15th IFK
Proc. of the 15th International Fluid Power Conference <Symposium/Conference>
<DOI>

Additive Manufacturing in Hydraulics: Design Methodologies for Manifolds

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Abstract.

Additive Manufacturing (AM) has established itself as a promising technology in the field of hydraulics, offering new opportunities for the design and optimization of components [1]. For converting classic designs into AM-compatible models, there are guidelines and methodologies available, including even specific approaches for manifolds [2]. However, the guidelines are usually very vague and provide limited concrete design specifications. In addition to this challenge, the available software solutions for the rapid creation of asymmetrical or bionic geometries are quite limited. Although there is a variety of software solutions on the market for designing AM components, their functionalities are not tailored to the requirements of AM. While conventional computer-aided design (CAD) is based on 2D sketches evolving into volumetric bodies, there is an increasing demand for advanced software solutions that facilitate freeform spatial design and provide constructive guidelines to enhance flow-optimized designs. This paper compares and evaluates various software and design methodologies to assess their suitability for additively manufactured hydraulic components.

In this paper we perform an analysis of the entire design process, including a comparison of pressure losses. The primary objective is to establish specific methodologies for the design of AM components. Results indicate significant shortcomings in conventional CAD software, which often limits designers' capabilities. To address these challenges, this study introduces an innovative design configurator implemented in the software Rhinoceros 3D® according to the approach of Biedermann [3]. This configurator facilitates the automated creation of manifolds by adjusting channel geometries to minimize pressure losses in hydraulic channels.

Keywords. Design, Additive Manufacturing, Manifold, Flow-Optimization.

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1. INTRODUCTION

The use of AM compared to conventional production has increased in recent years. Consequently, the demand for integrated software solutions for product development is also increasing, particularly those that enable the automated creation of three-dimensional freeform surfaces.

To analyze which software solutions are currently available and how advanced their level of automation is, four different CAD software are compared in Table 1 based on various evaluation criteria. The programs considered are Siemens NX®, SolidWorks®, Rhinoceros 3D® (including Grasshopper®) and nTopology®. The evaluation criteria include a general definition, the capability for generative design, and automation possibilities. Due to the significant potential for material and weight reduction, the topology optimization capabilities of each program are also compared.

Table 1: Comparison of different software solutions for designing additively manufactured components

	Siemens NX	**SolidWorks**	**Rhino 3D + Grasshopper**	**nTopology**
Definition	Characterized by functionality, performance & stability [4]	Software known for conventional manufacturing [5]	Graphical programming approach [6]	Interesting for AM purposes [7]
Generative design	Direct Modeling [8]	Direct Modeling [8]	Based on NURBS [9]	Implicit modelling by utilizing functions [10]
Automation possibilities	Using external software [11]	Design automation of a cube [12]	Design automation of cable routing [6]	No current data found
Topology optimization	Yes [13]	Yes [14]	Yes [15]	Yes [10]

Siemens NX® was selected because it represents a widely used software solution in industrial product development and is characterized by extensive functionality, high performance, and stability [4]. SolidWorks®, in contrast, was originally designed for conventional manufacturing processes. Rhinoceros 3D®, including Grasshopper®, follows a graphical programming approach, whereas nTopology® is particularly suited for AM applications. It was developed within the DfAM framework and utilizes advanced design methods such as topology optimization and lattice structures, enabling increased design freedom [6]. In this paper, a comparison is drawn between classical CAD design (conventional design) using Siemens NX® and an automated design approach in Rhinoceros 3D®.

Design Automation (DA) refers to the computer-based automation of repeatable tasks in the design and design process. The advantages of DA are manifold: it reduces the time and effort required for the design of components through the automated creation of geometric bodies as well as their easy adaptation. This enables efficient design adjustments, facilitates the iterative design process, and minimizes human errors as well as the risk of faulty designs. [16], [17], [3].

For the design of valve block channels, which are represented by paths between valve cavities and connections, DA is presented through iterative path generation based on Position-Based Dynamics (PBD) simulation. PBD is already applied in areas such as special effects in films, physics engines in video games, and form-finding techniques. [3], [18]

2. METHODS

In order to compare conventional and AM-optimized design methods, both approaches must first be defined. To do this, the selected procedure is presented in each case. Conventional design refers to the approach in which the design is created manually in a CAD program. The alternative is a design configurator that automatically creates paths between the components. The methods presented in this chapter reflect the actual approach used in the design development and outline optional additional steps. These methods should not yet be regarded as general design methodologies. The results presented in this paper elucidate various aspects of the design process and highlight potential improvements in fluid-dynamic performance.

2.1. Conventional design process for product optimization

There are various methods for product development, such as the widely used VDI 2221 [19]. These methods provide a structure for the individual steps of product design. In practice, method-based approaches that simplify certain aspects of the methodology are often employed. The approach adopted in this paper is frequently used at the institute to implement application-oriented product development and is also employed in industry.

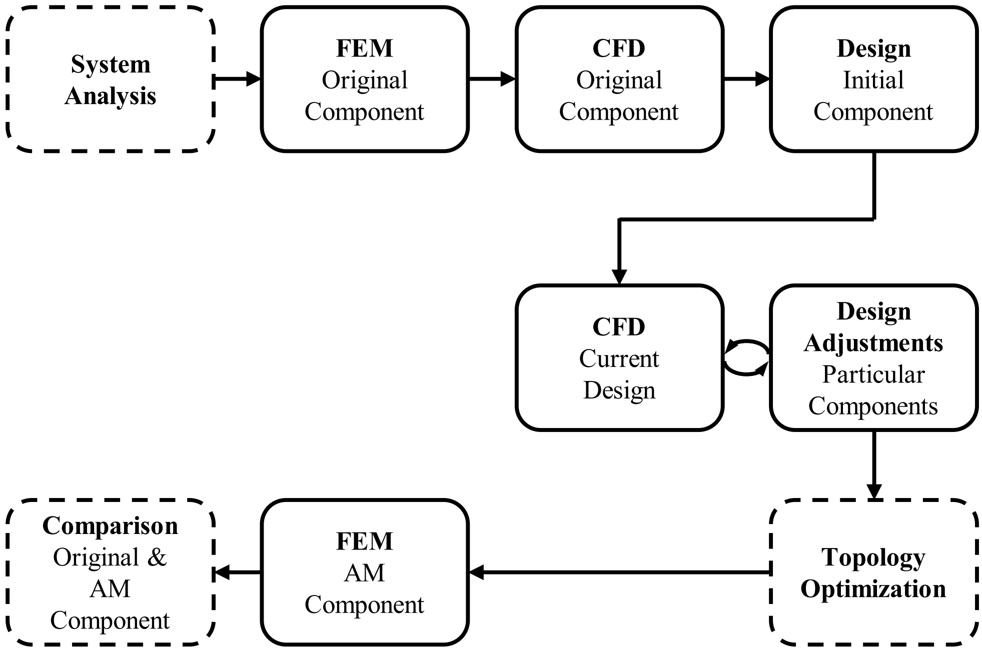

Figure 2.1. Methodological approach to the design of an AM manifold

The methodological approach follows the problem-oriented development process shown in Figure 2.1. This approach is based on established procedures for the structural optimization of hydraulic components and has been adapted to the specific requirements of a hydraulic manifold. It is divided into the necessary analysis steps and optimization processes, which lead, step by step, to a functional, production-ready optimization of the component. In addition, the process includes a comparison between the original and the new states of the manifold with respect to pressure drop, strength, and mass.

The steps shown with a dashed outline are not strictly required for the development of an AM manifold. In this paper, however, they are implemented to improve and validate the result. Topology optimization is generally advisable; since it was not implemented in the automated methodology used for comparison, it is presented here as optional. The mandatory steps for the (re)design of a manifold are the initial design, the iterative cycle of flow analysis and design adjustments, and strength verification. The intermediate topology optimization makes the FEM analysis a safety check; otherwise, it would be mandatory to verify the strength of the design.

The conventional design approach is applied to the manifold of a compact hydraulic power unit from a forklift. This manifold includes a high-pressure filter and two valves in the return line to the tank that controls the lowering of the fork. The primary functions implemented by the manifold are therefore “lifting” and “lowering” of the fork. The CFD simulation was performed in Ansys Fluent with an element size of 0,7 mm. During the lowering operation, a volumetric flow rate of 40 l/min was assumed. The fluid was modeled with a kinematic viscosity of 46 cSt and a density of 850 kg/m³. The thickness of the first prism layer was set to 68 µm. The number of prism layers was limited to 10, with a growth rate of 1,2. The SST turbulence model was used.

2.2. Design Configurator

The procedure shown in Figure 2.2 represents an alternative design methodology. It is important to note that, within the scope of design development using the design configurator, no topology optimization has been implemented to date; instead, wall thicknesses are selected according to the system parameters, and the model is designed accordingly.

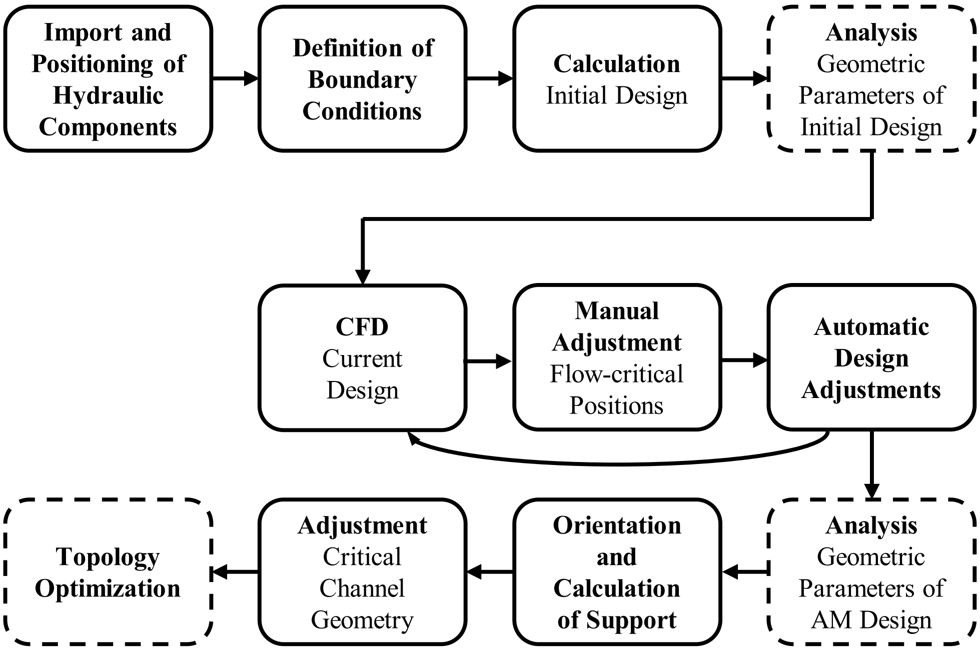

Figure 2.2. Methodological approach of the design configurator

The main differences to the conventional approach lie in the simplification of design adjustments using the configurator. Flow-critical areas can be modified in a targeted manner, and the rest of the model is automatically rebuilt. However, this carries the risk that manual channel adjustments may create new critical positions.

The design configurator used, which builds on the work of Manuel Biedermann, is implemented using Grasshopper®, a visual programming language and environment within the CAD software Rhinoceros 3D® [3], [20]. Version 8.1 of Rhino and version 1.0.0008 of Grasshopper are used. The path generation of the valve block channels is realized using a PBD algorithm through the Grasshopper plugin Kangaroo2 by Daniel Piker [18], [21]. The standard Kangaroo solver and its default settings are implemented. The implementation of the design configurator takes place on the valve block from Schmelzle, with the arrangement of the valve cavities based on Biedermann's layout [3], [22]. To implement the geometric boundary conditions, the blocks Anchor, Equal Angle, Coincident, Collider, Constant Tension, Direction, Dynamic Weight 1D, Length (Line), Load, and Rod are utilized in Grasshopper. With the help of these boundary conditions in the Kangaroo solver, various geometric parameters of the design are modified. These include the channel length L [mm], the curvature radius R [mm], the curvature angle W [°], as well as the branching angles α, β, and γ.

In the first step, the hydraulic components, such as valve cavities and screw-in fittings, are imported and positioned within the build space of the valve block to be developed. During the second step, the channel routing is defined by initializing a path. This path is represented as an abstract line between the inlet(s) and outlet(s), with a distinction made between simple and branched paths. For simple channels with only one inlet and one outlet, a direct path is created, while for branched channels, branching points are used to account for multiple connections. Subsequently, the abstract line along the path is discretized with particles. Figure 2.3 shows the implementation of the first two steps in the design configurator.

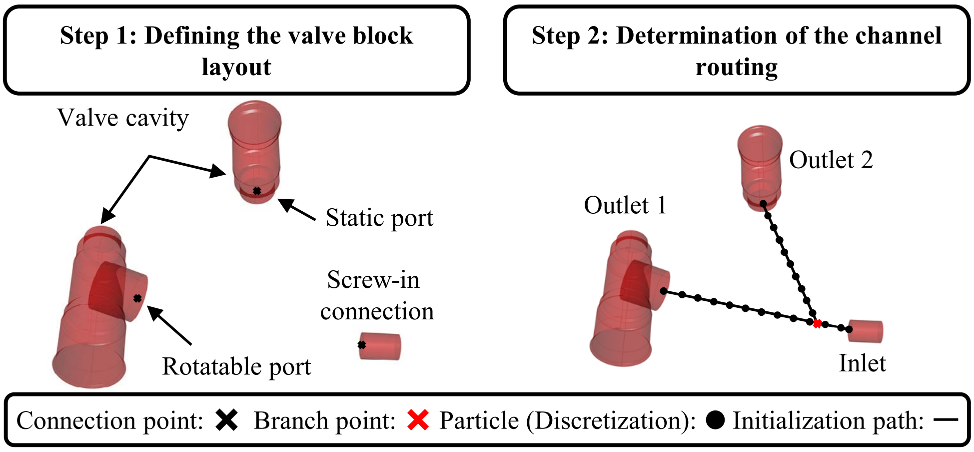

Figure 2.3. Defining the valve block layout and determining the channel routing

Within the third step, the boundary conditions of the paths or particles are defined, as they significantly determine the subsequent course of the channel path. The individual boundary conditions are weighted against each other, depending on the strength of this weighting, the influence of each boundary condition on the channel routing is determined. It may occur that two or more boundary conditions counteract each other, and a specific weighting must be provided for this purpose, as certain boundary conditions, such as collision avoidance, must be adhered to [6]. The boundary conditions are channel-specific.

In the fourth step, a suitable solver processes the defined boundary conditions using the PBD algorithm iteratively until either the convergence criterion is met or the maximum number of iterations is reached. Convergence is achieved when the threshold ϵ is reached. The threshold is calculated by dividing the square of the velocity of all path particles by the total number of particles N_{total} [3]. The solver gradually adjusts the position of the particles along the initial path in accordance with directions specified by the boundary conditions. The boundary conditions generate displacement vectors for each individual particle; the resulting displacement vector of a particle is obtained from the superposition of these various displacement vectors. Figure 2.4 shows the implementation of the boundary condition from step 3 in Grasshopper and step 4, illustrating both the initial and finished paths in the design configurator.

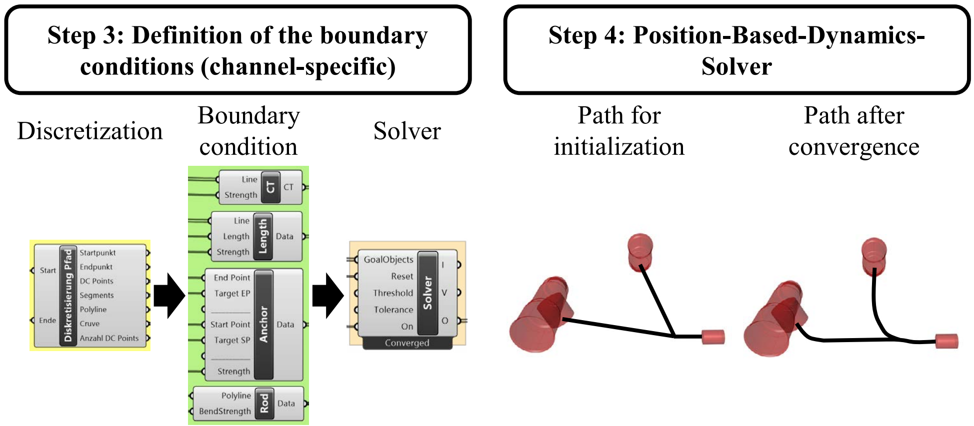

Figure 2.4. Definition of the boundary condition and Position-Based-Dynamic Solver

Finally, in the fifth step, the geometry of the valve block channel is constructed from the post-solver path by specifying the channel diameter and wall thickness. Figure 2.5 shows the CFD volume body and the AM channel geometry derived from the post-solver path.

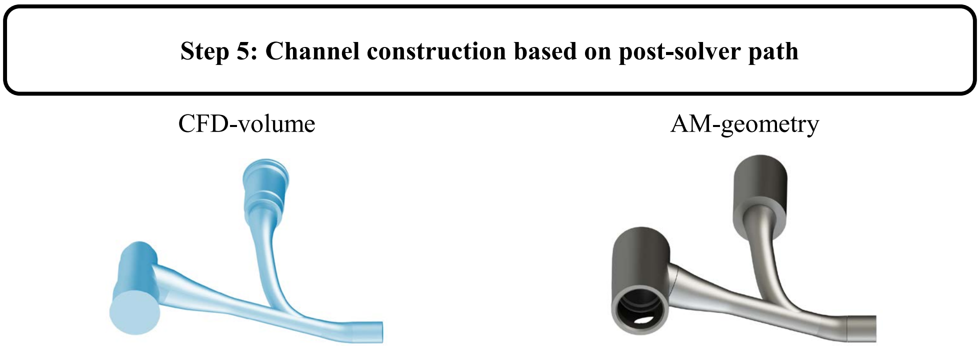

Figure 2.5. Finished valve block channel as CFD volume body and AM channel geometry

To illustrate the general applicability of the design methodology of the design configurator, various designs are created and examined. Based on this data set, a correlation analysis is conducted to determine guidelines for the design of the valve block channels for a specific operating point. To determine the Pearson correlation coefficient, the influences of the geometric parameters on the pressure loss are assessed using the correlation coefficient r. The correlation coefficient r is explained in detail in [24].

3. Results

In this chapter, a fluid-dynamic comparison is made between the original forklift manifold and the component created using conventional design. This includes comparing the overall pressure drop across the component and presenting individual design adjustments at flow-critical locations. In addition, the results obtained with the design configurator are presented and compared in fluid-dynamic terms using a flow-path geometry.

Figure 3.1 shows a comparison between the original manifold and the component obtained through conventional design for AM. The component shown in a) is manufactured by cold extrusion followed by subsequent machining. Component b) is designed for AM, and the cavities likewise require finish machining. The individual optimizations that were carried out to achieve the final design are explained in detail. Compared to the original component, the new design saves 40 % in mass. When considering the change in pressure losses, a distinction must be made between two load cases: extension of the cylinder and retraction of the cylinder. During extension, 43 % pressure loss can be saved, and during retraction, 38 %.

a) b)

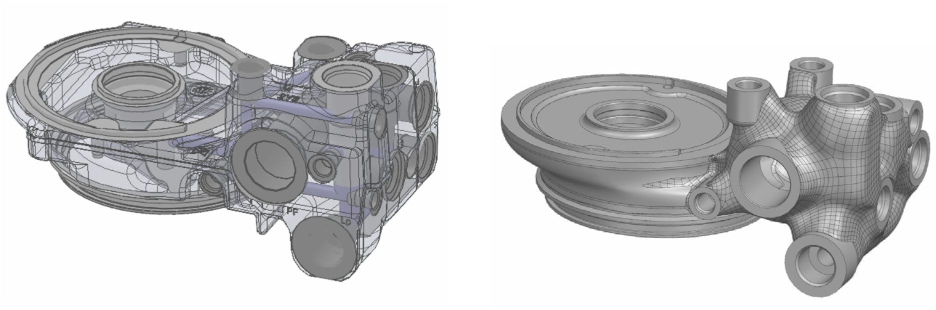

Figure 3.1. Results for the design of the valve block for a) conventional and b) additive manufacturing

The new layout of the hydraulic channels can be seen in Figure 3.2. Eliminating the 90° intersections when merging channels alone leads to a significant reduction in pressure losses.

a) b)

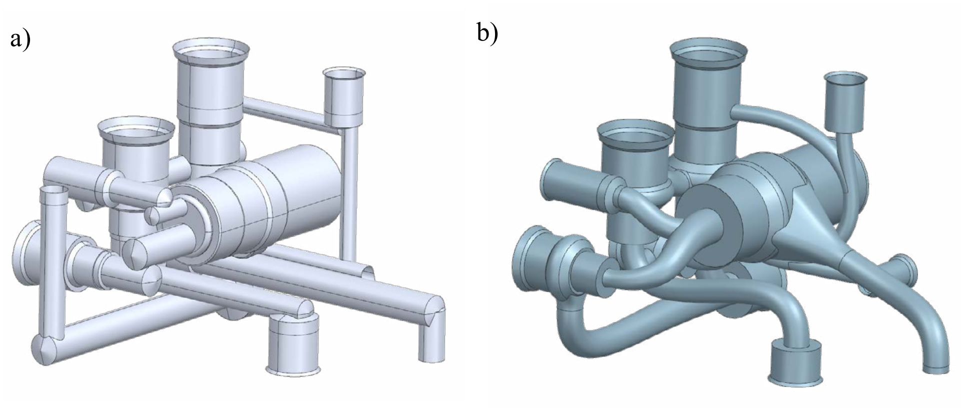

Figure 3.2. Channel route for the design of the valve block for a) conventional and b) additive manufacturing

Figure 3.3 shows the result of the CFD simulation for the old and new manifolds in the case of the cylinder lowering by the load mass. The 38 % reduction in pressure drop is evident from the color-coded contours in the CFD simulation.

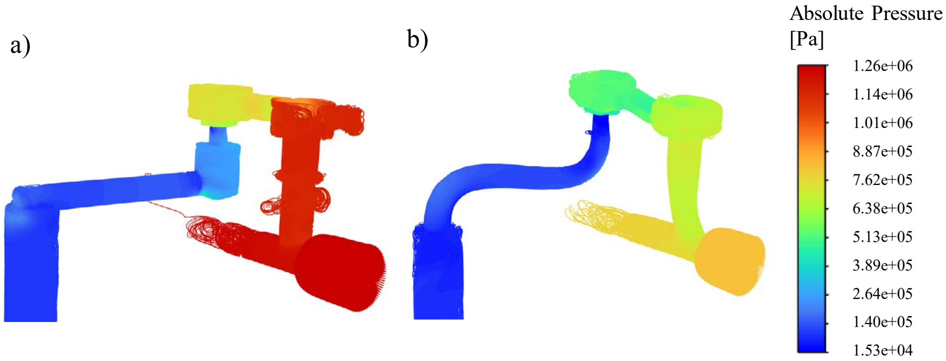

Figure 3.3. CFD-Simulation results of the manifold for a) conventional and b) additive manufacturing in the event of cylinder retraction (lowering)

The Figure 3.4 shows how the potential offered by the design freedom of AM can be exploited. Although the pressure loss is largely determined by the valve, the adapted valve outlet design and a flow-optimized connection can achieve an improvement of 35 %. The valve modification illustrates the approach used in conventional design. Components are optimized sequentially and verified in simulation. Flow paths are routed as NURBS curves between components without any optimization algorithm. At necessary locations, such as the connection to the filter, self-supporting channel cross-sections are implemented.

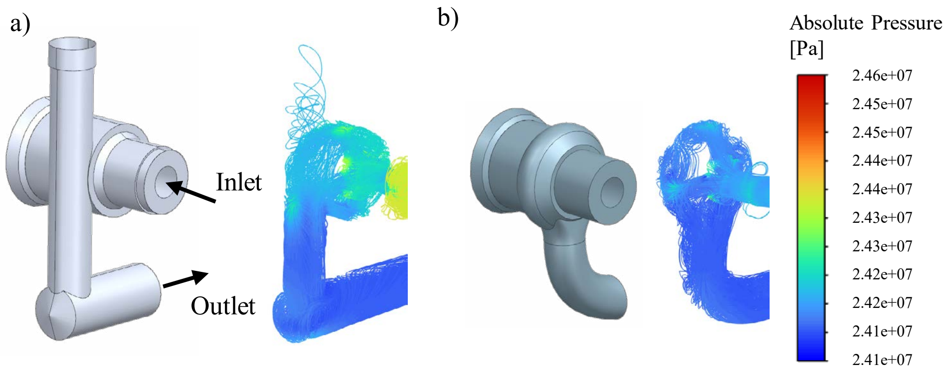

Figure 3.4. Valve design for a) conventional manufacturing and b) additive manufacturing

Conventional design highlights the substantial potential for efficiency gains; however, the design process itself is not particularly efficient. Once modifications are made, dependencies no longer hold, and repositioning components is feasible only with substantial effort. DA provides an alternative to this process. Thanks to the freely programmable and flexible extension of the design configurator, it is capable of creating a wide variety of channel designs and layouts. By adding or removing boundary conditions, as well as by inserting different components into the design space, customized valve manifold layouts and designs are possible. Figure 3.5 illustrates this diversity by showing the possible modifications of a channel and the flexible adjustment of the valve manifold layout.

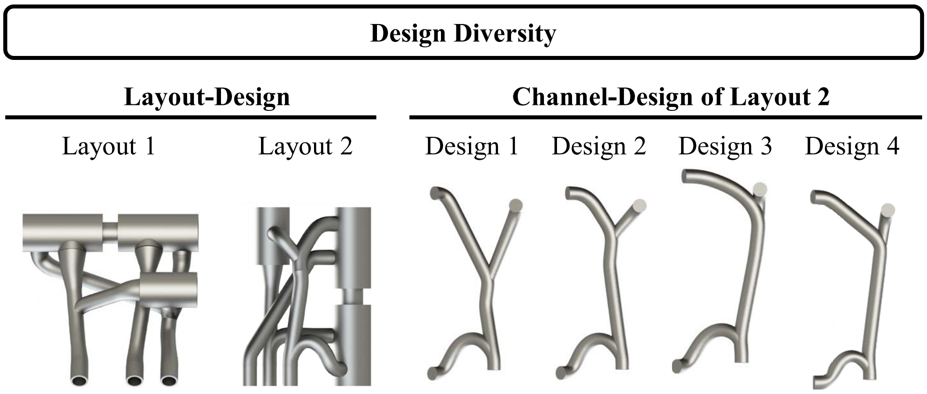

Figure 3.5. Realizable design variety using the design configurator

The design configurator enables the iterative optimization of channel flow due to its simple and rapid creation of various designs [23]. The workflow of this process is illustrated in Figure 3.6. Starting with the initial design, a CFD simulation is carried out and evaluated. In the evaluation, flow-critical positions are identified, and in the next step, the channel geometry is adjusted at these critical locations by modifying the boundary conditions in the design configurator. The resulting valve manifold layout is then generated, and the process is repeated until the predefined optimum is achieved.

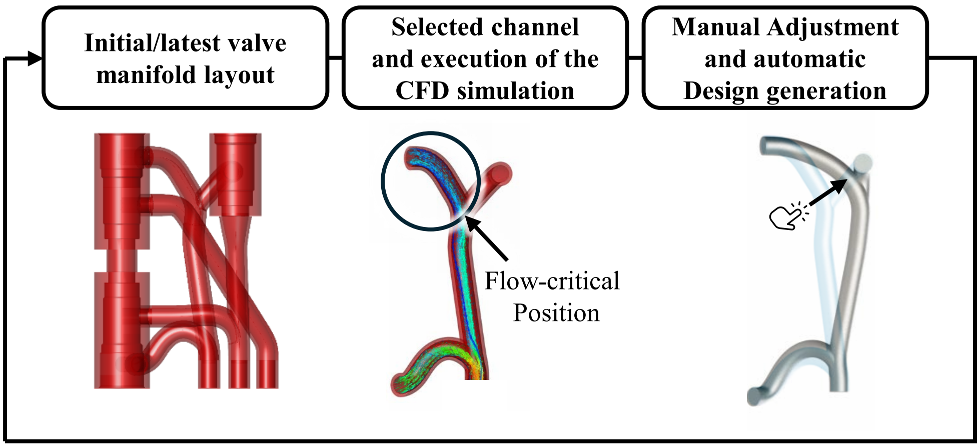

Figure 3.6. Workflow of flow optimization using the Design Configurator

The results of the case study for Layout 2 based on four channel designs are presented below. The case study examines flow optimization based on a defined operating point. The examined designs are iteratively created according to the workflow for flow optimization of the design configurator. To determine a local optimum, the pressure loss across the channel (Δp) is selected as an optimization parameter. Additionally, another parameter (the specific pressure loss) is introduced that describes the pressure loss across the channel divided by the channel length l ($\Delta p/l$) to determine the influence of geometry independent from channel length. The pressure loss and the specific pressure loss of Designs 1 to 4 are shown in Figure 3.7.

The calculated results are determined using the simulation software ANSYS Fluent. The k-ω-(SST) solver is employed, and between 1000 and 3000 iterations are performed per design. HLP 46 hydraulic oil is used as the working medium for the simulation, with a density of 858 kg/m³ and a kinematic viscosity of 46 cSt. The mesh has the following characteristics: The minimum edge length is at least 0.5 mm, while the maximum edge length does not exceed 1 mm. The boundary layer consists of five layers, and the initial boundary layer has a thickness of approximately 66.71 µm with a growth rate of 1.2. The volume flow varies depending on the channel variant and ranges between 7.12 l/min and 125.61 l/min.

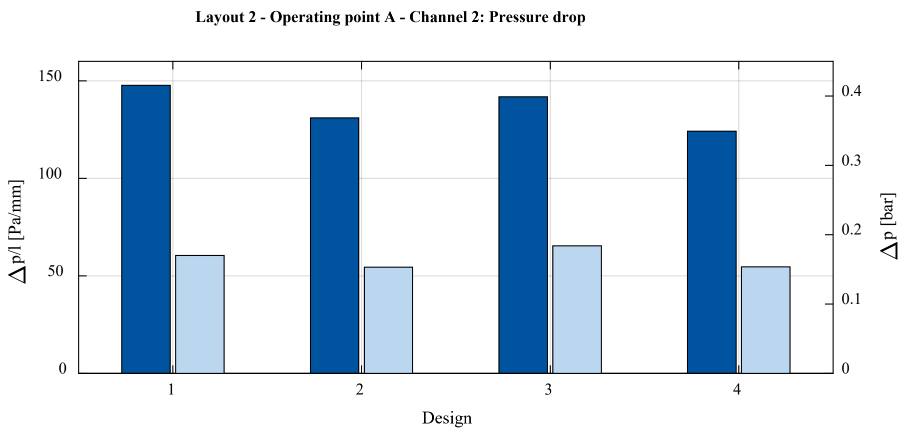

Figure 3.7. Pressure loss and pressure loss divided by channel length for designs 1 to 4

Design 2 has the lowest pressure loss at 0.153 bar. The specific pressure loss is 131.032 Pa/mm, making it the second lowest. Design 4 shows the lowest specific pressure loss with 124.187 Pa/mm; however, here the absolute pressure loss is at 0.154 bar, which is only slightly higher than that of Design 2. The reason for Design 4's poorer performance lies in its channel length; this measures 123.734 mm. The channel length of Design 2 is shorter and measures 116.896 mm. The shortest channel examined in this case study is the one of Design 1 with a length of 115.144 mm. For the case study, a correlation analysis is also conducted to investigate the correlation between various geometry parameters and the optimization parameter pressure loss. Conclusions regarding how to adjust the parameters cannot be drawn from the results due to the difficulty in classifying the geometry of the channels, as the geometric description depends on several individual parameters. The results of the correlation analysis indicate tendencies that certain parameters have a greater influence on the pressure loss of the channels, particularly the channel length should be mentioned.

For the investigation of operating point A, channel 2 from the Layout 1 and 2, the correlation coefficient is calculated to analyze the relationship between the number of occurring curvature radii and angles with specific pressure loss (pressure loss divided by channel length), as well as channel length and absolute pressure loss. The correlation coefficient quantifies the potential influence of channel geometry on pressure loss. The significance is considered sufficient when a strong correlation exists with a correlation coefficient of at least ±0.5. The results from this analysis are presented in Figure 3.8, with the existing geometric parameters categorized into discrete ranges. This is due to the complex structure of the channels, which exhibits a variety of different curvatures with various parameters. Therefore, it is useful to categorize the geometric parameters into discrete ranges for a correlation analysis. The operating point considered has two inlets and one outlet. The volumetric flow rate at Inlet 1 is 12.88 l/min, and the volumetric flow rate at Inlet 2 is 7.12 l/min.

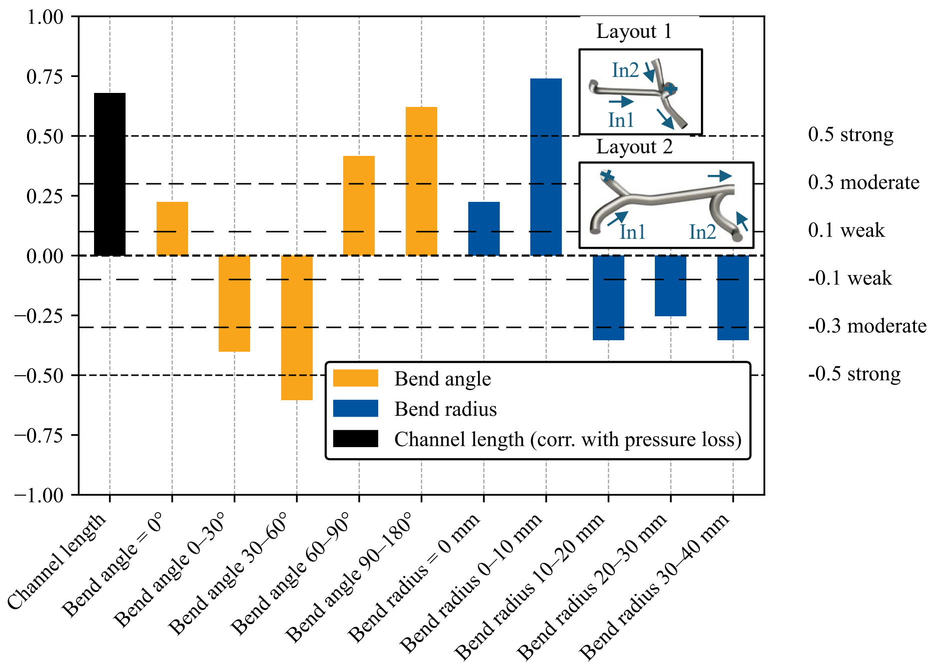

Figure 3.8. Correlation coefficients for operating point A – Channel 2

The analysis provides recommended design guidelines to achieve minimal pressure loss. The curvature angle shows two strong correlations. To reduce pressure loss, it is beneficial for the curvature angle to be in the range between 30° and 60°, where the correlation coefficient is strongly negative. Curvature angles from 90° to 180° should be avoided, as they exhibit a strong positive correlation; in this case, pressure loss increases with an increasing number of such curvature angles.

For curvature radii, a strongly positive correlation coefficient is observed in the range from more than 0 mm to 10 mm. Small radii should be avoided in design. The channel length shows a strongly positive correlation with pressure loss as well, leading to the conclusion that pressure loss increases with increasing channel length.

The design configurator was also used to automatically redesign the forklift manifold shown in Figure 3.1. The implementation process of this design configurator incorporated the use of parametric inputs. In the automated design process of the manifold, the flow-critical positions are identified and modified with minimal effort by utilizing the parametric input of the design configurator. With this a new manifold layout is devised by adjusting the position of the valve cavities or branches using parameters. By considering selected flow-paths in the CFD simulation and comparing them to the conventional valve block, the capabilities of AM are clearly visualized. Figure 3.9 shows the modification of a flow channel, which has led to a 44.6 % reduction in pressure loss.

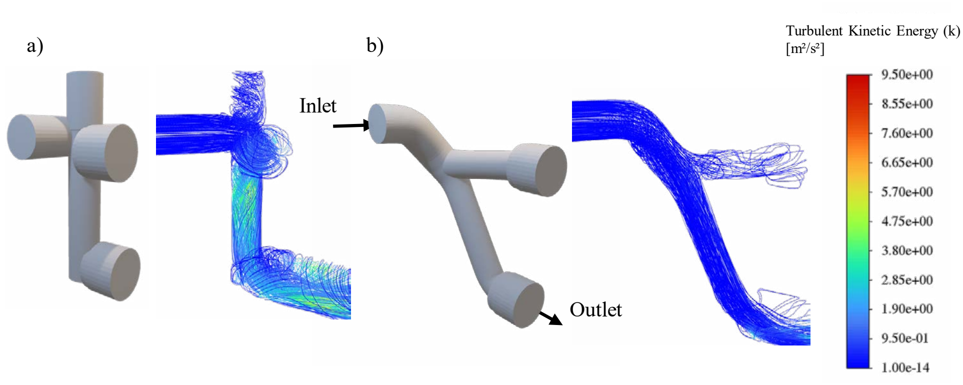

Figure 3.9. Channel optimization using design automation on the manifold

4. DISCUSSION

The analysis of pressure losses along one flow channel highlights the challenges of automated design optimization. Due to the high degree of design freedom, geometric characterization of the channel is very difficult, and losses cannot be attributed to individual parameters. An optimization focused solely on one geometric parameter, such as reducing channel length, does not lead to an optimal pressure-reduced flow in most cases within the valve block. Longer channels with geometries such as bends or branches often exhibit a lower specific pressure loss compared to shorter channels with the same geometries; however, this advantage is offset by extending the channel, resulting in a higher overall absolute pressure loss. For flow optimization of channel geometry, this means that a compromise must be found: between a preferably short channel length and bending as well as branching geometries that exhibit a lower specific pressure loss.

Although conventional design highlights the potential of the new AM design, its implementation is highly inflexible and time-consuming. A compromise would be to derive universally applicable rules that can be implemented in both design methodologies.

5. SUMMARY AND OUTLOOK

Based on the methods and results presented, two main conclusions can be drawn:

1. AM offers the opportunity to significantly reduce pressure drop in manifolds (up to a 43 % improvement).

2. DA enables the rapid generation of various manifold layouts that would be very time-consuming to achieve with conventional manufacturing.

These two findings reinforce both the use of AM in hydraulics and the development of automated design approaches. The next step toward establishing DA is the targeted adaptation of the algorithm for automated flow optimization. To this end, software solutions were already compared in the Introduction. In addition, simple design parameters must be defined so that knowledge-based engineering can be implemented. This includes, for example, defining suitable curvature radii, investigating channel intersections, and providing guidance on suitable self-supporting channel cross-sections. All of these goals are already being addressed within the HyRess research project to develop a guideline for designers. The resulting design guidelines are intended both to implement the constraints of AM and to achieve a flow-optimized component.

ACKNOWLEDGEMENTS

This research and development project is funded by the Federal Ministry for Economic Affairs and Energy (BMWE) within the Technologietransfer-Programm Leichtbau (TTP LB) and supervised by Projektträger Jülich.

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