on printability assessment and are usually not broadly available for download. A common test part from (Moylan *et al.*, 2012) does not offer all features, such as different horizontal holes or wall thicknesses, to be a good sample for evaluation.

Therefore, a custom test part was created to ensure the best coverage of relevant features. It is shown in Figure 8. The part has different variations of walls, gaps, cylindrical features (holes and cylinders), as well as different overhang angles.

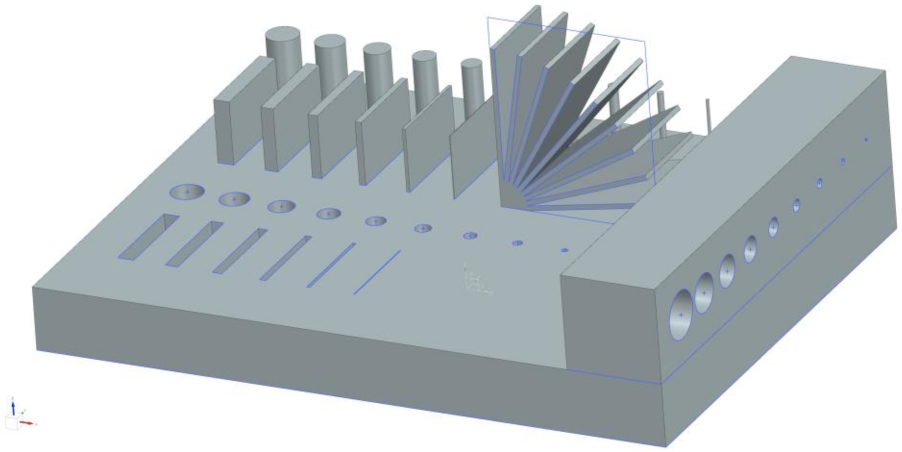
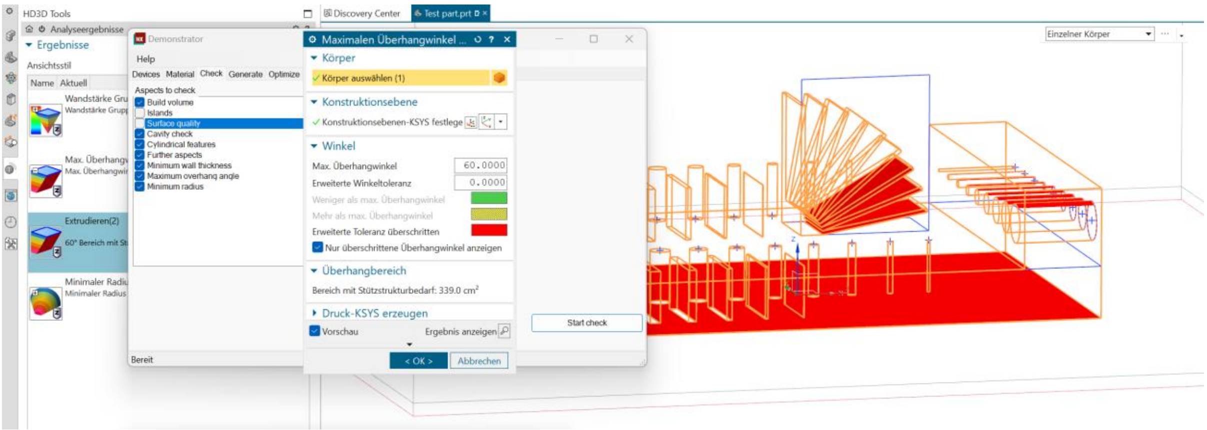


Figure 8. Part for evaluation

For evaluation, a run of the implemented design checks was executed on the part to assess the implemented toolchain. Afterwards, an automated design modification (hole shape transformation as shown in Figure 7) was performed. The chosen machine and material were EOS M 400-4 (EOS GmbH, 2023) and TiAl6V4, respectively.

After running the checks, the results were reviewed, and the design workflow was assessed. Overall, it could be shown that most checks (see below for the problematic ones) run reproducibly and without errors on the test part. Additionally, the overall integration with user workflows seems to be good.

The results of the *NX*-integrated checks are shown in Figure 9, which displays the check for critical overhang angles. For the selected machine and material, the KB returned a critical maximum overhang angle of 60 degrees. In the automated run of checks (seen in the "Demonstrator" window), the support tool invoked the internal *NX* check with that value. This can be seen in the small pop-up window at the front that users would normally need to invoke and fill in manually. In the part design view on the right, the analysis result is shown, marking critical angles in red. Additionally, the frame of the build volume box of the AM machine is visible, which was loaded by the plugin after selecting the machine.



Aspects to check
- ☑ Build volume
- ☐ Islands
- ☐ Surface quality
- ☑ Cavity check
- ☑ Cylindrical features
- ☑ Further aspects
- ☑ Minimum wall thickness
- ☑ Maximum overhang angle
- ☑ Minimum radius

✓ Körper auswählen (1)

✓ Konstruktionsebenen-KSYS festlege

Max. Überhangwinkel 60.0000

Erweiterte Winkeltoleranz 0.0000

Weniger als max. Überhangwinkel 🟩

Mehr als max. Überhangwinkel 🟨

Erweiterte Toleranz überschritten 🟥

☑ Nur überschrittene Überhangwinkel anzeigen

Bereich mit Stützstrukturbedarf: 339.0 cm²

☑ Vorschau

Figure 9. Analysis result for overhang angles

Even for *NX*-integrated design checks, having a software run several of them at once and filling in required critical threshold values can be time saving. This is especially helpful in cases where there is only little knowledge about which values are relevant to fill in.

However, some checks did not run robustly on the test part (islands check, surface quality prediction and identification of cylinders). For the islands check, the part is sliced. However, this slicing operation can cause problems in *NX*, depending on the part height (this seems to occur if a resulting slice is too thin). Adjusting the internally used slice thickness helps to mitigate this. Surface quality prediction is currently only based on the center of a face (position and angle). This works well for most triangulated surfaces but is inaccurate for CAD models. The check for critical cylinders falsely identified the rounded ends of the overhang structure as cylinders. This shows the need for more robust and generalized algorithms that also deal with a broad variety of special geometric edge cases.

Additionally, there is still room for improvement regarding the integration into the user interface of *NX*. For example, the menu integration currently requires *NX* to be launched through a script. Furthermore, after running the *NX*-integrated checks, users need to manually navigate to the results pane, as for the prototypical implementation, no way to open it automatically was found. Ensuring a more integrated experience in the future will help make AM knowledge even more accessible and could thereby increase the frequency of tool usage.

Another aspect to improve is the current long runtime of the islands check and surface quality prediction. This will cause an interruption in the normal design workflow. Therefore, some further optimizations and possible lower -level implementations might be beneficial, as well as potentially running the analyses asynchronously in be background.

In general, it has been demonstrated that the proposed design from section 2 offers benefits of leveraging a KB as input for a CAD-integrated design support tool. Dividing the knowledge backend from the actual user interface allows centralized knowledge management in a powerful environment, as already been seen in previous publications. On the other side the novel ability to tightly integrate that knowledge into traditional, CAD-integrated product design workflows has been demonstrated successfully. However, there is further potential to implement optimizations for a better, uninterrupted workflow. The architecture is flexible and extensible, so further features like a suggestion system for design improvements could be valuable additions in the future. Additionally, with increasing automation of design workflows, that can already be observed in existing publications, one should pursue a tighter integration with traditional workflows.

5. Conclusion and outlook

In this paper, a concept for a knowledge-driven design support tool for additive manufacturing has been presented. The novel approach links a central knowledge base with a CAD-integrated plugin through a generalized interface. This allows well-informed, extensible, and powerful DfAM support early in the product design process. The approach was implemented prototypically using a Python-based knowledge base in combination with a plugin for *Siemens NX*. It offers automated design checks, optimizations, and further information through an integrated Wiki. An evaluation confirmed the general feasibility and benefits of the approach, including improved accessibility of AM knowledge and time savings in design checks.

Future research may include the extension of the knowledge base with more data for different machines and materials. Additionally, more functions like different design checks or optimizations can be added. Two possibly areas of potential are the usage of dynamic design checks that do not just use one single critical threshold value but evaluate printability of a feature based on several different input factors. Also, reasoning capabilities could be used for making suggestions, e.g., that a part should be printed on a certain machine. Additionally, it will be interesting to assess the potential in real world applications and workflows, which may require further improvements to the architecture and overall robustness of the prototype. This might also include further additions like the consideration of product manufacturing information (PMI) and post-processing. However, the prototype is already in a stage, where usage can be beneficial to designers of AM parts without expert knowledge.

Statement of contribution

Claudius Ellsel developed the described approach and wrote the script. Rainer Stark supervised the research, commented and revised the script. All authors have read and agreed to the published version of the manuscript.

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