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# Automated Knowledge-Based Design for Additive Manufacturing: A Case Study with Flow Manifolds

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Additive manufacturing (AM) enables novel process equipment devices. However, the manual 3D design of complex part geometries is frequently challenging as designers need to fulfill functional requirements and consider the restrictions of AM. One promising approach is to automatically generate the design of parts. This work aims to introduce such an automated design approach to practitioners in the area of process engineering. The work describes the basic steps required to develop an automated, knowledge-based design tool for AM and demonstrates the approach using a case study on flow manifolds.

**Keywords:** Additive manufacturing, Design automation, Flow manifolds, Knowledge-based design

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## 1 Introduction

Additive manufacturing (AM) is more and more used as a manufacturing technology to fabricate process equipment devices [1–7]. Applications are flow manifolds [8, 9], nozzles [10–13], heat exchangers [14–16], reactors [17–20], and lattice structures [21–23]. For example, Fig. 1 shows a multiflow nozzle fabricated out of stainless steel using laser powder bed fusion (L-PBF) [24]. The nozzle integrates multiple flow channels to guide separate fluid flows. The different channels are tightly nested in each other, leading to a very compact part design. AM enables the fabrication of such complex-shaped parts, which were previously impossible or too costly to produce using conventional manufacturing technologies such as milling and drilling [25, 26]. The design freedom of AM makes it possible to combine multiple functions into a single part that integrates design features on different length scales for mixing, heat exchange, and chemical reaction. This advantage makes AM a promising enabler in advancing the field of process intensification [27]. In addition, AM allows customizing the design of process equipment devices [28]. Therefore, a device fabricated using AM is no longer predetermined as a standard part but can be tailored to the individual needs and requirements of a specific application.

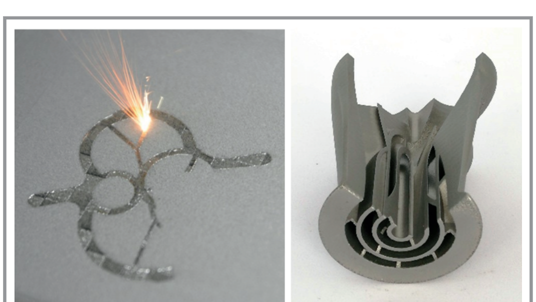

**Figure 1.** Complex-shaped multiflow nozzle fabricated using L-PBF of stainless steel [24].

However, despite the potential of AM, practitioners are frequently faced with several challenges when implementing parts using AM processes such as L-PBF [25, 26]. For example, one challenge concerns the fabrication of parts without defects or extensive thermal warpage. Other challenges are related to the post-processing of parts. In particular, removing sacrificial support structures can be time-consuming and labor-intensive if supports are removed manually. In the case of L-PBF, such supports are necessary to support geometrical features with critical overhangs and dissipate heat from the local melt pool through the solid material to the base plate. Another challenge concerns the removal of loose powder after L-PBF, which can be difficult for parts with complex internal features such as intricate flow channels [29]. Also, practitioners must consider the increased surface roughness and dross formation that can occur at

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geometrical overhangs, for instance, located at the inner surfaces of flow channels [30]. Hence, when designing parts for AM, practitioners must fulfill the functional requirements of a part and consider the restrictions of the chosen AM production technology. These manufacturing restrictions are specific to the selected AM process, material, machine, and process parameters [25, 26].

Previous works support the design for AM (DFAM) using techniques such as design rules for different AM processes and materials [31–34]. For example, experimental works recommend values for the minimum build angle $\alpha_{min}$, which defines the minimum required angle between inclined surfaces and the build plate to produce the surfaces without additional support structures. Other works present design guidelines for AM. For instance, guidelines are provided to define a suitable build orientation of a part to the build plate considering different criteria (e.g., production costs, mechanical properties) [35, 36]. Design rules and guidelines help in the design of AM parts. However, creating the 3D geometry of complex AM parts is often still a challenge for practitioners [37–41]. Frequently, it requires profound skills with computer-aided design (CAD) tools, which prevents novice CAD users from taking advantage of the design freedom of AM. However, even for expert CAD users, designing AM parts can be tedious if they employ a manual CAD approach. As shown in Fig. 2, a traditional manual CAD process typically involves the creation of many low-level design features (e.g., sketches, curves, surfaces), causing many manual and repetitive routine tasks. Frequently, such a manual CAD approach leads to a time-consuming process for designing complex parts and making iterative design changes in the development of a part.

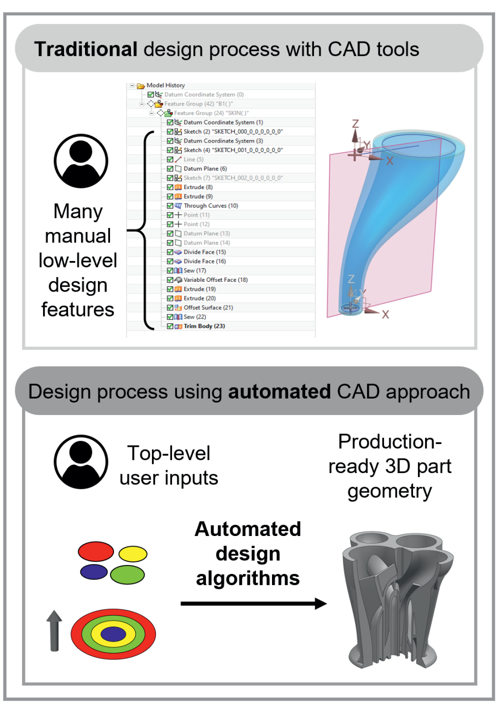


**Figure 2.** Comparison of traditional manual approach with CAD tools and automated design approach.

Therefore, prior works propose using an automated design approach for AM to address the drawbacks of manually designing parts [42, 43]. An automated design approach aims to avoid manual routine design activities and create complex part designs with reduced manual effort. As an example, Fig. 2 illustrates such an approach using the example of multiflow nozzles [24]. Users define high-level inputs concerning functional requirements (e.g., inlets and outlets of channels) and restrictions for AM (e.g., $\alpha_{min}$). Algorithms use these inputs to automatically generate a production-ready 3D nozzle geometry. Thus, in contrast to a traditional manual CAD approach, designers specify only top-level inputs but must not create the part geometry from scratch using many operations with low-level CAD primitives. Such an automated design approach lowers the barrier for novice designers and allows users to explore an increased number of design variants, make quick design changes during the iterative development of parts (e.g., based on feedback from simulations or experimental tests), and tailor parts to individual requirements of a specific application or customer.

The design of parts can be automated using different methods such as feature databases, CAD templates, topology optimization, and shape grammars [42–46]. This work focuses on automated design tools that follow a knowledge-based engineering (KBE) approach [47–50]. The basic idea of a KBE approach is to capture the design knowledge and activities required in a specific application and implement recurring design activities as automated and reusable design algorithms. One common framework to develop KBE systems is called MOKA (methodology and software tools oriented to knowledge-based engineering application) [51]. However, also other KBE frameworks, such as KNOMAD or CommonKADS, may be used to implement automated design tools for AM [52, 53].

This work aims to introduce practitioners in the area of fluid and process engineering to the topic of design automation for AM. The goal of the work is to show how an automated, knowledge-based design tool can be developed using the MOKA framework (Sect. 2). For this purpose, the work presents a case study to show the development and implementation of an automated design tool for AM (Sect. 3). The case study outlines the basic steps from knowledge capture to algorithm implementation. The focus lies on the automated design of flow channels, which are frequently required for many process engineering applications. The case study shows how to develop and implement a design feature that generates flow channels for AM under the consideration of the overhang restriction. The developed design feature automatically considers the potential adaption of channel cross sections for AM, thereby reducing the manual effort of designing complex-shaped AM flow components and ensuring their manufacturability with AM. The automated design procedures are implemented in the CAD program *Rhinoceros*® using the integrated visual editor *Grasshopper*®. Based on the case study, the work discusses a number of lessons learned (Sect. 4). Finally, the work concludes with a summary (Sect. 5).

## 2 MOKA

A KBE approach aims to capture the design knowledge required in a specific application and implement recurring tasks as automated, reusable algorithms [47–50, 54, 55]. Prior works describe various frameworks that can be used to conceptualize, implement, and operate KBE systems. MOKA is one common methodology for building KBE systems. Fig. 3 shows the basic steps of the MOKA methodology.

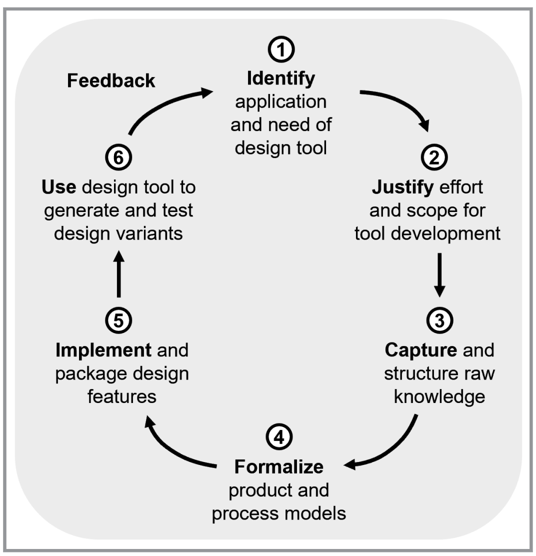


**Figure 3.** Basic steps of MOKA methodology for developing a design tool (adapted from [47, 48]).

The MOKA lifecycle starts by identifying a need and an application for a design tool (step 1). For example, one reason can be that parts of a particular application field contain recurring design features. Under such circumstances, a design tool offers the opportunity to automate the design of similar parts that belong to a larger family of parts. Another reason can be that a company requires a design tool to automatically generate the design of many different part variants customized for the individual requirements of potential customers.

In the next step, it is necessary to justify the effort for developing a design tool and define its scope (step 2). Previous work describes several prerequisites that help in deciding whether to implement an automated design tool [47, 48, 51]. For instance, the examined design tasks should not be simple enough to be solved by CAD users with little manual effort. In addition, the design tasks should be rule-driven, clearly defined, and not subjected to frequent changes.

The subsequent step is to capture the knowledge needed to create the part design in a specific context and build an informal knowledge base (step 3). Possible knowledge sources include case studies, prior publications, expert interviews, technical documents, and standards. The MOKA framework suggests clustering the different knowledge artifacts into six categories: illustrations, constraints, activities, rules, and entities (e.g., assembly, part, design features).

The next step is to further structure the acquired knowledge artifacts and formalize the knowledge base (step 4). The goal is to define formal product and process models that software engineers can use to implement an automated design tool. Product models aim to define the basic functional and structural relationship between a part and its design features. Process models specify how design features are combined based on the specific user inputs and used to generate the part geometry.

The next step is to implement the examined design activities as automated design algorithms and package them as a design tool (step 5). Then, users can apply and test the design tool (step 6). Feedback from users allows validating the design features, identifying missing features, and improving the design tool.

## 3 Case Study

This case study demonstrates the development of an automated, knowledge-based design tool for AM using the MOKA framework. It shows the various steps of the MOKA process, from knowledge capture to algorithm implementation. Flow manifolds serve as an application example.

### 3.1 Identification of Application and Need (Step 1)

Many prior works highlight the use of AM for flow manifolds [56–60]. The design freedom of AM leads to many advantages for flow manifolds compared to conventional manufacturing methods such as milling and drilling. Th use of AM makes it possible to tightly integrate multiple, freely formed flow channels in a single part. AM allows to minimize pressure losses, avoid leakages, and reduce the mass and the size of parts.

The design of flow manifolds can be identified as a recurring design task that is needed in different applications. For example, Fig. 4 shows two manifolds fabricated using L-PBF of stainless steel. The two displayed flow manifolds are used for hydraulic applications. However, similar flow manifolds may also be utilized for other fluidic applications, in which it is necessary to guide fluid flows between multiple inlets and outlets.

One approach is to create the CAD geometry of each variant of a flow manifold from scratch using a manual

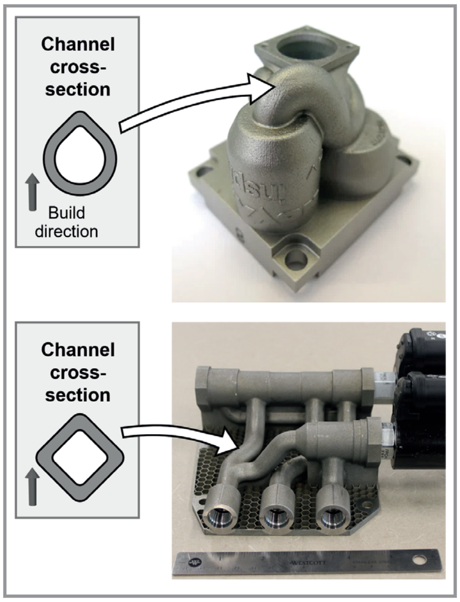


**Figure 4.** Examples for AM flow manifolds showing required adaption of flow channels (top: Nova Werke and inspire [61]; bottom: CIMP-3D and NAVAIR Lakehurst [56]).

traditional CAD approach (see Sect. 1). However, such a manual approach can often increase the manual design effort, especially for complex-shaped flow manifolds with multiple integrated flow channels. Therefore, using a design tool (developed specifically for AM flow manifolds) offers the opportunity to automatically create the 3D geometry of parts, thereby reducing the manual effort for expert CAD users and simplifying the design process for novice users.

### 3.2 Justification of Design Tool and Definition of Scope (Step 2)

Flow channels represent an essential design feature of flow manifolds. As shown in Fig. 4, flow channels can be oriented to the build direction in different directions. Flow channels are aligned horizontally to the build plate, which can lead to critical overhangs located at the inner surfaces of flow channels. In the case of AM processes such as L-PBF, such critical overhangs may need to be supported using additional sacrificial support structures. However, such supports inside flow channels are often inaccessible and difficult to remove during post-processing. Therefore, common design practice is to change the shape of circular cross sections to adapted shapes (e.g., droplet, diamond) to prevent the occurrence of critical overhangs and avoid the use of sacrificial support structures.

If CAD users implement such manufacturing-related design changes manually, it can oftentimes be a time-consuming and tedious task for parts with multiple flow channels such as flow manifolds. It can require several manual iterations of analyzing and modifying design features for manufacturability. Thus, it is desirable to provide CAD users with custom-programmed design features that automatically consider such manufacturing restrictions for AM. The goal of this case study is to implement a design feature that automates the creation of flow channels under the consideration of the AM overhang restriction. The idea is to generate flow channels and, if necessary, adapt the local shape of channel cross sections to fulfill the overhang constraint at the inner surface of channels.

### 3.3 Capturing of Raw Knowledge (Step 3)

The two previous steps identify the need for an automated design tool and define its scope (= automated creation of flow channels considering AM overhang restriction). The next step is to capture the knowledge needed to design flow manifolds and flow channels. As described in Sect. 2, the required knowledge can be extracted from various sources. Fig. 5 provides an overview of different knowledge artifacts relevant to the design of flow manifolds for AM. The knowledge artifacts represent selected examples and are chosen to give readers a first overview of potential knowledge artifacts.

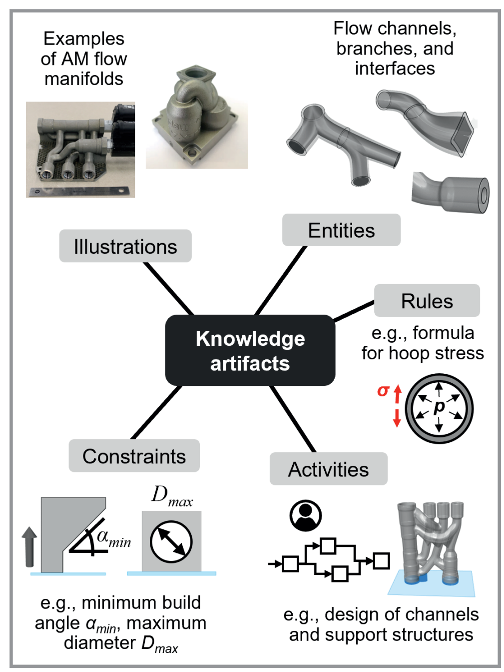


**Figure 5.** Overview of different knowledge artifacts for capturing design and production knowledge.

The knowledge artifacts are grouped into six categories based on the MOKA framework. Illustrations include case studies of prior works showing different embodiments and illustrations of flow manifolds. Manufacturing constraints of AM can be related to the constraints category. Examples of this category are design rules for AM processes such as

  

L-PBF [31–34]. Prior works recommend values for the minimum build angle $\alpha_{min}$ required to fabricate inclined surfaces without additional sacrificial support structures. Prior works also provide rules on the maximum diameter $D_{max}$, which marks the maximum diameter of circular cross sections that are horizontally oriented to the build plate and can be fabricated as self-supporting geometries without adapting the shape of circular cross sections.

The activities category describes steps that are performed in the design process. The design of AM flow manifolds requires modeling multiple flow channels. As described above, it can be necessary to adapt the circular cross section of flow channels to avoid critical overhangs inside flow channels. However, channels may also contain critical overhangs at the bottom of the outer channel walls. In this case, designers can add arch-shaped support structures below the channels that are united with the channels. Such integrated supports do not need to be removed after AM compared to sacrificial supports.

Rules can be described as knowledge artifacts that guide design activities and control choices in the design process. For example, the wall thickness of flow channels may be defined using analytical formulas such as the hoop stress formula [60]. This formula relates the stress in the channel walls, the thickness and length of the channel segment, and the fluid pressure inside the channel. Another example of a design rule is that the length of flow channels should be minimized to reduce pressure losses inside channels. Also, one important rule can be that channels guiding separate fluid flows should not overlap to avoid intersections between different flow channels.

The final category of knowledge artifacts is related to entities, which allow defining the structure of a part or product. Structural entities include elements such as the assembly, part, and design features. In the case of flow manifolds, structural entities include design features such as different cross-section shapes, flow channels, branches of channels, or interface elements such as connectors.

## 3.4 Formalization of Knowledge (Step 4)

The knowledge base stores different knowledge artifacts relevant to the design of AM flow manifolds and flow channels. The next step is to relate the different knowledge artifacts to each other using more formal models and representations such as flowcharts and class diagrams. Such more formal representations are checkable and processable by computers and can be used by software developers to implement the corresponding design activities as automated design algorithms.

As an example, Fig. 6 shows a flowchart that defines whether it is necessary to use a circular or an adapted shape for the cross section of a flow channel. The flowchart connects design activities (e.g., design of channels using a set of cross sections), structural entities (e.g., different shapes of cross sections), and constraints of AM (e.g., $D_{max}$, $\alpha_{min}$). The parameter $D$ marks the channel diameter. The angle $\gamma$ defines the inclination angle between the build plate and the normal vector of the channel segment.

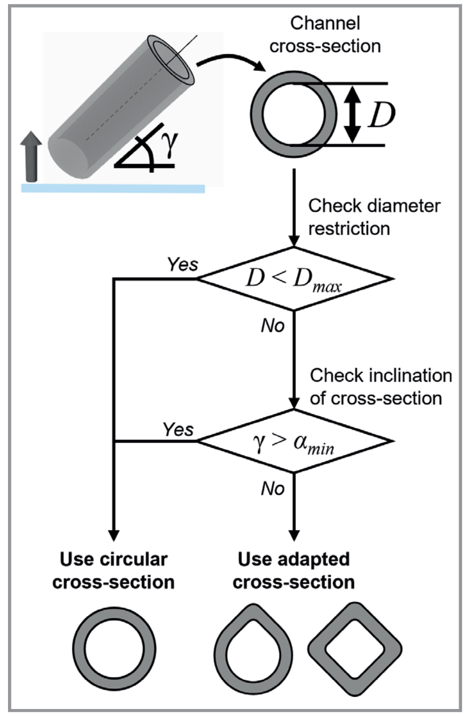


**Figure 6.** Flowchart for creation and adaption of channel cross sections for AM (adapted from [62]).

In the first query, the flowchart compares the channel diameter $D$ to the value $D_{max}$, which defines the maximum diameter of circular cross sections with horizontal orientation to the build plate. If $D < D_{max}$, the channel cross section can remain circular and does not need to be adapted. If $D > D_{max}$, it can be necessary to adapt the circular cross section to a modified shape to prevent critical overhangs inside the channel. The decision depends on the channel inclination $\gamma$ to the build plate and the minimum build angle $\alpha_{min}$. If $\gamma > \alpha_{min}$, the channel can be produced as a circular-shaped channel. If $\gamma < \alpha_{min}$, it is necessary to use an adapted cross-section shape (e.g., droplet, diamond).

The presented flowchart is one example of a rule-driven procedure. Similar procedures can be defined to formalize the generation of other design features, such as sacrificial supports, integrated supports, and detailed features such as interface elements. In this regard, the reader is referred to a prior work of the authors, which describes rule-based procedures for these design features [62].

## 3.5 Implementation of Design Features (Step 5)

Different CAD tools can be used to implement the formal models (e.g., flowcharts) as automated design algorithms.

This work uses the CAD program *Rhinoceros*, which integrates a visual programming editor called *Grasshopper*. The *Grasshopper* plugin can be applied to build procedural design workflows by creating different logic blocks in a canvas and connecting them using wires. This visual approach allows users to graphically implement an automated design workflow using prebuilt logic blocks.

Fig. 7 shows a procedural workflow developed for the automated design of flow channels considering the AM overhang restriction. Inputs include the channel centerline (defined by 3D curve), channel diameter $D$, wall thickness $t$, build direction, minimum build angle $\alpha_{min}$, and maximum diameter $D_{max}$ of horizontal cross sections. The procedure starts by sampling the centerline using equally placed points. For each sample point, the procedure computes the local inclination $\gamma$ of the normal vector of the centerline to the build plane. Then, the workflow creates channel cross sections at the sample points and locally determines at each point whether to use a circular or adapted shape to fulfill the AM overhang restriction. This step implements the flowchart shown in Fig. 6. The subsequent steps are to connect the cross sections using additional cross curves to create a wireframe of the channel. Finally, the procedure generates the channel surface and channel walls. The final result is a flow channel created considering the AM overhang constraint and the local adaption of the cross-sectional shapes.

As shown in Fig. 7, the implemented design procedure comprises many blocks and wires, making it difficult to reuse the procedure in different workflows. To improve the reusability of the design feature, one common approach is to cluster the different blocks and combine them into a single feature, as depicted in Fig. 8. This clustering approach allows hiding and abstracting the different subroutines in a single, higher-level design feature that can be easily shared and reused for different applications.

### 3.6 Use of the Design Tool (Step 6)

After implementing and packaging the design feature, users can apply it. Within this study, the design feature for flow channels is used in a larger workflow that automatically generates the 3D part geometry of flow manifolds fabricated using L-PBF of stainless steel. Fig. 9 shows an overview of the workflow.

As inputs, users define top-level variables related to functional requirements (e.g., centerlines of flow channels, diameters) and restriction of AM (e.g., $\alpha_{\rm min}$, $D_{max}$). Based on the inputs, the workflow generates the geometry of flow channels and, if necessary, locally adapts the shape of cross-sections. In the subsequent step, the workflow detects critical overhangs located at the outer surface of the channels. If

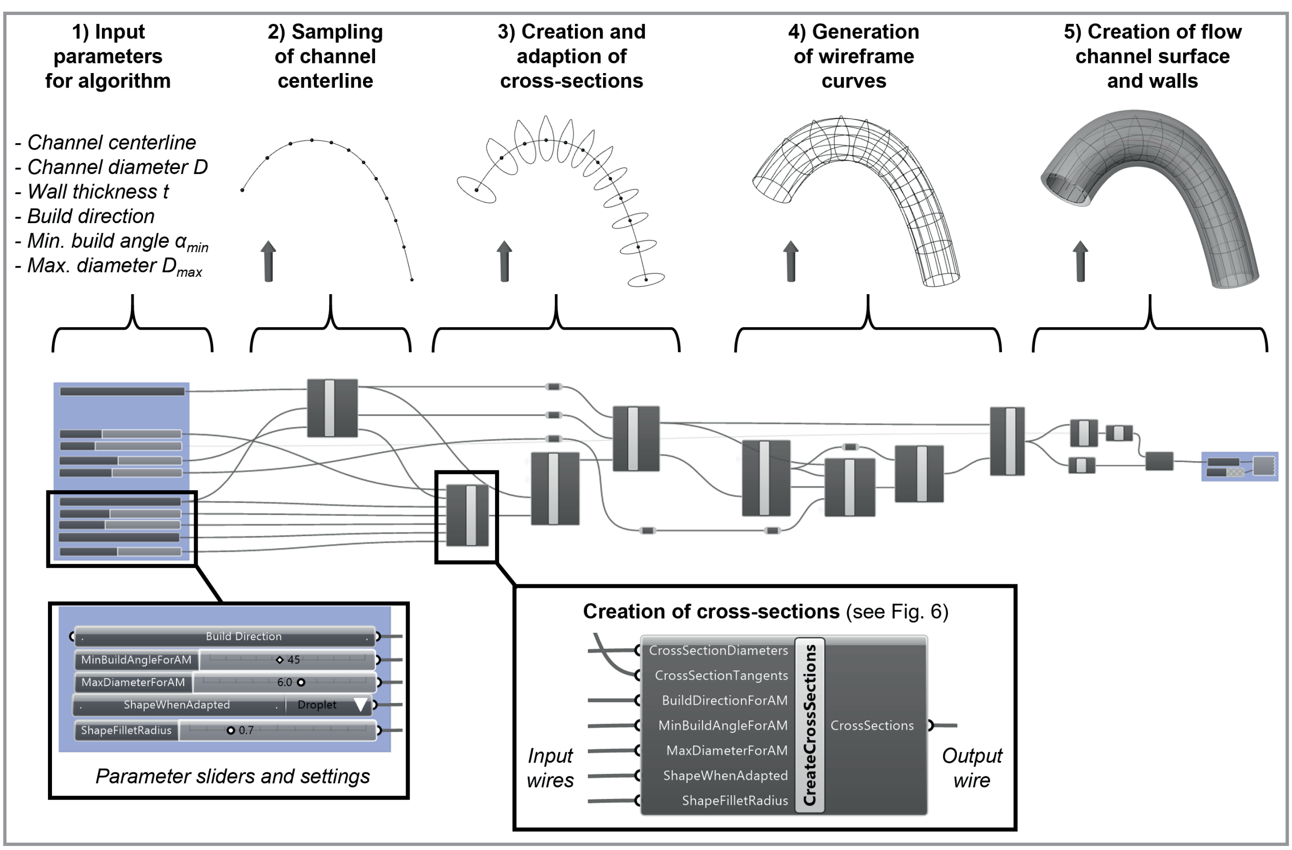


**Figure 7.** Automated creation of flow channels for AM using visual programming of *Grasshopper*.

  

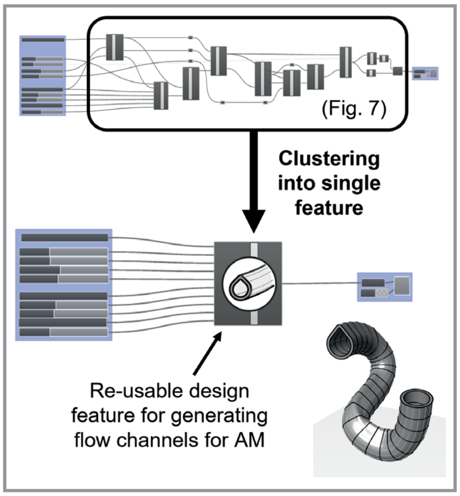


**Figure 8.** Clustering of procedural workflow into a single, higher-level design feature.

overhangs are critical, they are supported using integrated supports and sacrificial supports. For this purpose, additional design features are developed to generate both support types automatically. These features are implemented like the flow channels by capturing the required design knowledge and automating the corresponding tasks using rule-driven procedures (see details in prior work [62]). The final output is a production-ready 3D part geometry of the flow manifold.

Users can utilize the workflow to create the detailed 3D part geometry of flow manifolds automatically. They do not need to manually create and modify low-level design features (e.g., sketches, curves, surfaces), causing many manual and repetitive routine tasks. As the workflow requires only top-level inputs, it is accessible to novice designers who do not have advanced CAD modeling skills. Users can generate different design variants of a flow manifold at reduced manual effort for different input settings.

The automated design workflow can be reused to automatically generate design variants for different purposes, which would require an increased manual effort using a traditional manual design approach with CAD tools. For example, users can study different design concepts and modify the centerlines of the flow channels. They may also generate design variants for various build directions to examine and compare different production scenarios.

## 4 Lessons Learned

The case study uses the MOKA framework to implement recurring design activities as knowledge-based automated design features. This section summarizes a number of lessons learned.

One learning is that frameworks such as MOKA provide an easy-to-follow guideline for developing automated design tools for AM. In this regard, it is crucial to focus on a specific application field (e.g., flow manifolds) and narrow the scope of the developed design features. Otherwise, it may be challenging to capture all the design and production knowledge required to implement the related design activities.

In an early development stage of an automated design tool, it is advisable to first automate simpler, rule-based tasks. Examples are the presented design features for generating the flow channels and support structures. The use of flowcharts makes it possible to describe the related design activities and specify the influence of manufacturing

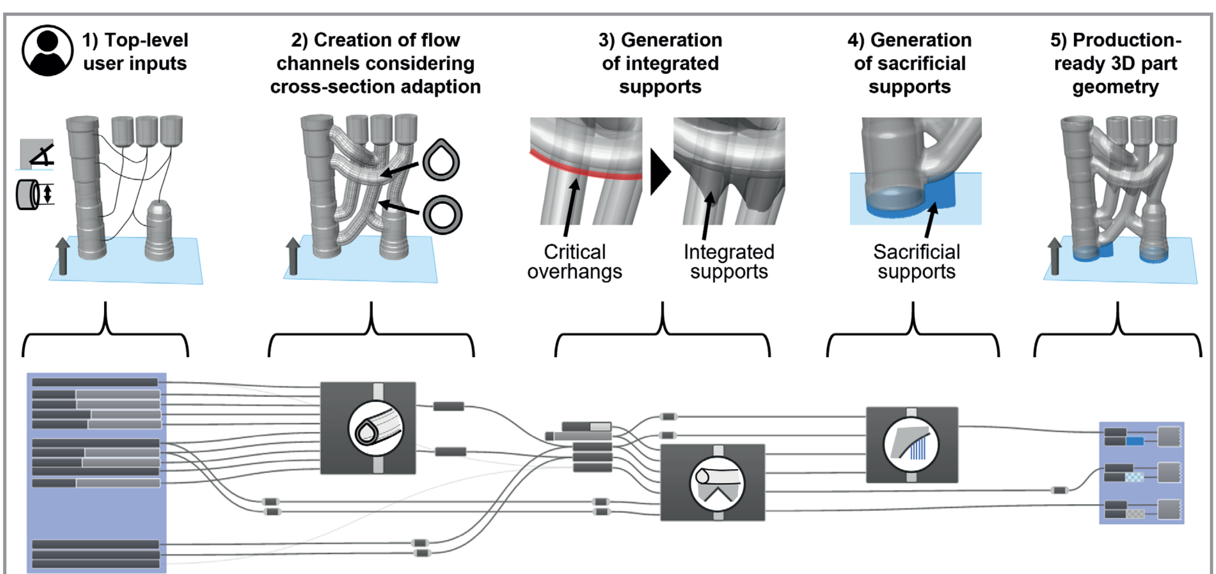


**Figure 9.** Procedural design workflow to generate production-ready 3D part geometry of flow manifolds based on top-level user inputs (e.g., flow channels pathways) and restrictions of AM (e.g., $\alpha_{min}$, $D_{max}$).

  

restrictions of AM on the creation and adaption of geometric features. Over time, developers can aim to achieve a higher level of automation in the design process and implement more difficult design tasks (e.g., automated creation of paths of flow channels).

As illustrated in the case study, the use of visual programming editors such as *Grasshopper* is one approach for creating automated design workflows. Such a visual approach allows users to graphically implement automated design features instead of creating them using text-based programming languages. The technique of clustering allows combining multiple subroutines into a single design feature. Such high-level features can be (re-)used to build more complex automated design workflows (e.g., automated design of flow manifolds including generation of channels and supports).

Another learning is that the development of automated, knowledge-based design tools for AM requires different skill sets. Therefore, it is recommended to set up interdisciplinary teams consisting of application specialists, AM engineers, KBE experts, computational designers, and software engineers.

## 5 Conclusion

AM offers tremendous potential to rethink the design and functionality of process equipment devices. However, the manual design of complex-shaped parts is often challenging for AM. This work highlighted the use of an automated design approach to generate the geometry of parts for AM at a reduced manual effort. The goal was to introduce practitioners in the field of fluid and process engineering to an automated design approach for AM. For this purpose, the work described the basic steps for implementing an automated design approach using a knowledge-based approach and the MOKA framework. The work demonstrated the approach and implemented an automated design approach using the example of flow manifolds. Future works can further examine the use of an automated design approach for AM for different devices in fluid and process engineering.

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## Automated Design for Additive Manufacturing: Application of Knowledge-Based Approach for Flow Manifolds

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**Research Article:** Additive manufacturing (AM) makes it possible to redesign process equipment devices. However, manually designing complex parts is often challenging. This work highlights the use of an automated design approach for AM and shows the basic steps to develop automated, knowledge-based design algorithms. The approach is demonstrated using AM flow manifolds as an application example.