Additive Manufacturing 35 (2020) 101231

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Research Paper

Computational design synthesis of additive manufactured multi-flow nozzles

Manuel Biedermann*, Mirko Meboldt

Product Development Group Zurich pd|z, ETH Zurich, Zurich, Switzerland

ARTICLE INFO

Keywords:
Design for additive manufacturing
Design automation
Computational design synthesis
Co-extrusion

ABSTRACT

Additive manufacturing (AM) enables highly complex-shaped and functionally optimized parts. To leverage this potential the creation of part designs is necessary. However, as today's computer-aided design (CAD) tools are still based on low-level, geometric primitives, the modeling of complex geometries requires many repetitive, manual steps. As a consequence, the need for an automated design approach is emphasized and regarded as a key enabler to quickly create different concepts, allow iterative design changes, and customize parts at reduced effort. Topology optimization exists as a computational design approach but usually demands a manual interpretation and redesign of a CAD model and may not be applicable to problems such as the design of parts with multiple integrated flows. This work presents a computational design synthesis framework to automate the design of complex-shaped multi-flow nozzles. The framework provides AM users a toolbox with design elements, which are used as building blocks to generate finished 3D part geometries. The elements are organized in a hierarchical architecture and implemented using object-oriented programming. As the layout of the elements is defined with a visual interface, the process is accessible to non-experts. As a proof of concept, the framework is applied to successfully generate a variety of customized AM nozzles that are tested using co-extrusion of clay. Finally, the work discusses the framework's benefits and limitations, the impact on product development and novel AM applications, and the transferability to other domains.

1. Introduction

Based on the layerwise adding of build material, additive manufacturing (AM) enables the fabrication of intricate, organic-shaped structures with high complexity [1–3]. A part can be complex because of its shape, material composition, functionality, and hierarchically organized features [4]. As an example, Fig. 1 shows a redesigned AM burner nozzle that is produced using powder bed fusion (PBF) [5]. It integrates multiple flow channels for cooling water and different reactants. The part demonstrates that AM processes have become mature enough to fabricate highly integrated and functionally optimized structures. However, to create such complex part designs it is necessary to provide suitable design tools, which is considered a major barrier for the implementation of AM [1–3,6,7]. Especially complex AM parts are based on profound application-specific knowledge of experts and oftentimes require a time-consuming manual process of modeling with computer-aided design (CAD) tools. The reason is that today´s CAD tools were originally developed for conventional manufacturing processes such as milling and are still based on combining low-level, geometric primitives [8]. CAD tools have evolved over the past decades but since the introduction of *SketchPad* as the first CAD system geometric modeling has remained a manual process with a low degree of abstraction [8]. In case of the burner in Fig. 1, the CAD model was created within six months and contains over 2500 features. Especially for such a complex design, a manual, low-level process limits rapid and iterative design changes as well as the quick embodiment of a variety of design concepts. Therefore, with the rise of AM, the need for improved design tools and an automated design approach is seen as a decisive factor in design for AM (DFAM) and applications such as customization [3]. To capture the design intent of a user on a higher level, one commonly applied tool of computational design synthesis [6,7,9] is topology optimization (TO), in which a designer defines high-level requirements like design space, loads, and boundary conditions. TO algorithms are used for specific problems like lightweight parts and compliance mechanisms [9,10], parts for heat transfer [11,12] or problems with one or two mixing flows [13–15]. Although TO allows creating very complex structures, the raw result is a non-parametric design proposal in form of a discretized material distribution. Therefore, the result of a TO usually represents a rough concept, which demands a manual interpretation and redesign of a CAD model [16–18] or a reverse engineering approach [19,20].

Besides computational design tools another approach to assist

* Corresponding author.
E-mail address: manuel.biedermann@mavt.ethz.ch (M. Biedermann).

https://doi.org/10.1016/j.addma.2020.101231
Received 14 November 2019; Received in revised form 25 February 2020; Accepted 6 April 2020
Available online 15 May 2020

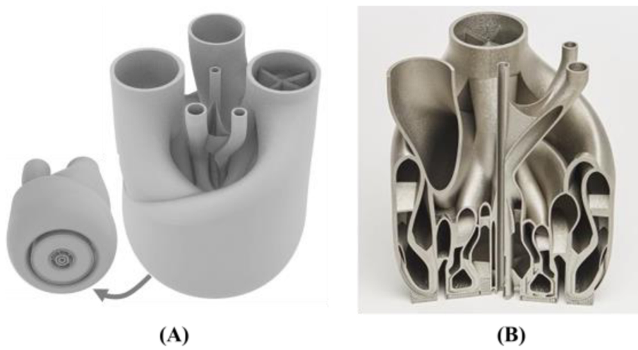


Fig. 1. (A) AM burner nozzle with multiple flow channels (developed and provided by Siemens Corporate Technology, further described in [5]); (B) Section cut of part fabricated with PBF (Image by MBFZ toolcraft).

DFAM is to capture and store design knowledge using expert systems and databases, for which prior works focus on feature taxonomies [21,22] and ontologies for AM [23,24]. In general, the use of a knowledge-based engineering (KBE) approach for design automation in AM is highlighted but proposed frameworks are yet to be implemented [7,25] or exist only for domains such as lightweight parts [26,27]. Although KBE offers many benefits for an automated design approach [28,29], prior works focus only on larger assemblies like aircrafts or robots [30] and a lack of cases is criticized [31]. Likewise, many techniques exist in computational design synthesis [32–34] but the implementation for DFAM is yet to be more fostered and demonstrated for AM applications [9,35].

The aim of this work is to present and implement a computational design synthesis framework that enables the automated design of AM nozzles that guide multiple fluid flows. An overview of the framework is given in Fig. 2. Similar to prior works [27,32,36], the main idea is to provide users a software-based design toolbox with a set of design elements, which function as high-level building blocks. Given the concept of a nozzle including inlets and outlets, a user specifies the layout design of a part meaning the arrangement of design elements. The layout serves as an input for the toolbox that automatically translates it into the corresponding 3D nozzle geometry. To analyze manufacturing restrictions of AM [37,38] the toolbox provides functions to check wall thickness values and critical overhang angles. These allow detecting and excluding non-manufacturable AM designs. Furthermore, a nozzle can be evaluated for its performance using computational fluid dynamics (CFD) analysis. Overall the framework is based on:

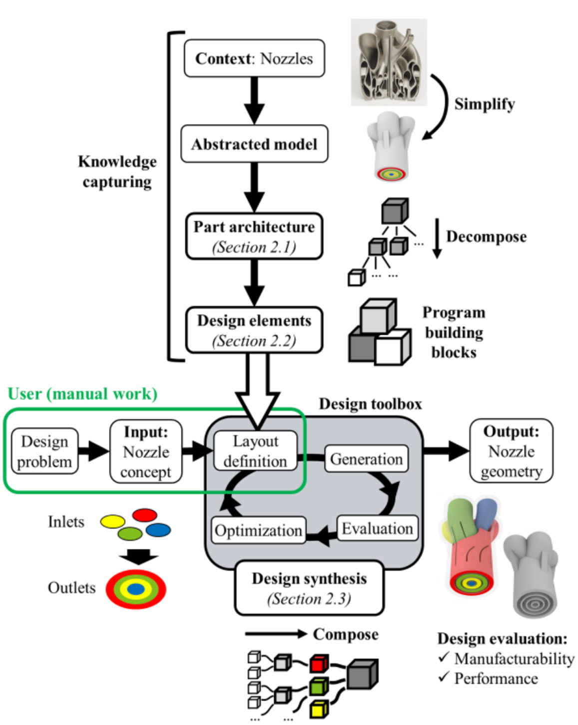


Fig. 2. Overview of computational design synthesis framework including knowledge capturing of part architecture and design elements as well as steps of design synthesis process for creation of 3D nozzle geometry ©CC4.0 pd|z ETH Zürich.

(1) A *part architecture* that organizes an AM nozzle with multiple integrated flows as a hierarchy of design elements (Sec. 2.1).

(2) A set of *design elements*, which are implemented through object-oriented programming and represent building blocks of multi-flow nozzles (Sec. 2.2).

(3) A *design synthesis process* that enables novice users through a visual interface and CAD plugin to define a layout, generate a nozzle geometry and evaluate it for manufacturability and performance (Sec. 2.3).

After outlining the framework, a case study in Sec. 3 demonstrates its use to automatically generate a variety of customized AM nozzles that are tested using co-extrusion of clay. Sec. 4 discusses the framework´s benefits and limitations and emphasizes the impact on product development and novel AM applications. In addition, the discussion comments on the transferability of the approach to other domains. Sec. 5 finishes with a summary and the conclusions of the work.

2. Computational design synthesis framework

2.1. Part architecture

To capture the design logic of a system or part, a common step in the area of knowledge-based design is to decompose it into its individual components and design elements, which have different functions and properties [28,29,39,40]. As shown in Fig. 3, a nozzle part with multiple integrated flow channels can be decomposed into a number of building blocks or design elements.

The depicted nozzle represents a simplified version of the burner nozzle of Fig. 1. The nozzle in Fig. 3 has four pipe inlets and four ring-shaped outlets. It guides four different fluid flows that are marked by the colors blue, yellow, green, and red. As mentioned, the nozzle represents one single example to visualize the developed part architecture for multi-flow nozzles. Other nozzle variants with a similar architecture may differ in the number, shape, and positionings of the inlets and outlets as well as other design features and characteristics.

The part architecture in Fig. 3 results from a top-down decomposition of the nozzle and is defined by a hierarchy of design elements. The geometry of a nozzle is modeled in such a way that it consists of a structure, which integrates multiple flow channels that guide different fluid flows within a monolithic geometry.

Within the structure multiple flow channels are interlaced and nested in each other. Units are introduced to model the separate flow channels that correspond to the different fluid flows. In the example the nozzle integrates four units to guide the four separate flows. Other nozzle variants may integrate a different number of units.

A unit can be composed out of multiple flow channel segments. Connections are introduced to model the individual flow channel segments of a unit. Multiple connections can be aligned as a series or parallel network within a unit. To describe the geometry of a connection, it is necessary to specify its start and end section conditions. For this purpose, sections are used to define the start and end position of a connection together with the cross-sectional shape.

As a whole, the hierarchical part architecture represents a form of a master model or blueprint design [28–30,41] to generate different multi-flow nozzle designs. The design elements function as object-oriented building blocks. Instead of low-level CAD primitives, the design elements can be seen as predefined, high-level objects. To implement

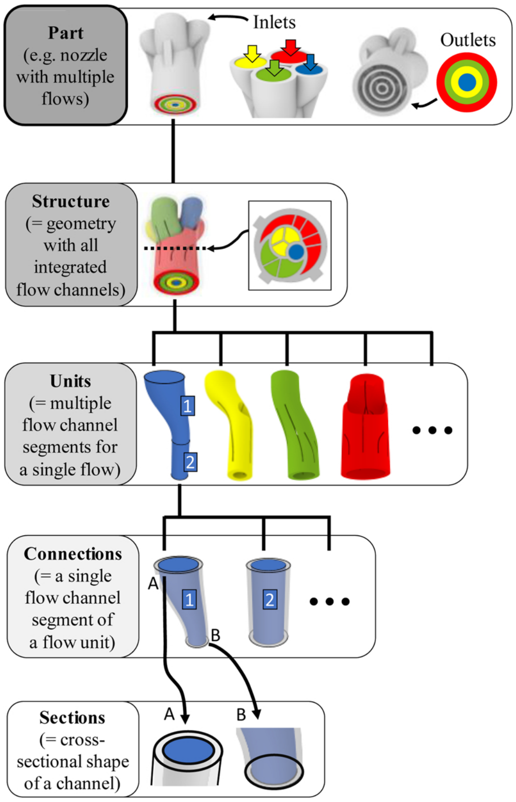


Fig. 3. Top-down decomposition of a nozzle geometry with multiple integrated flow channels into its individual design elements within a hierarchical part organization ©CC4.0 pd|z ETH Zürich.

the design elements, this work applies object-oriented programming to instantiate design elements as objects and synthesize nozzles from them.

2.2. Design elements

Object-oriented programming is used to implement each design element as a class. In the following, the blueprint of each design element is described and serves as a basis to program the functions and properties of its class.

2.2.1. Section class

A section is defined by a local coordinate system and two planar, non-intersecting, and closed curves (Fig. 4). The inner curve specifies the flow domain. A wall thickness parameter determines the offset between the inner and outer curve. Based on a type parameter the section curves are created from analytical curves (ellipsoids, rectangles), Unicode characters and letters, and custom input curves. Examples for various sections are shown in Fig. 5. Section objects are also used to integrate threads.

To further process a section, its shape is discretized by performing a sampling operation. As shown in Fig. 5 (A), sampling points are placed on the curves of a section and divide these into smaller curve pieces.

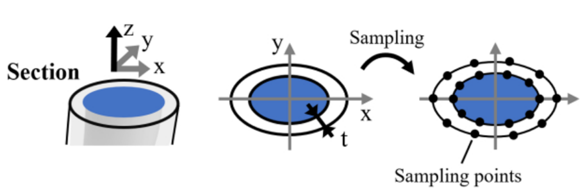


Fig. 4. Blueprint for section object to define cross-sectional shape of flow channel segments ©CC4.0 pd|z ETH Zürich.

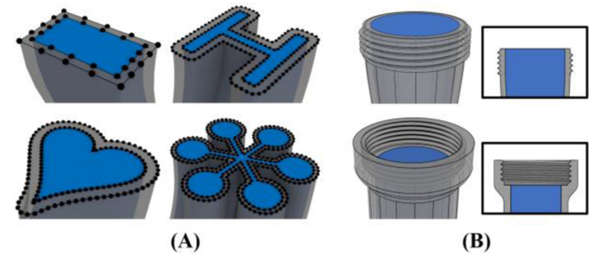


Fig. 5. (A) Example for sections with different curve types and generation of sampling points for further processing; (B) Integration of threads at sections ©CC4.0 pd|z ETH Zürich.

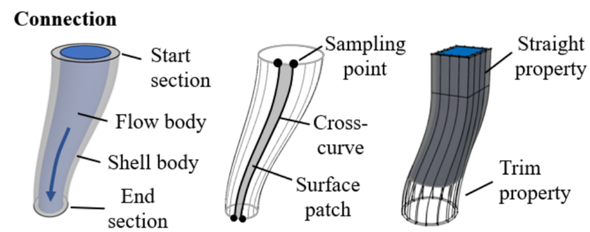


Fig. 6. Blueprint for connection object to represent one single flow channel segment ©CC4.0 pd|z ETH Zürich.

2.2.2. Connection class

A connection represents one single flow channel segment and connects two sections. The inner body defines the flow domain and the shell body corresponds to the wall.

The geometry of a connection is determined by the orientation and shape of its start and end section. The bodies of a connection are defined by a surface-based boundary representation (BREP). As depicted in Fig. 6, the surfaces are lofted using a wireframe that is created from the curve pieces of the sections and additional cross-curve splines. The cross-curves start perpendicular to each section and connect the sampling points of both sections. In case two sections differ in their sampling number, the larger number is chosen for the sampling operation. To further modify a connection, its sections can be assigned with a straight or a trim property.

As shown in Fig. 7, within a connection it is possible to integrate vanes for flow guidance and stiffening ribs as a reinforcement. The geometry of the generated vanes and ribs is defined by a set of design parameters, which are depicted in Fig. 7. The shape of each vane is parametrized by its start and end positions, thickness, opening angles, pitch angles, and trim angles. Ribs are parametrized using a wall thickness parameter as well as the width at the rib start and end positions. Similar to a connection, the geometry of vanes and ribs is generated using cross-curves and surface patches as shown in Fig. 6.

2.2.3. Unit class

A unit consists of multiple connections that form a network of flow channels to guide one single flow. A unit has a flow body and a shell body, which are composed of the flow and shell bodies of the contained connections. Connections can be arranged in series or parallel networks

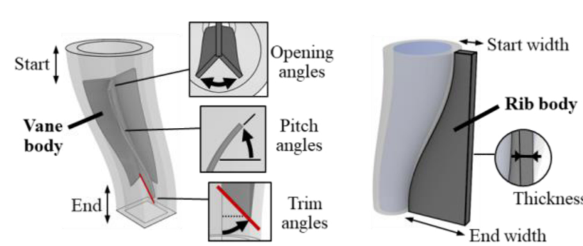


Fig. 7. Integration of flow guiding vanes and stiffening ribs into a connection object ©CC4.0 pd|z ETH Zürich.

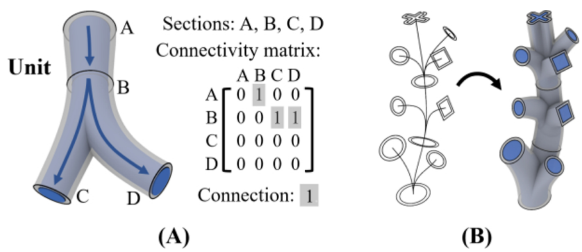


Fig. 8. (A) Blueprint for unit defined by network of sections and their connections; (B) Example for unit object containing connections in series and parallel ©CC4.0 pd|z ETH Zürich.

as illustrated in Fig. 8. To define the layout of connections, a connectivity matrix in form of an adjacency matrix is used, which stores all sections of a unit. In the matrix non-weighted entries refer to the flow direction between two sections and determine the connections and their layout within a unit.

2.2.4. Structure class

A structure integrates multiple units into a single part geometry. For this purpose, the geometric overlap between different flow regions needs to be detected and resolved. This is achieved by using boolean operations between the bodies of units. As an example, Fig. 9 shows one blue and one green unit. In the original state, the flow bodies of both units overlap and thus the resulting structure does not guide the flows in separated flow channels. To resolve this overlap, the flow body and shell body of the blue unit are subtracted from the bodies of the green unit. After this subtraction, the flow regions of both units do no longer overlap and a structure can be generated that guides both flow domains in separated channels. Different rules can be implemented to resolve overlaps between different units. The example illustrates a rule where units with a smaller flow body (e.g. blue) are prioritized over units with a larger flow body (e.g. green).

2.3. Design synthesis

The presented design elements function as predefined building blocks to automate the generation of multi-flow nozzles. Fig. 10 gives an overview of the design synthesis process. Starting from a specification of the design problem (e.g. conceptual definition of nozzle inlets and outlets), the design synthesis process requires a number of user inputs (regarding the employed design elements, fabrication data, performance evaluation and design optimization) to generate a manufacturable and optimized 3D nozzle geometry.

The main steps of the design synthesis process include the user-based definition of a parametric nozzle layout using the design toolbox and its preprogrammed design elements, the automated generation of a 3D nozzle geometry, and its automated evaluation regarding manufacturability and performance. The use of an additional parametric optimization offers the possibility to iteratively change the parametric nozzle layout and optimize a nozzle design (see details in Sec. 2.3.4).

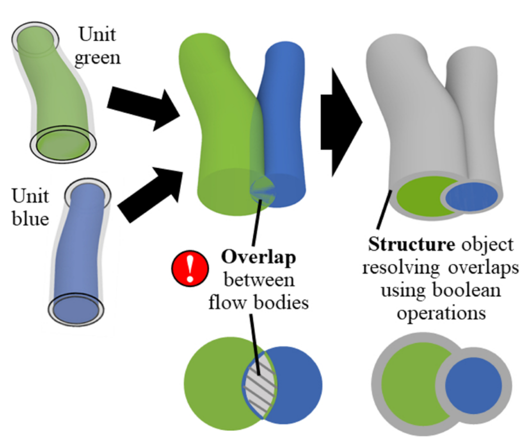


Fig. 9. Integration of units into structure by resolving overlaps between different flows ©CC4.0 pd|z ETH Zürich.

2.3.1. Parametric layout

To synthesize the design elements, a custom CAD plugin was programmed in the 3D-CAD software *Rhinoceros®* and its parametric design environment *Grasshopper®*. *Grasshopper* offers the possibility to specify the parametric layout of a nozzle using a visual, node-based editor. As shown in Fig. 11, a user selects a design element (e.g. section, connection, unit, structure, vane, rib object) from a toolbar and drags it into the *Grasshopper* canvas. Each element is assigned with a set of parameters that define its shape and properties. To specify the relation between elements, they are connected using wires. For instance, as depicted for the yellow colored unit in Fig. 11 two sections serve as an input for a connection object, which is extended with a vane and a rib object. In a similar manner, other units of a nozzle layout can be defined. Furthermore, this interface is used to specify user inputs from Fig. 10 such as build material, build direction and thresholds for AM process parameters (e.g. minimum build angle, minimum wall thickness).

2.3.2. Design generation

Once the layout is defined, it can be automatically translated into the corresponding 3D nozzle geometry based on the preprogrammed design elements. As an example, Fig. 12 shows the generation for the nozzle variant with four flow channels. The process starts with the sampling of sections and continues with the creation of connections, vanes, ribs and units. Overlaps between units are identified and boolean operations are performed to interlace different units within a monolithic structure. The result is a surface-based 3D geometry of the nozzle and flow channels. If the geometry generation aborts due to geometrical CAD errors, the user is notified.

2.3.3. Design evaluation

The design generation step itself does not prevent the creation of designs, which violate AM manufacturing restrictions. Design elements are only translated into the corresponding 3D geometry but do not adapt themselves. Therefore, it is necessary to evaluate the designs for AM restrictions and exclude non-manufacturable designs. As shown in Fig. 13 custom programmed functions are used to detect critical wall thickness values or critical overhangs for a given build direction using a mesh-based description. Critical process parameters such minimum build angle and minimum wall thickness need to be defined by the user. These depend on the select AM process, build material, and machine, and can be defined based on prior studies on AM processes [37,38]. Non-manufacturable AM designs are detected and marked. To evaluate the nozzle performance, a CFD analysis can be conducted. An interface was programmed to the external CFD tool STAR-CCM+ to automatically export 3D geometries of flow channels and evaluate a CFD model for design responses such as pressure drop or flow velocity uniformity at a section outlet. Besides a CFD analysis, the reduction in cross-sectional area between two sections of a flow channel can be calculated.

2.3.4. Parametric optimization

Design elements make it possible to automate the generation of 3D nozzle geometries. To optimize a nozzle design, a parametric optimization can be performed, in which an algorithm automatically modifies the parameters of the nozzle layout and its design elements, generates and evaluates 3D designs, and improves these in an iterative procedure. For instance, as an objective function the flow uniformity at a flow channel outlet can be maximized by changing the parameters of design elements such as guiding vanes. If the optimization generates non-

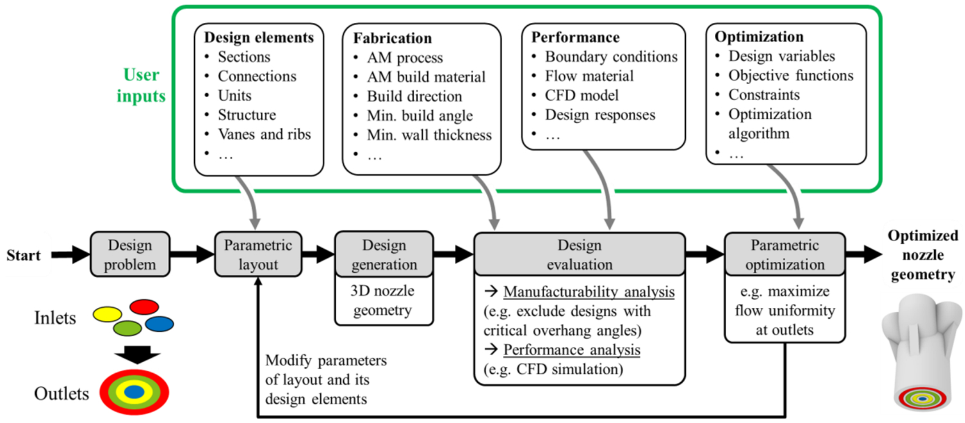


Fig. 10. Detailed overview of design synthesis process for multi-flow nozzles showing required user inputs (design elements, fabrication data, performance evaluation, design optimization) and process steps ©CC4.0 pd|z ETH Zürich.

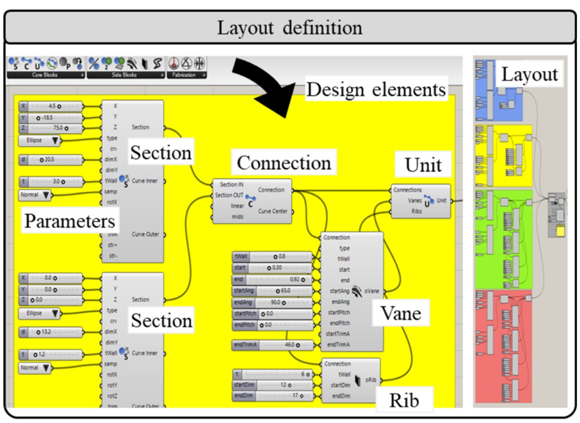


Fig. 11. Definition of layout of design elements using visual, node-based editor of *Grasshopper* ©CC4.0 pd|z ETH Zürich.

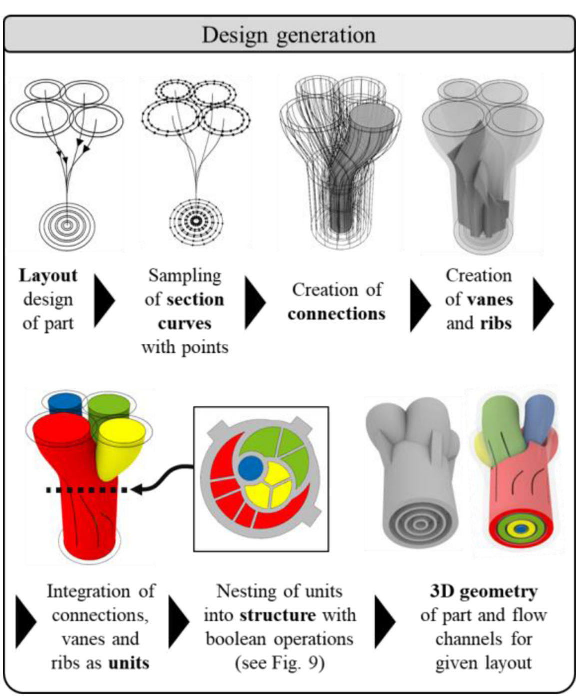


Fig. 12. Steps of design generation starting with layout as an input leading to 3D nozzle geometry ©CC4.0 pd|z ETH Zürich.

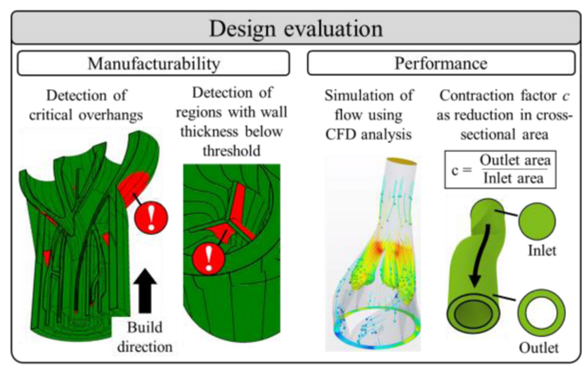


Fig. 13. Evaluation of nozzle design for AM manufacturing restrictions and performance ©CC4.0 pd|z ETH Zürich.

manufacturable AM designs (e.g. vanes with critical overhang angles), such design variants are filtered out in the design evaluation and thus excluded during an optimization. A parametric optimization can be set up in *Grasshopper* using plugins such as *Galapagos*, *Optimus* or *Wallacei* that provide different algorithms for design space exploration.

3. Case study: automated design of a variety of FDM fabricated nozzles for clay co-extrusion

The following case study demonstrates the application of the framework and shows that it can be used to generate a variety of nozzle designs. Fused deposition modeling (FDM) of polylactide (PLA) is applied for the fabrication of nozzles. Their function is examined by extruding modeling clay as a viscous flow material. To study the generated nozzle designs, the approach is to use a cross-head extruder as a standardized part and mount customized generated nozzles with a thread interface. Different colors refer to flows of differently colored clays. As shown in Fig. 14, the cross-head extrudes four flows of clay into each other as concentric rings, whereas the nozzle tip merges the concentric flows and defines the shape of the extrudate that exits at the nozzle outlet.

Table 1 lists the studied nozzles. The inlets of each nozzle equal the

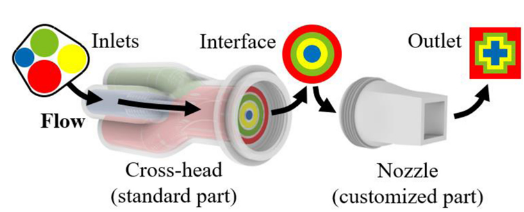
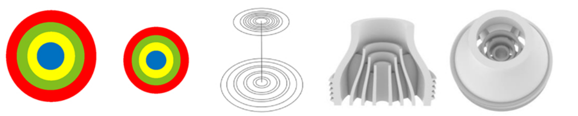
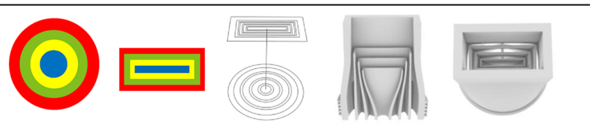
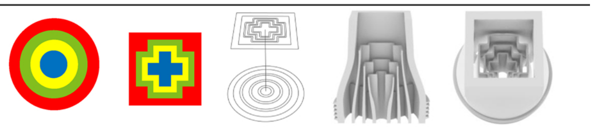
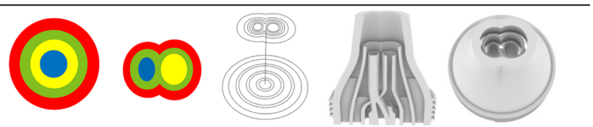
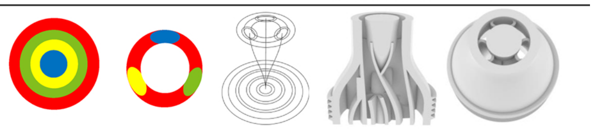
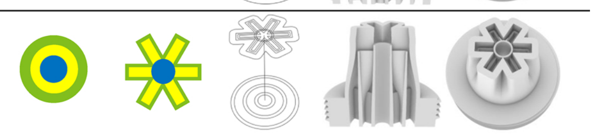
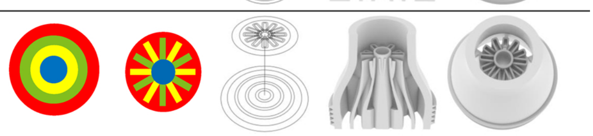


Fig. 14. Modular assembly consisting of automatically generated cross-head and nozzle ©CC4.0 pd|z ETH Zürich.

Table 1
Overview of nozzles showing inlet and outlet, layout preview and generated designs ©CC4.0 pd|z ETH Zürich.

ID	Nozzle inlet	Nozzle outlet	Layout design	Generated nozzle geometry (cut view and full model)
1				
2				
3				
4				
5				
6				
7				

interface of the cross-head. The outlets have various shapes. The selection of the outlet shapes is motivated by applications of a co-extrusion process. Similar shapes are used to co-extrude wires, tubes, profiles, heat sinks, packaging films, fuel cells, food, hydrogels, and applied for other products and processes [42–50].

The design synthesis process is used to generate the nozzle geometries. As shown in Fig. 15, the first step is to define the layout of each nozzle. The design elements and their assigned parameters are then automatically translated into the corresponding 3D nozzle geometry within 5–10 seconds. The generated designs are evaluated for manufacturing restrictions of FDM. The build direction is defined in the z-axis. The nozzle design is checked for a minimum required build angle of 45°. If necessary, the layout is modified by the user to adapt regions with critical overhangs and recreate and reanalyze the 3D geometry. In addition, for the co-extrusion process the flow channels are evaluated regarding the reduction in cross-sectional area in each channel. The generation of the nozzles is conducted without the use of a parametric optimization.

The resulting nozzle designs are fabricated using FDM and assembled with the cross-head part. The inlets of the cross-head are filled with modeling clay (e.g. *Play-Doh*). A hand press and plungers are used to push the clays through the cross-head and each nozzle. At the nozzle outlet, the co-extruded clay materials exit as shown in Fig. 16 (A). The extruded strands are cut using a thin wire. Sliced samples are shown in Fig. 16 (B).

As shown in Fig. 17, the positioning of vanes is critical to homogeneously distribute the flow material to a ring-shaped outlet. To maximize the velocity uniformity of the red flow channel, a CFD-driven parametric optimization can be used [5]. The red channel integrates four pairs of vane elements that are each defined by four parameters.

The initial, user-defined positioning of vanes leads to an outlet velocity uniformity of 69 % (baseline). To improve this objective, an optimization is applied that iteratively changes the vane parameters (16 in total), creates the 3D channel geometry, excludes non-manufacturable AM designs (e.g. vanes with overhangs) and runs a CFD analysis for manufacturable designs. The flow material is modeled as a laminar, incompressible flow with an inlet velocity of 4 mm/s and a dynamic viscosity of 1500 Pa*s.

In *Grasshopper* the parametric optimization is set up using the *Opossum* plugin and its unconstrained, single objective optimization algorithm *RBFOpt* [51]. During the optimization, 325 design variants are successfully generated, of which 173 fulfill the FDM overhang constraint (minimum build angle of 45°) and a CFD analysis is performed. After 8 h (AMD Ryzen, 32 cores, 64 GB RAM) the optimization converges with an optimized set of vane parameters and an improved outlet velocity uniformity of 80 % as shown in Fig. 17.

4. Discussion

4.1. Advantages of object-oriented design elements

The design elements serve as a blueprint to enable the automated design of complex, additive manufactured flow components. The elements leverage the benefits of knowledge capturing and object-oriented programming. Compared to prior works [21], knowledge is not stored as explicit rules, heuristics or databases but provided as (re-)usable, high-level building blocks. This makes it possible to capture the logic of AM parts and synthesize AM part designs with hierarchical complexity such as nozzles with multiple integrated flow channels, for which a metallic prototype is shown in Fig. 18.

4.2. Benefits for user and iterative design development

Compared to a manual CAD process, low-level and time-consuming routine tasks such as the creation of geometric primitives are automated. Users can focus on creative tasks, generate 3D geometries for many different design concepts and make changes with reduced effort. This is especially beneficial for the iterative design, fabrication and testing of AM parts. As design elements are provided through a graphical interface, the design process is accessible also for non-expert users. They can define, reuse and copy layout designs without deep CAD knowledge. This provides a viable alternative to existing strategies for modeling and reusing CAD models [52].

4.3. Impact on novel AM-enabled applications

Besides benefits in iterative development, an automated design approach with design elements can be leveraged for AM-enabled, digital process chains. Especially for the customization of many part and product variants, design automation acts as an enabler for efficient design adaptions and as a key value driver for new, innovative business models. The case illustrates this opportunity for co-extrusion nozzles. In this respect, the importance of software engineering rises in the area of DFAM and hardware products become like software-based services with the possibility for frequent design updates [41,53].

4.4. Comparison of approach to topology optimization

When performing a design exploration and exploitation, design elements have the disadvantage that they limit the searchable design space. The reason is that elements like sections predefine geometric features. This is a limitation compared to TO, in which design elements correspond to discretized finite elements and density values, and thus

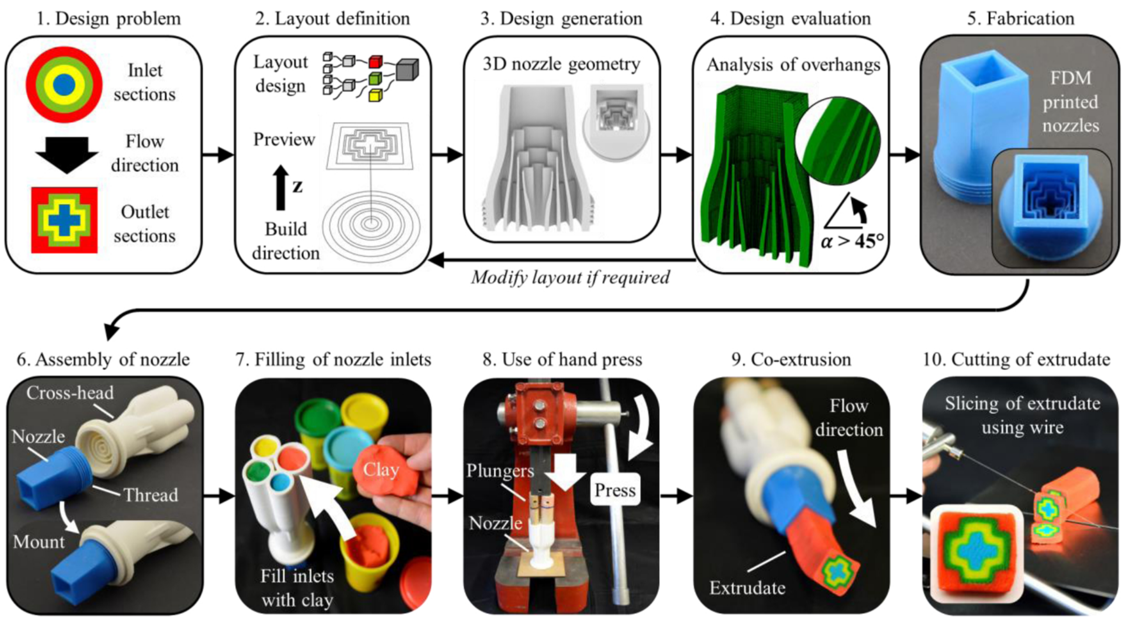


Fig. 15. Visualization of procedure to design and test customized nozzles showing steps of design generation and evaluation, fabrication of nozzles using FDM, preparation and filling of nozzles with soft clay material, use of a hand press to perform co-extrusion process, and resulting extrudate sample and slicing with wire ©CC4.0 pd|z ETH Zürich.

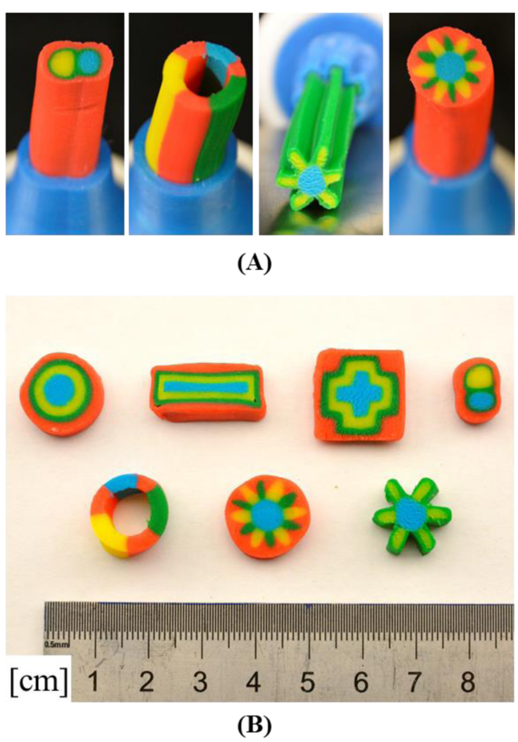


Fig. 16. (A) Visualization of extrudate flows exiting nozzle outlets; (B) Sliced extrudate pieces produced using FDM printed nozzles from Table 1 ©CC4.0 pd|z ETH Zürich.

no prior features are specified. In combination with the proposed approach, TO may be utilized to identify new or improved high-level design elements. Furthermore, also for TO the use of building blocks is examined in the context of moving morphable components [54,55].

4.5. Further integration of manufacturability for AM

In this work, manufacturability restrictions of AM such as overhang constraints and minimum wall thickness values are evaluated after the design generation. Therefore, design elements are not actively modifying themselves during the design generation step. Instead, non-manufacturable designs are detected and excluded (or filtered out) during a parametric optimization.

An improvement of this approach is to carry out a manufacturability adaption, for instance, for regions with overhangs already during the design generation step. Design elements such as sections and vanes would recreate and modify themselves according to a given build direction. For example, an elliptical cross-section of a flow channel may automatically transform into a droplet-shaped curve to fulfill overhang constraints.

Instead of classifying designs as manufacturable or non-manufacturable, other metrics can be used to better quantify the manufacturability for AM. For instance, the required amount of support structures [56], the part height, manufacturing costs or thermal distortions [57] can be used as measures. In a multi-objective parametric optimization such manufacturability measures can be combined with objective functions on the part performance. The weighting depends on the specific design problem and preferences of the designer.

4.6. Transfer to other AM application domains

This work implements a set of parametric design elements to synthesize a variety of multi-flow nozzles that integrate multiple flow channels. In general, the approach may be applied to similar flow components such as dies with cooling channels, valves, manifolds, heat exchangers, and reactor designs [58,59]. Such parts also require the design of one or multiple flow channels, for which the design elements can be reused. Furthermore, the same part architecture and design synthesis process may be employed. However, more case studies are needed to investigate the applicability.

Besides flow components other possible application domains include, for instance, heat sinks [12], compliance elements [60], truss structures [55] or antenna components [61]. For such application domains the required design elements and part architecture may differ and require adaptions and additional programming effort. However, major steps of the approach may be reused and serve as an implementation basis. These are 1) the decomposition of a part into its

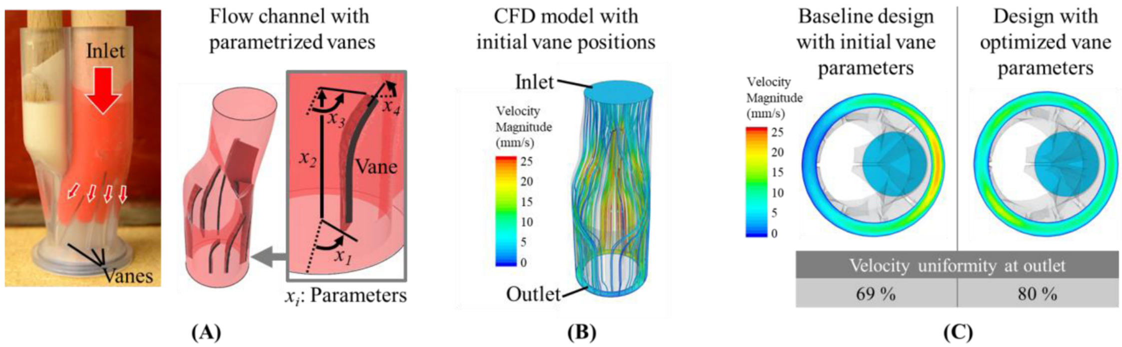


Fig. 17. (A) Uniform distribution of red clay material using four pairs of vanes that are each parametrized with four variables; (B) CFD model and streamlines; (C) Comparison of velocity profiles for baseline and optimized design ©CC4.0 pd|z ETH Zürich.

Fig. 18. Section cut of steel nozzle with multiple integrated flow channels fabricated with PBF ©CC4.0 pd|z ETH Zürich.

individual design elements, 2) the object-oriented programming of design elements as building blocks, and 3) the application of a design synthesis process and parametric optimization using a visual, node-based editor such as *Grasshopper*. Furthermore, different forms of design representations can be investigated such voxel-based geometries [62].

5. Conclusion

This work presents a computational design synthesis framework for the automated generation of AM multi-flow nozzles based on high-level, object-oriented building blocks. The preprogrammed design elements allow AM users to quickly translate a layout design into a 3D nozzle geometry, which is analyzed for AM manufacturability and functional performance using CFD analysis. Furthermore, a nozzle design may be improved using a parametric optimization. As a demonstration, a case study successfully shows the generation and test of a variety of co-extrusion nozzles. Next research steps include the implementation of design elements that dynamically adapt themselves for AM restrictions instead of being excluded during a parametric optimization as well as the transfer of the approach to other application domains of AM.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgement

This work was supported by the initiative “ETH Strategic Focus Area: Advanced Manufacturing”. The authors would also like to thank Daniel Erne for conducting a series of prior tests on clay co-extrusion.

References

[1] N. Guo, M.C. Leu, Additive manufacturing: technology, applications and research needs, Front. Mech. Eng. China 8 (2013) 215–243, https://doi.org/10.1007/s11465-013-0248-8.
[2] S. Yang, Y.F. Zhao, Additive manufacturing-enabled design theory and methodology: a critical review, Int. J. Adv. Manuf. Technol. 80 (2015) 327–342, https://doi.org/10.1007/s00170-015-6994-5.
[3] M.K. Thompson, G. Moroni, T. Vaneker, G. Fadel, R.I. Campbell, I. Gibson, A. Bernard, J. Schulz, P. Graf, B. Ahuja, F. Martina, Design for Additive Manufacturing: trends, opportunities, considerations, and constraints, CIRP Ann. Manuf. Technol. 65 (2016) 737–760, https://doi.org/10.1016/j.cirp.2016.05.004.
[4] D.W. Rosen, Research supporting principles for design for additive manufacturing: this paper provides a comprehensive review on current design principles and strategies for AM, Virtual Phys. Prototyp. 9 (2014) 225–232, https://doi.org/10.1080/17452759.2014.951530.
[5] M. Biedermann, T. Kamps, C. Kiener, Redesign of a Burner Tip with Multiple Integrated Flow Distributors: Presentation Held at Fraunhofer Direct Digital Manufacturing, (2018), pp. 14–15 n.d. DDMC 2018, Berlin, March.
[6] Y. Tang, Y.F. Zhao, A survey of the design methods for additive manufacturing to improve functional performance, Rapid Prototyp. J. 22 (2016) 569–590, https://doi.org/10.1108/RPJ-01-2015-0011.
[7] A. Wiberg, J. Persson, J. Ölvander, Design for Additive Manufacturing – a Review of Available Design Methods and Software, Rapid Prototyp. J. ahead-of-p, (2019), https://doi.org/10.1108/RPJ-10-2018-0262.
[8] R.F. Riesenfeld, R. Haimes, E. Cohen, Initiating a CAD renaissance: multidisciplinary analysis driven design: framework for a new generation of advanced computational design, engineering and manufacturing environments, Comput. Methods Appl. Mech. Eng. 284 (2015) 1054–1072, https://doi.org/10.1016/J.CMA.2014.11.024.
[9] D.W. Rosen, A review of synthesis methods for additive manufacturing, Virtual Phys. Prototyp. 11 (2016) 305–317, https://doi.org/10.1080/17452759.2016.1240208.
[10] J. Plocher, A. Panesar, Review on design and structural optimisation in additive manufacturing: towards next-generation lightweight structures, Mater. Des. 183 (2019) 108164, , https://doi.org/10.1016/J.MATDES.2019.108164.
[11] J. Alexandersen, O. Sigmund, N. Aage, Large scale three-dimensional topology optimisation of heat sinks cooled by natural convection, Int. J. Heat Mass Transf. 100 (2016) 876–891, https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2016.05.013.
[12] E.M. Dede, S.N. Joshi, F. Zhou, Topology optimization, additive layer manufacturing, and experimental testing of an air-cooled heat sink, J. Mech. Des. 137 (2015) 1–9, https://doi.org/10.1115/1.4030989.
[13] A. Pereira, C. Talischi, G.H. Paulino, I.F.M. Menezes, M.S. Carvalho, Fluid flow topology optimization in PolyTop: stability and computational implementation, Struct. Multidiscipl. Optim. 54 (2016) 1345–1364, https://doi.org/10.1007/s00158-014-1182-z.
[14] E.M. Papoutsis-Kiachagias, K.C. Giannakoglou, Continuous adjoint methods for turbulent flows, applied to shape and topology optimization: industrial applications, Arch. Comput. Methods Eng. 23 (2016) 255–299, https://doi.org/10.1007/s11831-014-9141-9.
[15] C.S. Andreasen, A.R. Gersborg, O. Sigmund, Topology optimization of microfluidic

mixers, Int. J. Numer. Methods Fluids 61 (2009) 498–513, https://doi.org/10.1002/fld.1964.
[16] P.-T. Doutre, E. Morretton, T.H. Vo, P. Marin, F. Pourroay, G. Prudhomme, F. Vignat, Comparison of Some Approaches to Define a CAD Model From Topological Optimization in Design for Additive Manufacturing, Springer, Cham, 2017, pp. 233–240, https://doi.org/10.1007/978-3-319-45781-9_24.
[17] C. Emmelmann, P. Sander, J. Kranz, E. Wycisk, Laser additive manufacturing and bionics: redefining lightweight design, Phys. Procedia 12 (2011) 364–368, https://doi.org/10.1016/j.phpro.2011.03.046.
[18] E. Dalpadulo, F. Pini, F. Leali, Assessment of Design for Additive Manufacturing Based on CAD Platforms, Springer, Cham (2020), pp. 970–981, https://doi.org/10.1007/978-3-030-31154-4_83.
[19] M. Marinov, M. Amagliani, T. Barback, J. Flower, S. Barley, S. Furuta, P. Charrot, I. Henley, N. Santhanam, G.T. Finnigan, S. Meshkat, J. Hallet, M. Sapun, P. Wolski, Generative design conversion to editable and watertight boundary representation, Comput. Des. 115 (2019) 194–205, https://doi.org/10.1016/J.CAD.2019.05.016.
[20] J.-C. Cuillière, V. François, A. Nana, Automatic construction of structural CAD models from 3D topology optimization, Comput. Des. Appl. 15 (2018) 107–121, https://doi.org/10.1080/16864360.2017.1353726.
[21] S. Bin Maidin, I. Campbell, E. Pei, Development of a design feature database to support design for additive manufacturing, Assem. Autom. 32 (2012) 235–244, https://doi.org/10.1108/01445151211244375.
[22] F. Laverne, F. Segonds, N. Anwer, M. Le Coq, Assembly based methods to support product innovation in design for additive manufacturing: an exploratory case study, J. Mech. Des. 137 (2015) 121701, , https://doi.org/10.1115/1.4031589.
[23] S. Kim, D.W. Rosen, P. Witherell, H. Ko, A Design for Additive Manufacturing Ontology to Support Manufacturability Analysis, in: Vol. 2A 44th Des. Autom. Conf., ASME, (2018), https://doi.org/10.1115/DETC2018-85848 p. V02AT03A036.
[24] E.M. Sanfilippo, F. Belkadi, A. Bernard, Ontology-based knowledge representation for additive manufacturing, Comput. Ind. 109 (2019) 182–194, https://doi.org/10.1016/J.COMPIND.2019.03.006.
[25] N. Boyard, M. Rivette, O. Christmann, S. Richir, A design methodology for parts using additive manufacturing, Int. Conf. Adv. Res. Virtual Rapid Prototyp. Leiria, Portugal, 2013, pp. 0–6 https://hal.archives-ouvertes.fr/hal-01197463.
[26] P.C. Gembarski, H. Li, R. Lachmayer, Template-based modelling of structural components, Int. J. Mech. Eng. Robot. Res. (2017) 336–342, https://doi.org/10.18178/ijmerr.6.5.336-342.
[27] L. Haibing, R. Lachmayer, Automated Exploration of Design Solution Space, (2019), pp. 5–8, https://doi.org/10.1017/dsi.2019.114.
[28] K. Amadori, M. Tarkian, J. Ölvander, P. Krus, Flexible and robust CAD models for design automation, Adv. Eng. Informatics. 26 (2012) 180–195, https://doi.org/10.1016/J.AEI.2012.01.004.
[29] G. La Rocca, Knowledge based engineering: between AI and CAD. Review of a language based technology to support engineering design, Adv. Eng. Informatics. 26 (2012) 159–179, https://doi.org/10.1016/j.aei.2012.02.002.
[30] C. Ledermann, C. Hanske, J. Wenzel, P. Ermanni, R. Kelm, Associative parametric CAE methods in the aircraft pre-design, Aerosp. Sci. Technol. 9 (2005) 641–651, https://doi.org/10.1016/J.AST.2005.05.001.
[31] W.J.C. Verhagen, P. Bermell-Garcia, R.E.C. van Dijk, R. Curran, A critical review of Knowledge-Based Engineering: an identification of research challenges, Adv. Eng. Informatics. 26 (2012) 5–15, https://doi.org/10.1016/J.AEI.2011.06.004.
[32] J. Cagan, M.I. Campbell, S. Finger, T. Tomiyama, A framework for computational design synthesis: model and applications, J. Comput. Inf. Sci. Eng. 5 (2005) 171, https://doi.org/10.1115/1.2013289.
[33] A. Chakrabarti, K. Shea, R. Stone, J. Cagan, M. Campbell, N.V. Hernandez, K.L. Wood, Computer-based design synthesis research: an overview, J. Comput. Inf. Sci. Eng. 11 (2011) 021003, , https://doi.org/10.1115/1.3593409.
[34] E. Rigger, K. Shea, T. Stankovic, Task categorisation for identification of design automation opportunities, J. Eng. Des. Technol. 29 (2018) 131–159, https://doi.org/10.1080/09544828.2018.1448927.
[35] M. Kumke, H. Watschke, T. Vietor, A new methodological framework for design for additive manufacturing, in: addit, Manuf. Handb. Prod. Dev. Def. Ind. (2017), https://doi.org/10.1201/9781315119106.
[36] M. Fuge, G. Carmean, J. Cornelius, R. Elder, The MechProcessor: helping novices design printable mechanisms across different printers, J. Mech. Des. 137 (2015) 111415, , https://doi.org/10.1115/1.4031089.
[37] G.A.O. Adam, D. Zimmer, On design for additive manufacturing: evaluating geometrical limitations, Rapid Prototyp. J. 21 (2015) 662–670, https://doi.org/10.1108/RPJ-06-2013-0060.
[38] J. Kranz, D. Herzog, C. Emmelmann, Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4, J. Laser Appl. 27 (2015), https://doi.org/10.2351/1.4885235 S14001.
[39] B. Leutenecker-Twelsiek, C. Klahn, M. Meboldt, Considering part orientation in design for additive manufacturing, Procedia Cirp 50 (2016) 408–413, https://doi.org/10.1016/j.procir.2016.05.016.
[40] L. Li, Y. Zheng, M. Yang, J. Leng, Z. Cheng, Y. Xie, P. Jiang, Y. Ma, A survey of feature modeling methods: historical evolution and new development, Robot. Comput. Manuf. 61 (2020) 101851, , https://doi.org/10.1016/J.RCIM.2019.101851.
[41] P. Pradel, R.I. Campbell, R. Bibb, When design never ends - a future scenario for product developement, Proc. Des. Soc. Int. Conf. Eng. Des. 1 (2019) 829–838, https://doi.org/10.1017/dsi.2019.87.
[42] J.R. Wagner, E.M. Mount, H.F. Giles, J.R. Wagner, E.M. Mount, H.F. Giles, Coextrusion applications, Extrusion (2014) 449–466, https://doi.org/10.1016/B978-1-4377-3481-2.00040-5.
[43] J. Lipton, D. Arnold, F. Nigl, N. Lopez, D. Cohen, N. Norén, H. Lipson, Mult-marterial food printing with complex internal structure suitable for conventional post-processing, J. Chem. Inf. Model. (2013), https://doi.org/10.1017/CBO9781107415324.004.
[44] F.C. Godoi, S. Prakash, B.R. Bhandari, 3d printing technologies applied for food design: status and prospects, J. Food Eng. 179 (2016) 44–54, https://doi.org/10.1016/j.jfoodeng.2016.01.025.
[45] S. Bodkhe, C. Noonan, F.P. Gosselin, D. Therriault, Coextrusion of multifunctional smart sensors, Adv. Eng. Mater. 20 (2018) 1800206, , https://doi.org/10.1002/adem.201800206.
[46] J. Mueller, J.R. Raney, K. Shea, J.A. Lewis, Architected lattices with high stiffness and toughness via multicore-shell 3D printing, Adv. Mater. 30 (2018) 1705001, , https://doi.org/10.1002/adma.201705001.
[47] M.A.H. Khondoker, A. Ostashek, D. Sameoto, Direct 3D printing of stretchable circuits via liquid metal Co-extrusion within thermoplastic filaments, Adv. Eng. Mater. 1900060 (2019) 1–8, https://doi.org/10.1002/adem.201900060.
[48] B. Mani, H.A. Tavakolinia, R. Babaie Moghadam, A new design for co-extrusion dies: fabrication of multi-layer tubes to be used as solid oxide fuel cell, J. Sci. Adv. Mater. Devices. 2 (2017) 425–431, https://doi.org/10.1016/J.JSAMD.2017.10.003.
[49] Y. Morimoto, M. Kiyosawa, S. Takeuchi, Three-dimensional printed microfluidic modules for design changeable coaxial microfluidic devices, Sensors Actuators, B Chem. 274 (2018) 491–500, https://doi.org/10.1016/j.snb.2018.07.151.
[50] M.A. Skylar-Scott, J. Mueller, C.W. Visser, J.A. Lewis, Voxelated soft matter via multimaterial multinozzle 3D printing, Nature 575 (2019) 330–335, https://doi.org/10.1038/s41586-019-1736-8.
[51] T. Wortmann, Opossum, CAADRIA 2017, 22nd Int. Conf. Comput. Archit. Des. Res. Asia Protoc, Flows Glitches, 2017, pp. 283–292, , https://doi.org/10.2307/j.ctv4g1rch.43.
[52] J.D. Camba, M. Contero, P. Company, Parametric CAD modeling: an analysis of strategies for design reusability, Comput. Des. 74 (2016) 18–31, https://doi.org/10.1016/J.CAD.2016.01.003.
[53] R. Jiang, R. Kleer, F.T. Piller, Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030, Technol. Forecast. Soc. Change 117 (2017) 84–97, https://doi.org/10.1016/J.TECHFORE.2017.01.006.
[54] X. Guo, W. Zhang, W. Zhong, Doing topology optimization explicitly and geometrically—a new moving morphable components based framework, J. Appl. Mech. 81 (2014), https://doi.org/10.1115/1.4027609.
[55] J. Bai, W. Zuo, Hollow structural design in topology optimization via moving morphable component method, Struct. Multidiscipl. Optim. (2019) 1–19, https://doi.org/10.1007/s00158-019-02353-0.
[56] B. Zhang, A. Goel, O. Ghalsasi, S. Anand, CAD-based design and pre-processing tools for additive manufacturing, Int. J. Ind. Manuf. Syst. Eng. 52 (2019) 227–241, https://doi.org/10.1016/J.JMSY.2019.03.005.
[57] B. Schoinochoritis, D. Chantzis, K. Salonitis, Simulation of metallic powder bed additive manufacturing processes with the finite element method: a critical review, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 231 (2017) 96–117, https://doi.org/10.1177/0954405414567522.
[58] S. Bettermann, F. Kandelhard, H.-U. Moritz, W. Pauer, Digital and lean development method for 3D-printed reactors based on CAD modeling and CFD simulation, Chem. Eng. Res. Des. 152 (2019) 71–84, https://doi.org/10.1016/J.CHERD.2019.09.024.
[59] A.K. Stark, Manufactured chemistry: rethinking unit operation design in the age of additive manufacturing, AIChE J. 64 (2018) 1162–1173, https://doi.org/10.1002/aic.16118.
[60] E.G. Merriam, J.E. Jones, S.P. Magleby, L.L. Howell, Monolithic 2 DOF fully compliant space pointing mechanism, Mech. Sci. 4 (2013) 381–390, https://doi.org/10.5194/ms-4-381-2013.
[61] S.S. Gill, H. Arora, V. Jidesh, Sheth, on the development of Antenna feed array for space applications by additive manufacturing technique, Addit. Manuf. 17 (2017) 39–46, https://doi.org/10.1016/J.ADDMA.2017.06.010.
[62] C. Bader, D. Kolb, J.C. Weaver, S. Sharma, A. Hosny, J. Costa, N. Oxman, Making data matter: voxel printing for the digital fabrication of data across scales and domains, Sci. Adv. 4 (2018) eaas8652, , https://doi.org/10.1126/sciadv.aas8652.