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Design of an additively manufactured hydraulic directional spool valve: an industrial case study

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ABSTRACT

An industrial case study of an additively manufactured hydraulic spool valve that was designed in close collaboration with our industrial partner Wandfluh AG is presented herein. An existing conventional valve design was redesigned for laser powder bed fusion while considering the current functional and technical requirements. The entire development process is described based on real world requirements, considering the manufacturing and post-processing constraints. The final design was manufactured, tested, and compared with the conventionally manufactured valve. The pressure drop was reduced by 60% through the valve redesign, and a weight reduction of 50% was achieved. This study is concluded by reflecting the development process and identifying potential, learnings, and challenges that can be transferred to other hydraulic components. The importance of generating a large variety of concepts in the divergent design generation phase and performing computational fluid dynamics simulations to assess the potential of these concepts are highlighted.

KEYWORDS

Additive manufacturing;
laser powder bed fusion;
hydraulic directional spool
valve; industrial case study

1. Introduction

Hydraulic systems have been used for decades in many industries and remain a commonly used power source for actuation in various systems and applications (Bauer 2016). In most cases, hydraulic components are conventionally produced by milling and drilling channels into metal blocks, making them bulky and significantly limiting the design options for these components (Semini et al. 2015; Zhang et al. 2020). Only the channel diameter and position can be varied, leading to sharp 90° bends and dead ends at the intersections of channels. This leads to a significant pressure drop and consequent energy loss (Ma et al. 2018).

However, in certain applications an increased efficiency and reduced weight of the hydraulic components are essential (Flores et al. 2020); for example the use of remotely operated vehicles (ROVs) for underwater applications, which are used for inspecting and repairing of subsea pipelines. The weight and performance of the hydraulic components in these vehicles are important factors because the availability of power to

drive the hydraulic components is limited, and the weight must be offset by buoyancy (Christ 2014).

In addition to milling and drilling, casting can also be used to manufacture more complex components (Zhang et al. 2020). However, while expendable mould casting uses non-reusable moulds, permanent mould casting only allows simple castings because the mould must be opened for removal of the moulded component (Groover 2010).

In contrast to conventional manufacturing technologies, additive manufacturing (AM) enables the manufacturing of components consisting of highly complex geometries with significant design freedom (Gibson, Rosen, and Stucker 2021). Laser powder bed fusion (L-PBF) can process metals, thereby offering a significant potential for improving hydraulic components (Zhang et al. 2020). However, to fully exploit the potential of AM, the design process must be adapted compared to that of the conventional processes (Kumke, Watschke, and Viotor 2016) when designing new parts and redesigning existing parts. Furthermore, the L-PBF process involves certain design restrictions; for example, the

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need for support structures for surfaces having a large overhanging angle. Because support removal is significantly time consuming, costly, and may not be possible at times, the need for support structures must be considered during the design phase (Gibson, Rosen, and Stucker 2021; Yadroitsev 2021), which can be reduced using appropriate design measures.

To address these two needs, the design for additive manufacturing (DfAM) guidelines and methods have been published, which can be differentiated into opportunistic, restrictive, and dual DfAM methods (Laverne et al. 2015). Opportunistic DfAM methods help the designer exploit the design space, which is provided by the design freedom of AM. On the other hand, restrictive DfAM methods highlight the limits of the AM processes and how these limitations can be accounted for with the help of design measures. The dual DfAM (Kumke, Watschke, and Viator 2016; Rolinck et al. 2021) methods, as the name suggests, combine the last two types of methods. These are often based on classical design methods, such as VDI 2221 (VDI 1993), which describes the four phases of systematic development and design.

Several additively manufactured hydraulic components that focus on different aspects have been published, such as weight reduction, compact design, fluidic performance, and functional integration (Alshare, Calzone, and Muzzupappa 2019; Barasuol et al. 2018; Biedermann, Beutler, and Meboldt 2021; Biedermann, Beutler, and Meboldt 2022; Diegel et al. 2020; Geating, Wiese, and Osborn 2017; Rolinck et al. 2021; Schmelzle et al. 2015; Semini et al. 2015; Zhu et al. 2020; Zhu et al. 2021). These can be divided into the following four groups based on which tasks are performed: design, manufacturing, and testing. Table 1 summarises this information and highlights the differences and shortcomings. The designs presented in group A were developed based on a design concept for a specific

use case, which are then manufactured and evaluated based on their achieved weight and volume reduction (Barasuol et al. 2018; Diegel et al. 2020; Geating, Wiese, and Osborn 2017; Schmelzle et al. 2015; Semini et al. 2015). Similarly, in group B, Zhu et al. (2021) redesigned a hydraulic spool valve for L-PBF based on the design concept using a design-for-property approach. However, in contrast to group A, the pressure drop was measured and compared to that of a conventional valve, achieving comparable results. Alshare, Calzone, and Muzzupappa (2019) and Zhu et al. (2020) (group C) improved the initial design concept, simulated the pressure drop, and validated the improvement on a test bench. They combined the use of simulations and experimental validations: however, only for one design concept. For the designs in group D, Biedermann, Beutler, and Meboldt (2022; Biedermann, Beutler, and Meboldt 2022) and Rolinck et al. (2021) developed several concepts for their given design problem and evaluated the designs based on different factors such as weight, size, channel length, material usage, and functional criteria. However, these designs consider a range of concepts and do not use computational fluid dynamics (CFD) simulations and experimental validation.

Overall, neither of the aforementioned case studies incorporated all the evaluated aspects by considering a wide range of design concepts that were simulated, manufactured, and tested to determine the best design. However, all these aspects may be beneficial for systematically achieving the best possible results when developing new AM designs (Kumke, Watschke, and Viator 2016). First, exploiting the design space and generating a variety of designs that meet the functional requirements initiates the potential for significant performance improvements. The publications presented in groups A, B, and C do not fully exploit the performance enhancement potential by considering only a limited

Table 1. Summary of published hydraulic components and respective performed tasks regarding design, manufacturing, and testing.

Group	Author, year	# of evaluated design concepts	CFD simulation	Manufacturing	Pressure drop measurement
A	Semini et al. (2015)	1	×	✓	×
	Schmelzle et al. (2015)	1	×	✓	×
	Geating, Wiese, and Osborn (2017)	1	×	✓	×
	Barasuol et al. (2018)	1	×	✓	×
	Diegel et al. (2020)	1	×	✓	×
B	Zhu et al. (2021)	1	×	✓	✓
C	Alshare, Calzone, and Muzzupappa (2019)	1	✓	✓	✓
	Zhu et al. (2020)	1	✓	✓	✓
D	Biedermann, Beutler, and Meboldt (2021)	7	×	✓	×
	Rolinck et al. (2021)	3	×	✓	×
	Biedermann, Beutler, and Meboldt (2022)	12	×	✓	×
	This work	5	✓	✓	✓

number of concepts in the conceptual design phase. Second, when considering several design variants, such as those indicated in group D, simulations are necessary to evaluate the performance of the design variants, because analytical calculations are not possible for complex geometries. By simulating these designs, the expected performance can be assessed, providing a basis for a quantitative decision. Finally, experimental performance measurements allow the validation of the manufactured design. Without experimental validation, the potential of L-PBF can only be evaluated based on the basic properties, such as the weight and volume reduction of the manufactured designs (groups A, B, and D). Therefore, the research gap lies in the need for case studies, which demonstrate the potential of incorporating all steps into the design process of AM hydraulic components. Furthermore, there is still a general need for industrial case studies to overcome the barriers to technology transfer at company level (Flores Ituarte, Partanen, and Khajavi 2016).

This work contributes an industrial case study to the community that describes the development of a hydraulic spool valve for L-PBF in collaboration with Wandfluh

AG and is based on real world requirements. The final valve design is shown in Figure 1. This study aims to share the design process in an industrial setting to benefit other potential industrial users further fostering the adoption of technology in the industry. The development steps are thoroughly described. The study builds on existing cases and demonstrates the potential of AM by validating the achieved pressure drop reduction in the experimental measurements (Figure 2). Furthermore, the design process is reflected, and the potential, learnings, and limitations are discussed. The following aspects are demonstrated:

- Potential of L-PBF for the performance enhancement of hydraulic components
- Influence of adopting fixed boundary conditions during the redesign for AM on design generation
- Importance of exploiting the conceptual design phase and simulating the design variants created to choose the most promising candidates
- Implementation of an industrial hydraulic component, including experimental validation of the achieved pressure drop reduction

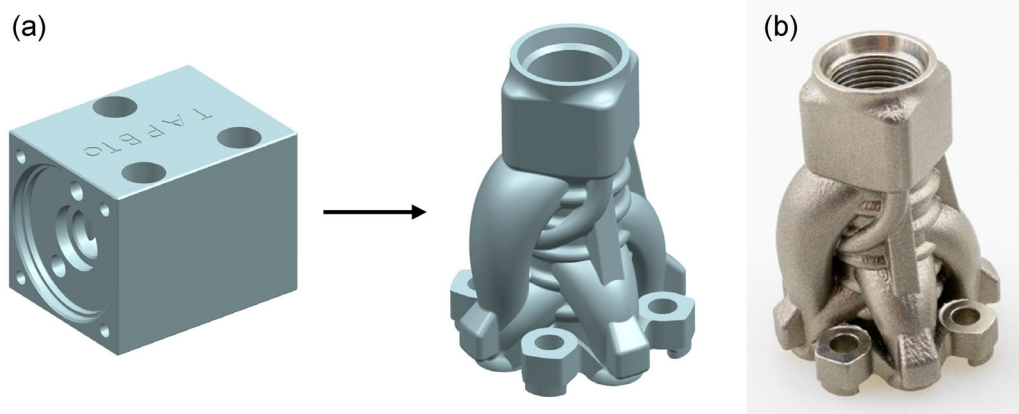


Figure 1. The redesign of a hydraulic spool valve for L-PBF in collaboration with Wandfluh AG: (a) Comparison of the CAD geometry of the original milled valve design with the L-PBF valve design; (b) Manufactured and post-processed spool valve.

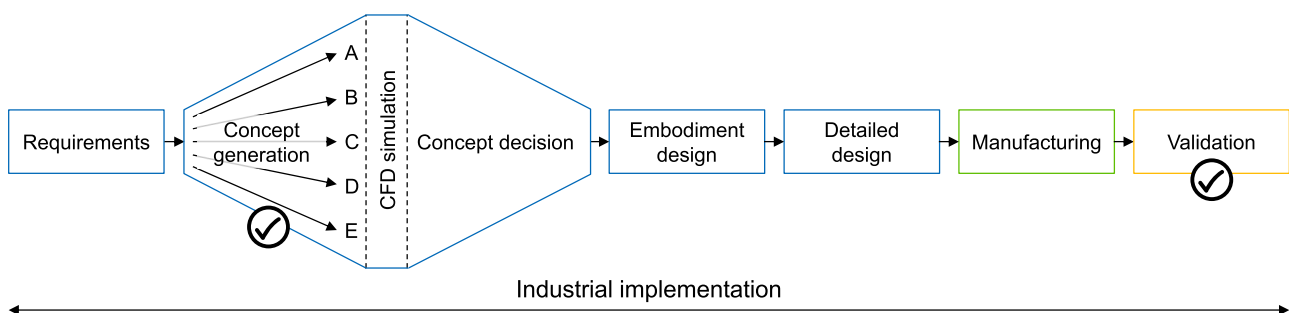


Figure 2. Visualisation of the performed tasks in this industrial case study and the research gap in existing case studies with shortcomings in the conceptual design phase and/or the validation.

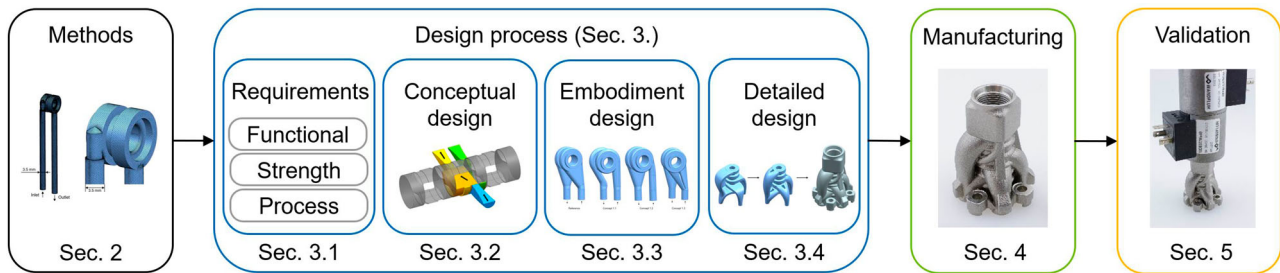


Figure 3. Overview of topics and workflow.

Figure 3 provides an overview of the workflow and the topics addressed. First, the design approach and simulation method are described in Section 2, which is followed by the design chapter in Section 3. After describing the background of the case, the design process itself is described in four steps. In the first step, all the relevant requirements regarding functionality, strength, and the L-PBF process are stated (Section 3.1). Next, by exploiting the design freedom of AM, new concepts were created and evaluated based on quantitative CFD simulation data (Section 3.2). After deciding upon a concept, it was iteratively improved by investigating the influences of minor design changes on the fluid volume (Section 3.3). To conclude the design phase, the valve body is designed based on the improved fluid volume, and the interfaces, connection elements, and clamping surfaces for clamping during the required post-processing steps are integrated (Section 3.4). A manual design approach was chosen for the design process because automated approaches, such as topology optimisation are incapable of exploiting the diversity of options for this system in the conceptual phase. This is due to the interaction of the two bodies in different valve states and additional requirements of the system, such as balanced radial forces (Section 3.1). After finalising the valve design, it was manufactured and post-processed (Section 4). Finally, the valve was validated, and the measured pressure drop was compared to the conventionally manufactured design (Section 5).

2. Methods

A workflow based on existing DfAM literature was followed for the redesign of the hydraulic spool valve (Kumke, Watschke, and Vietor 2016; Rolinck et al. 2021; VDI 1993). In the first phase, the required functions were stated, and the boundary conditions and strength requirements were defined. Furthermore, the given design restrictions were defined based on the available manufacturing infrastructure for this case study. In the

conceptual design phase, a preliminary flow channel design was developed by creating the overall design concepts. These were then evaluated based on CFD simulations, and the most promising concepts were chosen. In the third phase, the embodiment design, the influence of specific design adaptations on the flow channels of the chosen design concepts are investigated using CFD simulations. The design concepts were iteratively improved, thereby increasing the efficiency of the part. In the final phase, the detailed design phase, the part is designed by adding a wall thickness to the flow channels. The design was adapted to ensure buildability under defined process limitations. Next, reinforcement and connection elements were added, followed by structural simulations to verify the fulfilment of all the defined strength requirements.

CFD simulations were conducted using ADINA (ADINA R&D, Inc.) to quantify the performance of the individual design concepts and the influence of specific design adaptations in the embodiment design phase. To simplify the models, the CFD simulations only considered the fluid volumes of the design concepts. The following assumptions were made for the models: steady-state, incompressible fluid, no thermal coupling, omitted roughness of channel walls, and neglected influence of gravity. The inlet and outlet were extended to the exact positions of the pressure measurements in the experimental setup to validate the simulation results. An unstructured grid was generated using 4-node tetrahedral elements in SIEMENS NX (Siemens Product Lifecycle Management Software Inc.), given the complex 3D structure of the fluid volumes. Several mesh refinements were applied in regions with sharp edges, where the maximum velocity and pressure gradients occurred, to ensure an adequate grid size. In addition, boundary layer meshes were used to fully resolve the near-wall region down to the laminar sub-layer. Considering the grid shown in Figure 4, which has 460,804 cells for the reference model, the first grid points have an average dimensionless wall distance y^+ of 1.8 and a maximum value of 4.3 when the inlet flow rate is set to 12 l/min.

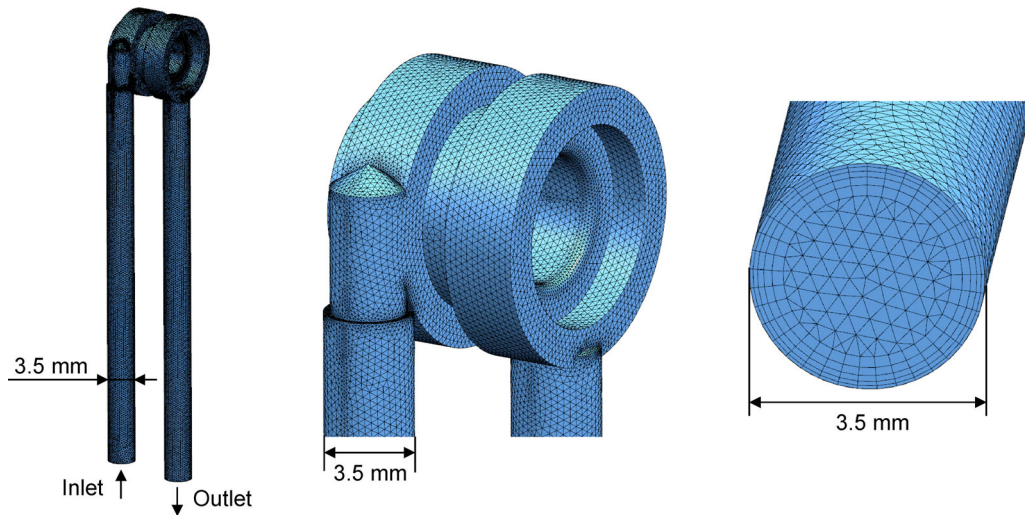


Figure 4. 3D grid of a single flow path (P-A) of the flow volume of the conventional valve design, including mesh refinements and boundary layer meshes.

After the mesh generation, pre-processing, solving, and post-processing were conducted using ADINA CFD. As recommended by ADINA for large fluid models, flow-condition-based-interpolation-elements (FCBI-Cs) were used (Bathe and Zhang 2002). The solution process associated with this element type uses iterative methods (AMG solver (Stüben 2001)).

The fluid density and dynamic viscosity were set to 854.8 kg/m^3 and $0.026778 \text{ Pa}\cdot\text{s}$ respectively, corresponding to the hydraulic oil COREX HLP46 at an operating temperature of 50°C (MOTOREX-BUCHER GROUP AG). The flow rate was defined at the inlet, which varied in different simulations (for example 15 l/min , average velocity of 26 m/s , Reynolds number of $2,903$). The static outlet pressure was fixed at 0 Pa , and a no-slip boundary condition was adopted for all internal walls. The $k\text{-}\omega$ model along with a shear-stress-transport model (SST) was chosen as the turbulence model (Menter 1994). The latter combines the accuracy of the $k\text{-}\omega$ model in the near-wall region with the free stream independence of the $k\text{-}\epsilon$ model. Furthermore, it is also accurate for low Reynolds numbers and transitional zones.

The CFD simulation was validated by using the conventional valve design. Therefore, the pressure drop in the flow path P-A was simulated for several flow rates and compared to the experimental results (Figure 5). The results of the CFD model were close to those obtained from the measurements. The differences in the pressure drop between the simulation and measurements did not exceed 10% in the range between 10 and 20 bar. Pressure drop testing was conducted at Wandfluh AG on an industrial hydraulic test bench. The hydraulic oil COREX HLP46 was used at an operating temperature of 50°C .

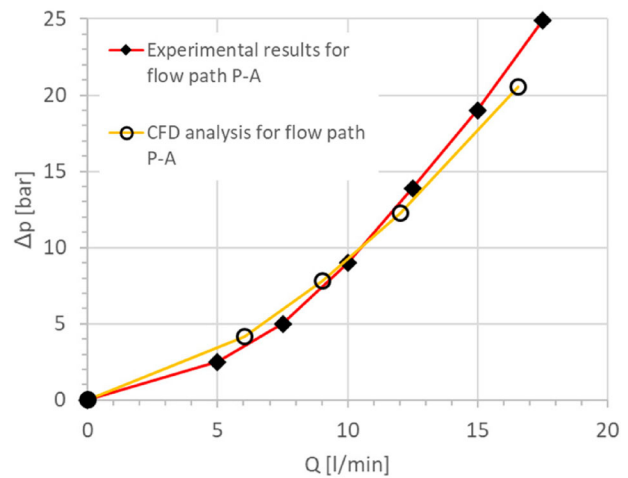


Figure 5. Validation of the CFD simulation model: Comparison of the simulation and experimental results for the conventional valve design.

In the later design phase, static structural simulations were conducted to evaluate the deformation of the valve body under pressure during different flows. Furthermore, the bolt connection of the valve to the manifold was simulated to ensure a sufficient bolt strength and a tight connection at the interface. These simulations were performed using the ANSYS static structural software (ANSYS, Inc).

3. Design

Hydraulic systems are used for actuation in several machines and industrial systems where a high power

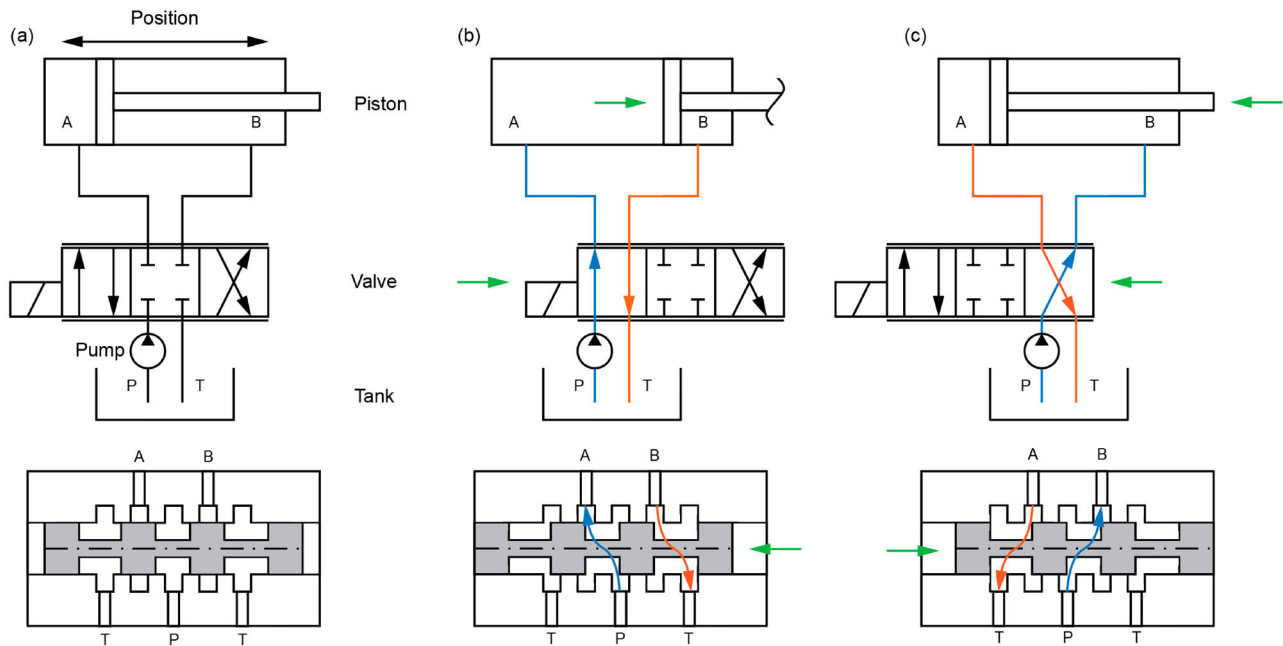


Figure 6. Schematic of a hydraulic system consisting of a tank, pump, directional spool valve, and piston (top), as well as a detailed schematic of the valve showing the position of the spool and the corresponding flow paths (bottom): (a) Valve in the centre position with no connection between the channels and therefore no flow; (b) Change in the state of the valve, connecting pump P to chamber A and releasing the hydraulic oil from chamber B to the tank T, thus moving the piston to the right; (c) Third position of the valve connecting P to B and A to T, moving the piston to the left.

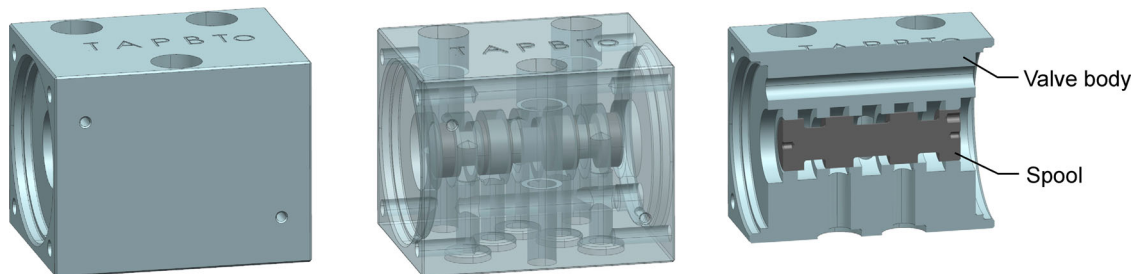


Figure 7. Conventionally manufactured directional spool valve with a nominal size of 3 (NG3, channel diameter 3 mm, spool diameter 8 mm).

density is required, such as aircrafts, excavators, or presses. The simplified hydraulic system is shown in Figure 6(a). The pump acts as an energy source for pumping the hydraulic fluid from the tank into the system. A valve then guides the hydraulic fluid from the power source to the actuator; in this case, a hydraulic piston. To control the direction and speed at which the piston moves, the valve must control the volumetric flow rate of the hydraulic fluid. This is achieved by controlling the cross-sectional area through which the fluid can pass.

Directional spool valves achieve this by moving the spool relative to the body of the valve. The conventional directional spool valve is displayed in Figure 7. By moving the spool to the left (Figure 6(b)), the

channel arising from the pump (P) is connected to channel A, guiding the oil into the left cavity of the actuator and leading to a movement of the piston to the right. The fluid in the right cavity of the actuator is simultaneously released through channel B back into the tank (T). Figure 6(c) demonstrates the system in the opposite configuration, leading to the movement of the piston to the left.

3.1. Requirements

The functionality, boundary conditions, strength, and process-related requirements must be defined in the design process, all of which are summarised in Table 2.

Table 2. Summary of all requirements for the redesign of the directional spool valve.

	Requirement	Value	Unit
Functional requirements	Type: 4/3 directional spool valve	–	–
	Maximum translational movement of the spool	1.5	mm
	Proportional valve characteristic	–	–
	Balanced radial forces	–	–
Boundary conditions	Size: Nominal size 3	–	–
	Inlet channel diameter	3	mm
	Spool diameter	8	mm
	Interface: ISO 4401 (preferred) or other	–	–
Strength requirements	Maximum internal fluid pressure	350	bar
	Maximum deformation at spool interface	6	μm
Process requirements	Maximum unsupported overhang angle	45	$^{\circ}$
	Maximum unsupported horizontal surface length	0.5	mm
	Minimum wall thickness	0.5	mm

Functional requirements: The primary functional requirement of the valve is to guide the hydraulic fluid between the four channels (the two T channels in Figure 6 are connected and therefore only counted once) in three different predefined configurations (4/3 directional spool valve). In general, the first state (Figure 6(b)) connects the pressure channel P with one outlet A (P-A), while connecting outlet B with tank T (B-T). The third position (Figure 6(c)) usually has the opposite effect, connecting P with B (P-B) and A with T (A-T). The centre position of the valve (Figure 6(a)) can have different flow configurations. Typical configurations either disconnect all channels from one another or simultaneously connect P to A and B while blocking the tank. The transition between the different valve states should be possible with a 1.5 mm maximum translational movement of the spool toward each side from the centre position. Furthermore, the valve should have a proportional characteristic, which indicates that the volumetric flow rate in each state can be continuously controlled by changing the distance at which the spool is shifted from the centre.

In addition to the functional requirements, balanced radial forces is the main requirement for the system to operate. If the circumference of the spool is not equally loaded from all sides, the high pressure of the hydraulic fluid leads to radial forces and consequent high frictional forces, which result in pitting and eventual system failure.

Boundary conditions: The following boundary conditions were applied for the design process of the AM valve. First, the valve should be developed for a nominal size of 3, corresponding to a channel diameter of 3 mm and a spool diameter of 8 mm. The interface connecting the valve to the hydraulic manifold was not strictly defined in this study. The mounting surface standardised by ISO 4401 (ISO 2005) was preferred; however, adapting it was also an option if required.

Strength requirements: The valve should withstand 350 bar of internal fluid pressure under which it should exhibit a maximum deformation of 6 μm at the interface with the spool to avoid jamming and reduce leakage.

Process requirements: The design restrictions imposed on the design by the manufacturing process were defined based on the available manufacturing infrastructure for this case study, the required material, and the corresponding parameter set for processing this material. The available L-PBF machine was a Concept Laser Mlab Cusing R. Owing to the application-related requirements of the material regarding corrosion resistance, 1.4404 stainless steel was chosen. For processing this material, the Concept Laser performance parameters were used, to ensure a high density and material integrity. The combination of the machine, material, and process parameters imposed the following process-related requirements on the design: A maximum overhang angle of 45 $^{\circ}$ was defined without requiring support. Unsupported horizontal surfaces may have a maximum length of 0.5 mm. Lastly, a minimum wall thickness of 0.5 mm should be complied with.

3.2. Conceptual design

It is often significantly beneficial to reconsider the design concept when redesigning existing components or systems for AM because several parts and systems are designed considering the manufacturing restrictions of the chosen manufacturing process; however, AM technologies present far fewer restrictions. This enables the manufacturability of more complex designs that primarily follow functional requirements (Klahn, Leutenecker, and Meboldt 2015). Generally, curved flow channels yield higher efficiencies for fluid components. For active components such as valves, where an interaction between two components with complex influences is

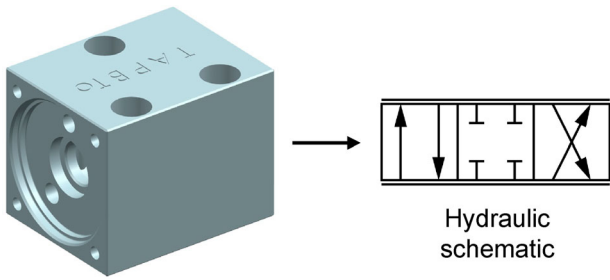


Figure 8. Extraction of the primary function of a 4/3 directional spool valve.

given, the design freedom of AM enables the manufacturability of components with entirely different functional concepts.

These concepts can be accomplished by analysing the primary function that a given component must fulfil. The concepts are then developed without considering how the function is achieved in the existing component and how it will be manufactured. This enables the design space for entirely new concepts.

For the 4/3 directional spool valve, the primary function is to connect four different channels in the three

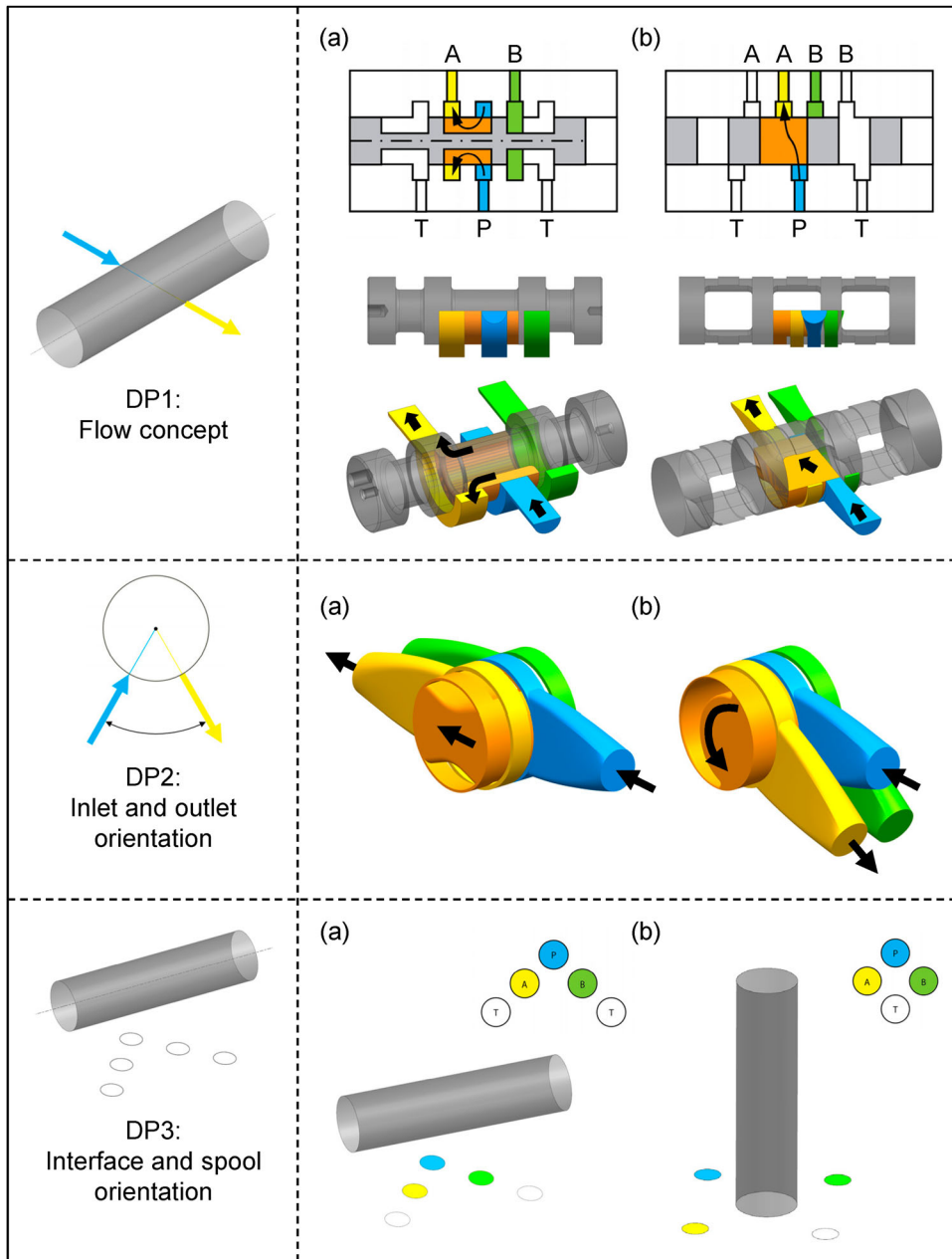


Figure 9. Visualisation of the following three sensitive DPs: (DP1) Flow concept; (DP2) Inlet and outlet orientation; (DP3) Interface and spool orientation.

given combinations. This information is often contained in the schematic (Figure 8) of the hydraulic components. Three sensitive design parameters (DPs) were identified to fulfil this functionality, which influence the overall design concept, as shown in Figure 9. First, the flow concept is defined by the interplay between the valve body and spool and allows the redirection of the hydraulic fluid flow path. The second parameter is the angular orientation of the inlets and outlets relative to one another. Finally, the interface that connects the valve body to the manifold and the relative spool orientation significantly influences the flow channel geometry. The variants of each DP are presented below.

First, considering the options for the interplay between the spool and valve body as an alternative to the conventional concept, a concept that relies on the design freedom of an AM spool was investigated. The underlying idea of this concept is to guide the fluid from the inlet on one side of the spool to the outlet on the other side on a straight path, as depicted in Figure 9. A smaller pressure drop is expected by avoiding to push the fluid through small gaps or redirecting it around sharp corners, which occurs in the conventional concept. Therefore, the goal is to design the

fluid volume in the spool cylinder such that the two channels are directly connected.

The second DP describes the relative angular orientations of the inlets and outlets. This parameter influences the flow conditions into and out of the spool volume and the length of the channels between the spool volume and interface, which is demonstrated on the direct flow concept in Figure 9. The first variation directly guides the flow from one side of the spool to another on a straight path. This variation has the advantage of a path with a straight flow. However, a redirection of the flow in the further course of the channel is required to bring the ports together. The second variant, which is the angled flow concept, redirects the flow at a large angle in the spool cylinder. Accepting the associated pressure drop reduces the necessity for long channels to connect the spool cylinder to the connection interface (Figure 10, Design concept 2 vs. Design concept 3).

The last sensitive DP presents the interface where the valve body is connected to the hydraulic manifold and relative spool orientation (Figure 9). A standardised triangular interface is used in conventional valves ISO 4401 (ISO 2005), where the valve has five inlets and outlets (P, A, B, T, and T0). Two outlets (T and T0) lead

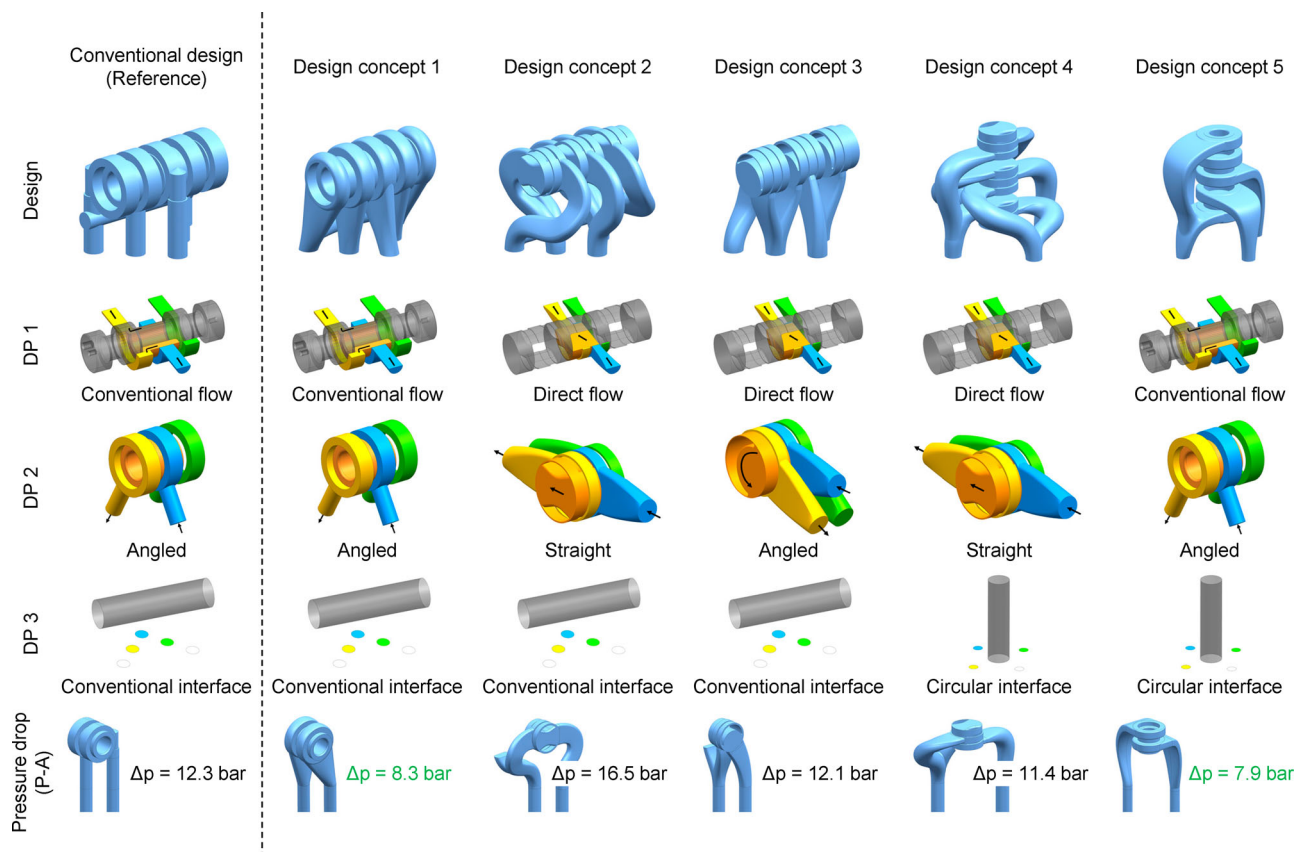


Figure 10. Design concepts 1 through 5 derived from different combinations of the options for the three sensitive DPs in comparison with the conventional valve design (reference) and the associated pressure drop of the path P-A at 12 l/min.

to the tank and are connected inside the valve to ensure pressure compensation. The spool is horizontally oriented above the interface. An alternative arrangement of the four channels in the shape of a circle was suggested. Using this interface allows the spool to be vertically positioned at the centre of the interface. Furthermore, by mounting the valve in 90° increments, different valve functions can be fulfilled using the same spool geometry.

The variants of the three sensitive DPs were then combined to create overall design concepts with various flows (Figure 10). The designs had to fulfil the requirements presented in Section 3.1 to only compare the designs that ensure functionality, such as balanced radial forces on the spool. The resulting topologies were manually designed to fulfil all the requirements and achieve a pressure drop that was as low as possible based on the given combination of DP variants.

The design concepts were evaluated based on CFD simulations, for which one path was chosen because there are various flow paths for each spool position inside the valve. Therefore, the most essential path connecting the pressure inlet P with outlet A (P-A) was chosen for the evaluation (P-B is equally important but consists of a significantly similar or identical channel design owing to symmetry). The models were trimmed to simulate individual paths, as shown in Figure 10 in the bottom row.

The resulting Δp values correspond to the simulated pressure drop at 12 l/min from the pressure sensor in the hydraulic block at the pressure inlet P to outlet A after being redirected in the valve body. The results demonstrate that both designs with the conventional spool concept yield a lower pressure drop than those with the direct flow concept. These results can be explained by examining the fluid velocity plot of the hydraulic fluid (Figure 11). Owing to the wide fluid volume inside the spool, which is necessary for this

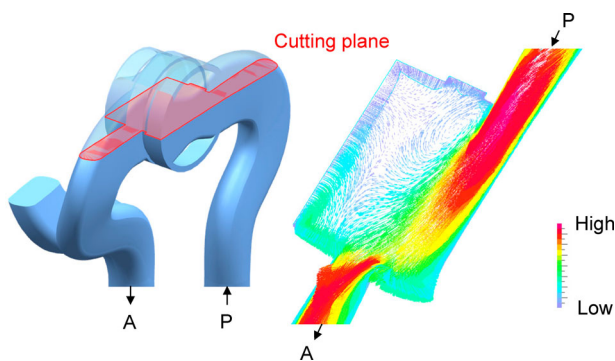


Figure 11. Vector Plot of the hydraulic fluid velocity in the highlighted cutting plane of design concept 2; one of the direct flow concepts.

concept to enable the different flow states of the valve, the hydraulic fluid does not entirely flow to the outlet directly but encounters turbulence in the remaining spool volume. Furthermore, design concept 2 yields the largest pressure drop owing to the long channels required to connect the chosen spool concept with the conventional interface. A comparison of design concepts 1 and 5 demonstrates that the difference in the simulated pressure drop was only marginal. Therefore, both concepts should be considered for further improvement.

3.3. Embodiment design

In addition to the possibilities for other flow concepts, the design freedom of the L-PBF process allows a detailed adaptation of channels to further decrease the pressure drop. This can be achieved by adapting the spline of the channel, varying the cross-sections, or adding design features such as guiding vanes and radii.

To reduce the number of simulations and simplify the design variations, one of the two selected concepts was investigated to identify the enhancements that can be applied to both selected concepts. Design concept 1 was chosen for the investigation owing to its in-plane inlet without curvature. In accordance with the evaluation of the design concepts, one flow path (P-A) with a conventional interface was chosen as the starting point for further improvement. The influence of specific changes to the flow channel design on the pressure drop was then investigated based on simulations.

Several different inlet concepts for entering and exiting the spool volume were tested in the first step (Figure 12(a)). These adaptations demonstrated that inlet concepts A1 (+2.26 bar) and A2 (+2.70 bar) did not lead to an improvement because the fluid started to swirl in the first chamber before moving through the gap into the second chamber. On the other hand, inlet concept A3 (−0.18 bar) did lead to an improvement, where the flow was split into two paths such that the fluid was distributed more equally over the spool circumference.

Following the findings discovered with inlet concept A3, the spline of the channels was varied to analyse the influence of the inlet entry angle into the chamber and the distance between the inlets (Figure 12(b)). The simulation results demonstrated that the distance between the two chamber inlets should be as short as possible, and ideally feed the chamber tangentially (concept B1, +0.10 bar). Concept B2 does not fulfil these criteria, leading to an increase in pressure drop of +1.24 bar. However, concept B1 did not lead to an improvement compared to the reference design/

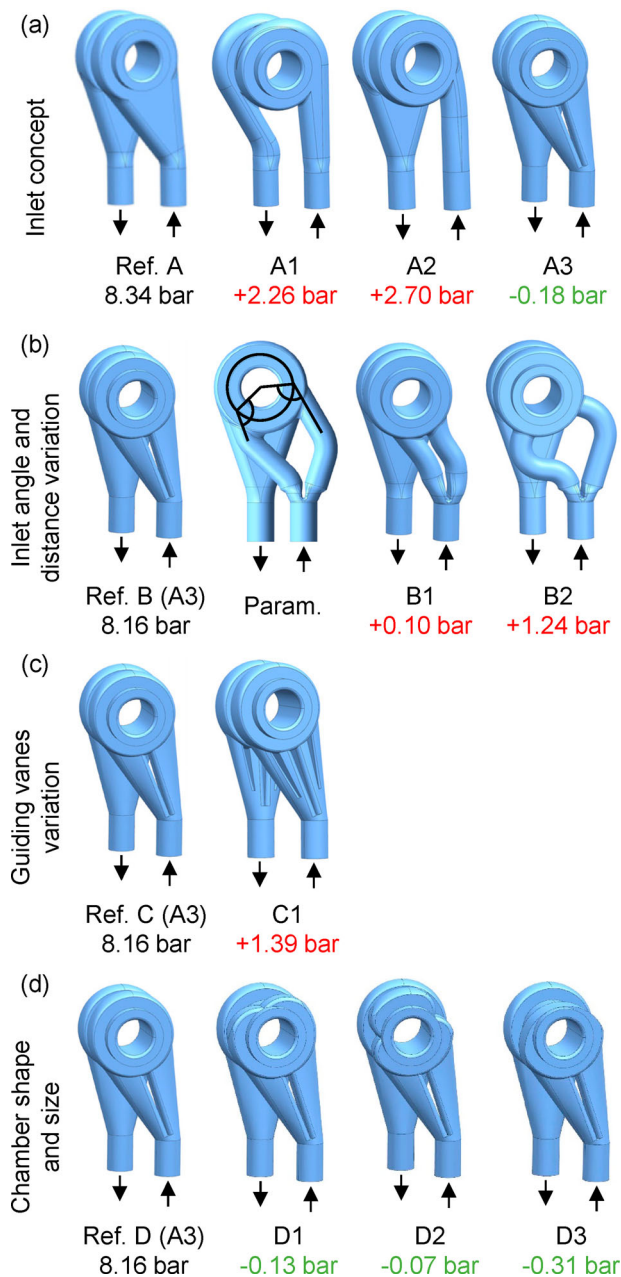


Figure 12. Design variants for investigating the influence of detailed design changes on the pressure drop compared to the reference geometry: (a) Inlet concepts; (b) Inlet angle and distance; (c) Guiding vanes; (d) Chamber shape and size.

concept A3, which also fulfils the aforementioned criteria. Therefore, the reference design was further investigated.

A further investigation was conducted on the number of guiding vanes that split the inlet and outlet (Figure 12 (c)). The number of guiding vanes varied between zero and three in several combinations, leading to one to four inlets and outlets. The simulation results demonstrated that increasing the number of guiding vanes leads to an increase in the pressure drop. Concept C1

with 4 inlets and outlets exhibited an increase of the pressure drop of +1.39 bar with respect to the reference. The lowest pressure drop for this variation can be achieved with only two chamber inlets and one outlet, as shown in the reference design for this investigation/concept A3 (Figure 12(c)).

Finally, the shape and size of the chamber (Figure 12 (d)) were varied, which should help the flow pass through the gap between the spool and body. The design adaptations of the chamber had an unexpected negligible influence on the pressure drop (range of -0.07 to -0.31 bar). In contrast, the process of the fluid leading into and out of the chamber substantially affects the efficiency of the spool valve (+2.70 to -0.18 bar).

The following can be concluded based on the aforementioned:

- (1) Single-sided tangential entry is not beneficial.
- (2) Splitting up the channel for an equal distribution over the circumference leads to an improvement.
- (3) The distance between the two inlets should be as short as possible; ideally, the chamber should be fed tangentially in opposite directions to avoid rotating flows.
- (4) The optimal number of divisions in the inlet and outlet results in only two chamber inlets and one outlet.
- (5) Design adaptations of the chamber geometry and size have a negligibly small influence.

These findings were finally applied to the two selected design concepts. Because both of the previously chosen design concepts already fulfilled most of the criteria, only the division of the inlets with a guiding vane was implemented. For the design using the conventional interface (design concept 1), the division led to a slight improvement, decreasing the pressure drop by -0.18 bar. This influence is negligible for the concept with the vertical spool (design concept 5). This is owing to the asymmetric nature of the inlet in design concept 1, which would prefer the right side of the chamber over the left; whereas in design concept 5, the fluid symmetrically approaches the spool. The adaptation of the chamber shape and size were not implemented due to their negligibly small influence on the pressure drop and their impact on required post-processing steps (Section 3.4 and 4).

Regardless, the investigations were beneficial because it was shown that most of the findings were already included in the design concepts and that highly performing concepts were already compared. Owing to the slightly smaller pressure drop in the simulations and the additional benefits of the vertical spool

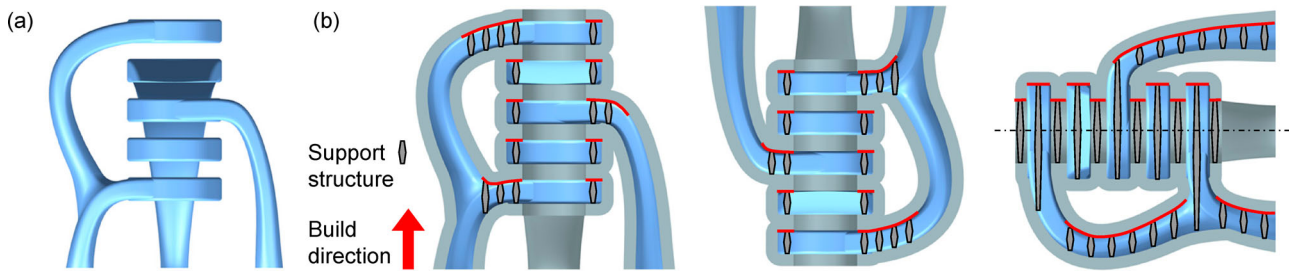


Figure 13. (a) Sectional view of the fluid volume of the chosen design concept (design concept 5) without the spool volume and the division of the inlets (to avoid occlusion of the overhanging regions); (b) Analysis of the three main part orientations with respect to the build direction regarding the necessity of internal support structures.

concept over the conventional interface, design concept 5 is further presented in the final design steps.

3.4. Detailed design

The final valve was designed after determining the final design concept and analysing the detailed design changes to the flow volume to reduce the pressure drop. This section presents the final design steps which are necessary to achieve a manufacturable valve design, including the determination of the build direction, adaptation of the geometry to minimise the amount of required support structures, the addition of reinforcements, and connection and clamping surfaces.

The optimal build orientation was evaluated in the first step. Therefore, a wall thickness was added to the flow volume of the selected design concept, as shown in Figure 13(a), to identify the overhanging surfaces. A

wall thickness of 1.5 mm was defined, which can be approximated based on the maximum operating pressure. Figure 13(b) presents a sectional view of the resulting valve body. The flow volume of the spool was hidden to demonstrate the overhangs in the valve body. Furthermore, the guiding vanes, which divide the inlets as indicated in the previous section, are hidden to avoid the occlusion of the overhanging surfaces. Three main part orientations were analysed with respect to the critical overhangs of the internal surfaces (marked in red); thus requiring internal support structures (Figure 13(b)). The second orientation was selected based on this analysis. The decisive points were the amount of support required and the potential to omit the need for the remaining support through design adaptations. The valve body was then divided into two regions, which are indicated by the yellow and green in Figure 14(b). Considering the yellow region, sacrificial

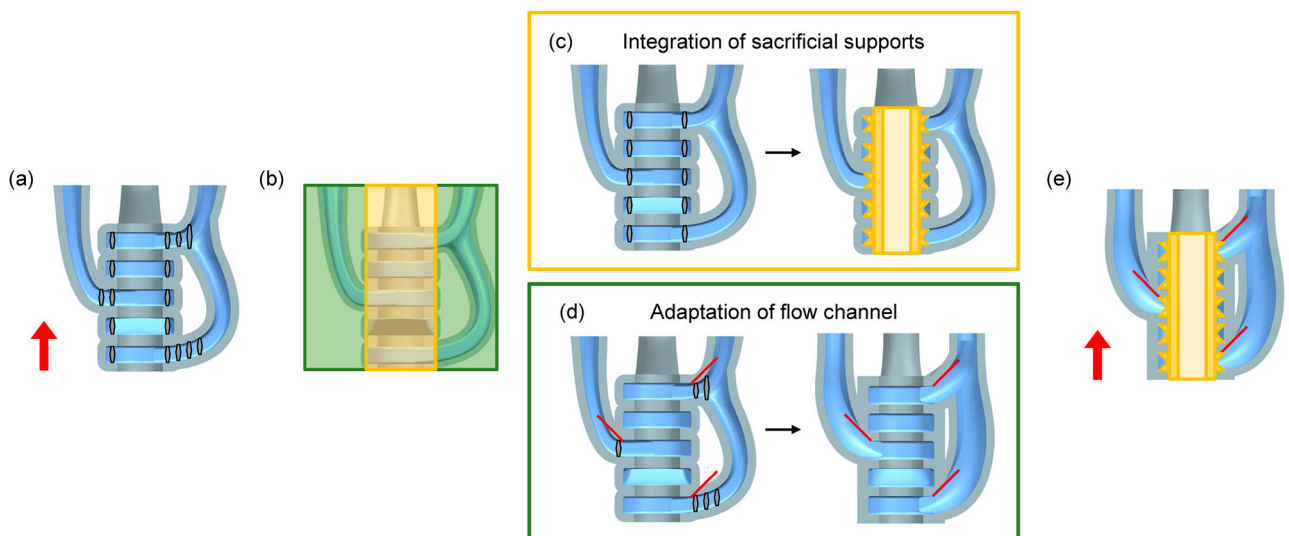


Figure 14. Adaptation of the chosen design concept for manufacturability: (a) Required support structures for the chosen build orientation; (b) Division of geometry into two regions; (c) Yellow region: integration of sacrificial supports, which can be removed during post-processing; (d) Green region: adaptation of flow channels to avoid internal support structures; (e) Adapted flow volume with sacrificial support structures.

supports can be used to support the overhanging surfaces because these can be removed when post-processing the contact surface to the spool by turning (Figure 14(c)). The internal supports cannot be accessed and removed in the green region; therefore, requiring adaptations to the flow channel for self-support. This can be achieved by adapting the inclination angle and thereby reducing the overhang angle (Figure 14(d)). Figure 14(e) demonstrates the adapted and self-supporting valve body with sacrificial support structures.

After adapting the flow channels for manufacturability, the interfaces to the actuator and the connection points to the bolts were added to the valve body and clamping surfaces for post-processing. For the post-processing steps, accessibility from both sides of the valve was required. Therefore, the valve can be clamped either on the bottom cylindrical surface or on the top parallel surface (Figure 16(c)).

Structural simulations of the design at the operating pressure demonstrated the need for local reinforcements; for example, at the valve body interface with the spool. This region is critical to avoid jamming the spool in the valve body. Therefore, the guiding vane, which is used for improving the pressure drop, was adapted to strengthen the valve and reduce deformation. In addition, the reinforcements outside the valve were integrated (Figure 16(c)). Figure 15

demonstrates the simulation results after the adaptation of the guiding vanes and the integration of the reinforcements. These results fulfil the specified requirements for deformation at the interface between the spool and valve body.

After finalising the valve design, a machining stock of 0.5 mm was added on all functional and sealing surfaces for removal during post-processing.

Figure 16 shows the development steps of the fluid volume from (a) the chosen concept after section 3.2 to (b) the improved and manufacturable design. The final part design with structural reinforcements, connection elements, and clamping surfaces is shown in step (c).

4. Manufacturing

Materialise Magics was used to prepare the build job and define the support structure. Only a minimal amount of support is required in the chosen build direction connecting the valve to the build plate and supporting the connection elements (Figure 17(a)). These supports can be easily manually removed. The valve bodies were then manufactured on a Concept Laser Mlab using R L-PBF machine using 1.4404 stainless steel powder and a layer thickness of 30 μm (Figure 17(b)). Standard process parameters were used with a laser power of 90 W, speed of 600 mm/s, and hatch distance

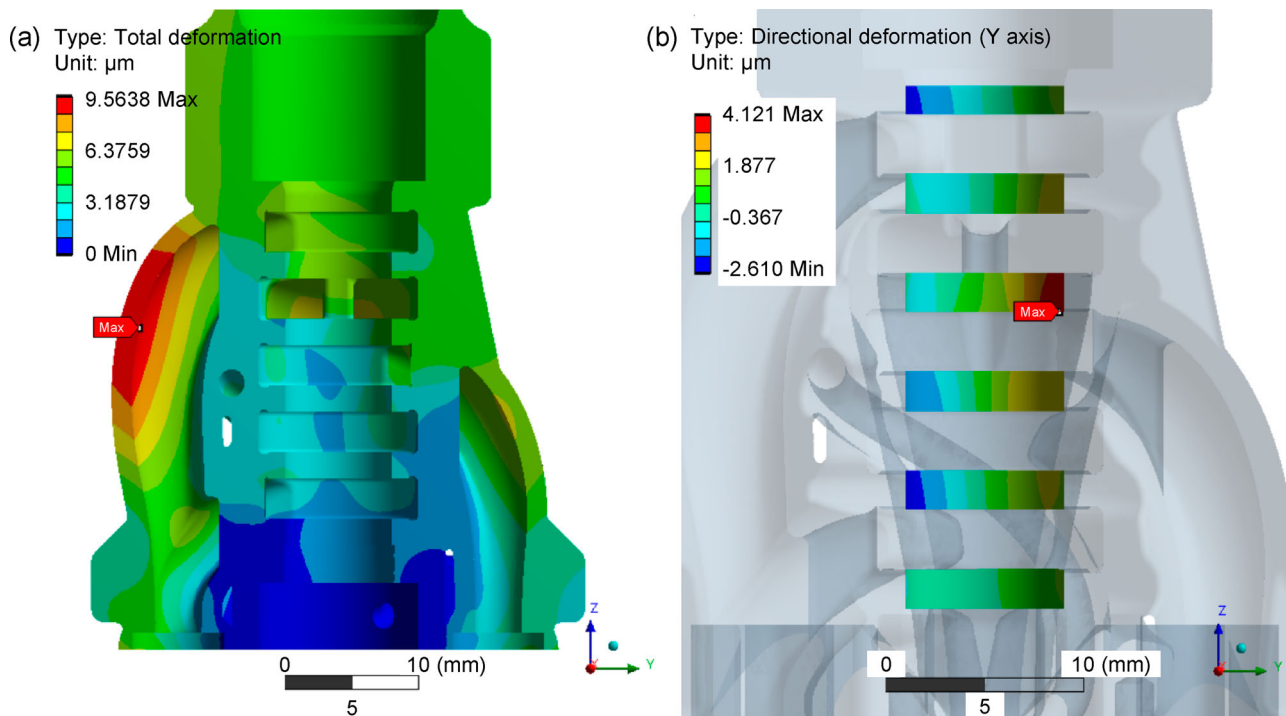


Figure 15. Simulation results after locally reinforcing the valve by adapting the guiding vanes: (a) Total deformation of the complete valve under an internal pressure load of 350 bar; (b) Directional deformation of the interface surface between the valve body and spool, which is critical to avoid jamming the spool.

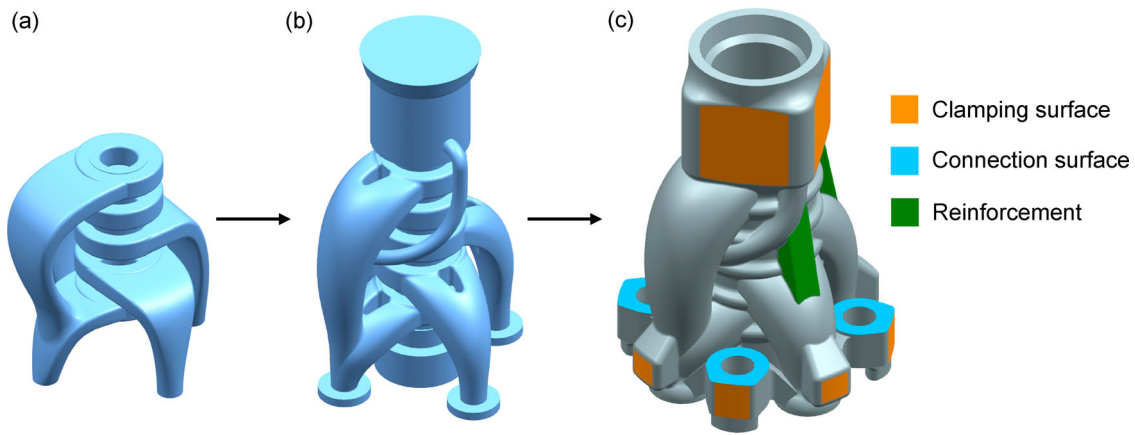


Figure 16. (a) Fluid volume of the chosen concept; (b) Fluid volume of the improved and manufacturable design; (c) Final part design with structural reinforcements, connection elements, and clamping surfaces.

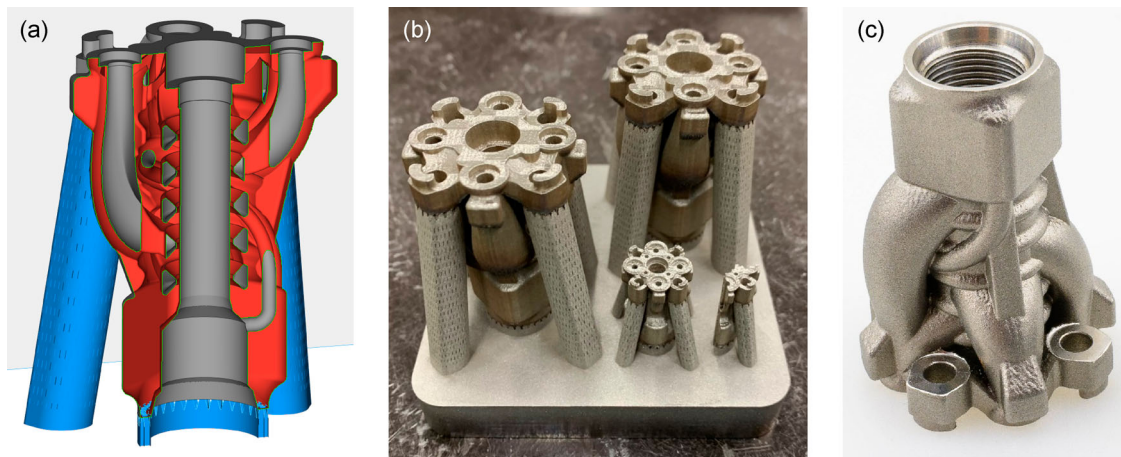


Figure 17. (a) Final design in selected build orientation with required support structures; (b) Build plate with manufactured valve bodies and support structures; (c) Valve body following post-processing.

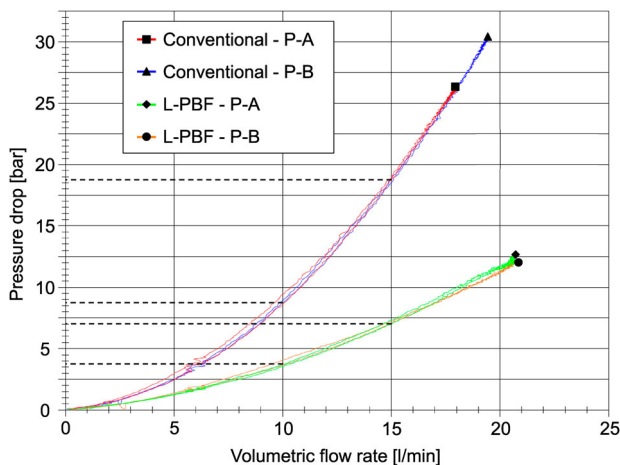


Figure 18. Measurement results of the pressure drop occurring in the hydraulic valve at different volumetric flow rates: Comparison between the conventional valve and the L-PBF valve design.

Table 3. Comparison of the conventional and the L-PBF valve in terms of pressure drop, material volume, and mass.

		Conventional	L-PBF	Reduction
Pressure drop	@10 l/min	8.75 bar	3.75 bar	-57%
	@15 l/min	18.75 bar	7 bar	-62%
Material volume		24.5 cm ³	12.3 cm ³	-50%
Mass		196 g	98.4 g	-50%

of 0.084 mm. Following support removal, the parts were sandblasted and post-processed. Post-processing via turning was required on the inner cylindrical surface to ensure a good fit between the spool and the valve body, which is essential for reducing leakage. Furthermore, the control edges were post-processed for a precise shift between the valve states. Finally, the threaded interface to the actuator and the sealing surfaces were milled. The final part is shown in Figure 17(c).

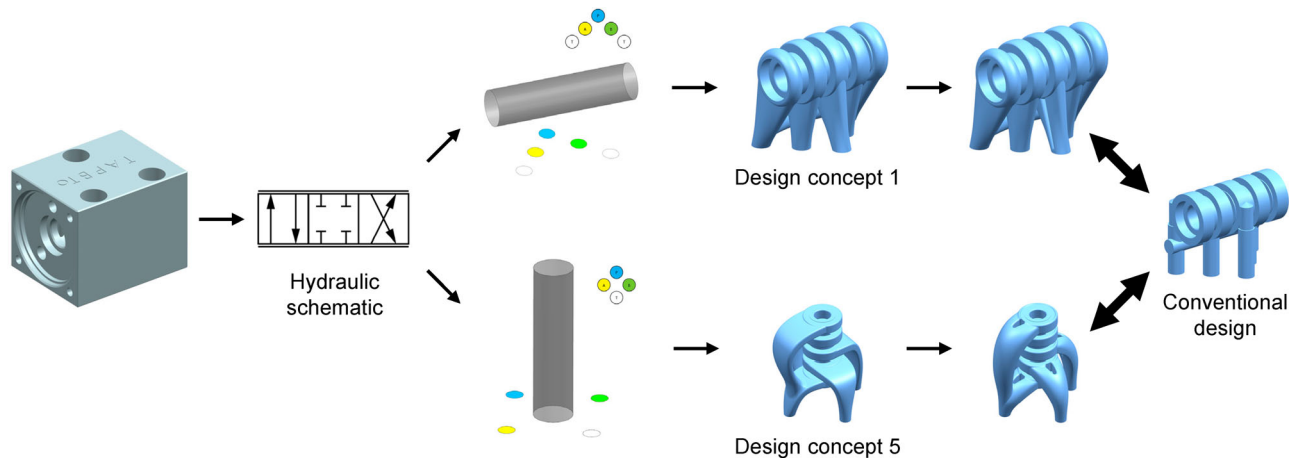


Figure 19. Comparison of the resulting topologies of design concept 1 (top, conventional interface), design concept 5 (bottom, circular interface), and the influence of the defined interface and spool orientation on the similarity to the conventional design.

5. Validation and results

The performance of the valve was evaluated after manufacturing and post-processing. The pressure drops of paths P-A and P-B of the additively manufactured design in comparison to the values of the conventional valve are plotted in Figure 18. These results demonstrate that reductions in the pressure drop of 57% and 62% were achieved for flow rates of 10 and 15 l/min respectively (Table 3). In addition to the performance improvement, a significant material and mass reduction of 50% was achieved. Furthermore, the redesigned L-PBF valve has more benefits. The circular interface allows the valve to be mounted in four different configurations, which enables several valve types and flow configurations to be fulfilled by the same valve, thereby reducing the number of spools required to cover the entire spectrum of configurations.

6. Discussion

This section discusses the results of this case study and the potential, learnings, and limitations identified during the process of redesigning the hydraulic spool valve for L-PBF.

6.1. Potential of L-PBF for pressure drop reduction in hydraulic applications

The pressure drop was improved by approximately 60% by redesigning the valve for AM, which demonstrates the significant potential of AM for improving the performance of hydraulic applications. AM significantly increases the design space for the manufacturing of different topologies. By avoiding conventional design restrictions and considering and comparing several different design concepts, AM has the potential to

significantly improve the performance of hydraulic components and further integrate functionality.

6.2. Influence of boundary conditions on design variance and the resulting topologies in the conceptual design phase

The defined boundary conditions strongly influenced the redesign outcome. In the conceptual phase, two design concepts are considered, both of which rely on the conventional flow concept. The first concept, depicted at the top of Figure 19, uses a standardised interface ISO 4401 (ISO 2005), which is used in all the other valves at Wandfluh AG. The second chosen concept, depicted at the bottom of Figure 19, is based on a circular interface and vertical spool position. Because the overall arrangement of all the concepts is strongly influenced by the interface and spool orientation (DP3), the topology of the first concept is similar to that of the conventional valve. In contrast, the second valve is significantly different than the conventional valve. Figure 19 demonstrates that if the boundary conditions for a redesign are set too strictly, there is only a limited amount of room for radically different designs. More room is provided for new concepts to emerge by allowing the adaptation of interfaces, which may be more efficient or implement additional functionality, thus justifying the additional costs of adapting conventional interfaces.

6.3. Importance of simulating generated design variants

In addition to generating a wide variety of part concepts, simulating these variants to assess their performance is

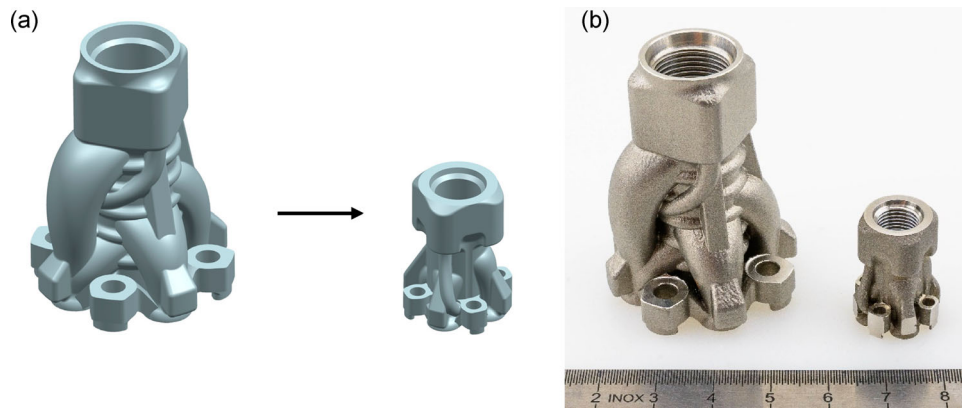


Figure 20. (a) Miniaturisation of the valve design from NG3 to NG1.5; (b) Photo of the manufactured NG3 and NG1.5 valve.

important. In the conceptual design phase, several different concepts were generated based on three DPs. The idea of the direct flow concept in DP1 was to guide the fluid through the spool volume on a straight path and not to push it through a thin gap, as in the conventional flow concept. This idea can be implemented using the design freedom of an AM spool and valve body; therefore, it was evaluated in the conceptual design phase with the goal of exploiting the design freedom. However, the potential of this concept was not confirmed by the CFD simulations (Figure 10). Without the use of simulations to evaluate the design variants, this development project may have ended in using a poorly performing concept for the upcoming design phases.

6.4. Potential for scalability

The potential of L-PBF for scaling is another noteworthy observation made during this project, especially the downscaling and miniaturisation of hydraulic components. After finalising the design for a nominal size of 3 (NG3), which corresponds to a channel diameter of 3 mm, miniaturisation of the valve was considered. The nominal size of 1.5 (NG1.5) was chosen because a conventional valve of this size is not available in the market and enables the control of hydraulic components in significantly compact systems. The final flow channel design after the embodiment design phase was scaled down to the desired size before following the steps of the detailed design phase. Simulations were conducted to ensure the mechanical strength and the valve was manufactured, post-processed, and tested. The final valve design is shown in Figure 20.

Because most process limitations, such as the maximum unsupported overhang distance or the maximum channel diameter for horizontal channels, are bound by upper limits, downscaling models that are well parameterised can be performed quickly.

However, lower bound process limitations, such as minimum feature sizes, must also be considered when approaching minimal dimensions. The most significant limitation for miniaturisation in the application field of a hydraulic spool valve arises from the required post-processing steps, which depend on the functionality of a given component.

6.5. Manual design process

Although the achieved pressure drop reduction and consequent potential of L-PBF for hydraulic components is substantial, one of the main limitations was the manual design effort. Designing the free-form surfaces of various design concepts requires extensive manual design efforts. Furthermore, changing the details to improve the pressure drop is time consuming.

This demonstrates the need for automated design tools for AM. By automatically generating manufacturable geometries, not only can a single design be efficiently generated, but it also enables the rapid generation of several different variations. The potential of AM can be further exploited by increasing the number of concept variants considered for evaluation.

Two main approaches for the automated design of flow components have been presented in the literature. Topology optimisation is one approach used in several studies to automatically design flow components considering the overhang constraint of AM (Behrou et al. 2002; Verboom 2017). Other studies used a computational approach to create manufacturable and self-supporting flow components (Biedermann, Beutler, and Meboldt 2021, 2022). However, neither approach is currently capable of automatically generating designs that can account for the interaction between two bodies in different valve states and additional requirements of the system, such as balanced radial forces.

7. Conclusion

An industrial case study of an L-PBF hydraulic spool valve was presented, which was developed in collaboration with Wandfluh AG based on real world requirements. After defining the requirements, the overall design concept for the hydraulic valve was developed in the conceptual phase. Subsequently, several detailed design variations were investigated, which can further improve the flow and reduce the pressure drop in the valve. The beneficial variations were applied to the chosen design concepts, and the final valve body was designed, simulated, manufactured, and tested. The measured pressure drop was then compared to that of a conventionally manufactured valve. Finally, the results are discussed, and the potential, learnings, and challenges of the development process are summarised.

This case study demonstrates the benefits of the design freedom of the L-PBF process for hydraulic components by achieving a pressure drop reduction of 60% and a weight reduction of 50%. The conceptual design phase that considers several design variants and the CFD simulation-based evaluation of these concepts, as well as the experimental validation of the final design are emphasised. Finally, the potential of AM for scaling generated designs with a low additional design effort was demonstrated and discussed.

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