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Design of internal structures to enhance the thermal performance of additively manufactured heat exchangers

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ABSTRACT: Bio-inspired designs offer innovative solutions for optimizing heat exchangers, though their complexity often exceeds the capabilities of traditional manufacturing methods. Additive manufacturing (AM) enables intricate geometries with enhanced surface areas for improved heat transfer. This study presents a modular algorithm to integrate internal structures into heat exchanger designs, balancing thermal performance and manufacturability. A case study demonstrates the design, simulation, and production of internal structures, identifying the "Diamond Radial" structure as the optimal choice due to its high R-factor and potential to improve efficiency. Future work includes exploring multi-material components and designs for hydrogen storage and fuel cell applications, paving the way for more efficient, application-specific systems.

KEYWORDS: design for additive manufacturing (DfAM), Inspired design/biomimetics, computer aided design (CAD), heat exchangers, thermal efficiency

1 Introduction

Nature provides a wealth of innovative solutions to technical challenges. Bionics offers a systematic approach to analyze, abstract, and adapt these principles for engineering applications (Lachmayer et al., 2024; Nachtigall, 2002). One prominent example is the efficiency optimization of heat exchangers, essential components across various industrial applications (Deng et al., 2021; Rong et al., 2023; Stephan et al., 2019; Yu et al., 2024). Systems found in nature, such as the specialized vascular structures in seagull feet, demonstrate effective thermoregulation with minimal energy loss under extreme conditions (Zerbst, 1987). Bio-inspired designs hold significant promise for creating heat exchangers that are more compact, lightweight, and resource-efficient, without compromising performance (Pieper & Klei., 2011; Wu et al., 2023; Zhu et al., 2023). However, the complexity of these designs often exceeds the capabilities of traditional design and manufacturing methods. Additive manufacturing (AM) provides a viable solution, enabling the production of intricate geometries and already being successfully applied in the development of high-performance, compact heat exchangers (Ehlers et al., 2023; Kahlfeld et al., 2023; Niedermeyer et al., 2023). Designing heat exchangers, however, presents significant challenges. The development of internal structures often relies heavily on expert knowledge, shaped by individual experience in simulation and thermodynamics (Lebaal et al., 2022). Standardized approaches for identifying suitable internal structures and integrating them into heat exchangers remain limited. Furthermore, harnessing the potential of additive manufacturing to thermodynamically and structurally optimize heat exchanger development requires new strategies to address existing process limitations (Niknam et al., 2021; Scheithauer et al., 2018).
This work aims to tackle these challenges by developing a modular, extendable generative CAD algorithm that facilitates the integration of internal structures into heat exchanger designs. The algorithm

focuses on enhancing thermal performance while ensuring manufacturability and scalability. The study begins with a review of strategies for improving heat exchanger performance. A case study then explores the design, simulation, and manufacturing of optimized internal structures for heat exchangers. Finally, the findings are synthesized into actionable recommendations and future directions for advancing heat exchanger design and development.

2 Strategies for improving heat exchanger performance

While conventional methods for improving heat transfer have made significant progress, they face manufacturing and thermodynamic limitations. AM enables the targeted design of complex, flow-optimized structures, offering new approaches to enhancing efficiency. This section provides an overview of the current state of research on existing optimization strategies, including both conventional methods and additively manufactured structures for improving heat exchanger performance.

2.1 Conventional methods for optimizing heat transfer

In a heat exchanger, heat transfer occurs through convective heat transfer from the hot fluid to the wall, thermal conduction within the wall, and subsequent heat transfer to the cold fluid (Baehr & Stephan, 2019; Ning et al., 2022). The heat flow $\dot{Q}$ is determined by the temperature difference ($\vartheta_1 - \vartheta_2$) and the total thermal resistance R. For cylindrical walls, this relationship can be expressed as:

$$\dot{Q} = \frac{\vartheta_1 - \vartheta_2}{R}, \quad R = \frac{1}{\alpha_{\text{inner}} \cdot A_{\text{inner}}} + \frac{\delta}{\lambda \cdot A_{\text{middle}}} + \frac{1}{\alpha_{\text{outer}} \cdot A_{\text{outer}}} \tag{1}$$

A lower total resistance R results in a higher heat flow, which is desirable for efficient heat transfer (Cengel & Ghaja., 2020; Fawaz et al., 2022; Jouhara et al., 2023). The equation suggests the following approaches for optimization:

- Maximizing the surface area A
- Maximizing the heat transfer coefficient α
- Maximizing the thermal conductivity λ through material selection
- Minimizing the wall thickness δ

This work focuses on geometric adaptation. Bergmann et al. (2018) distinguish four conventional approaches to improving heat transfer in internal pipe flows. An increase in α can be achieved through surface roughness or pipe inserts. Such inserts allow for retrofitting existing heat exchangers but may introduce thermal resistance due to poor contact with the pipe surface (Webb, Ralph L. & Kim, Nae-Hyun, 2005). Helical spring inserts generate turbulence through additional roughness, while twisted-tape inserts induce tangential flow components and enhanced mixing due to their helical geometry (Webb, Ralph L. & Kim, Nae-Hyun, 2005). Another approach involves increasing the wetted surface area A. Shah and Sekulić (2003) distinguish between primary surfaces, which are directly in contact with the fluids and conduct heat, and secondary surfaces (extended surfaces), which create a larger area through additional geometries, such as longitudinal fins, but do not allow direct contact between the fluids. Extended surfaces are often used on the gas side of flow, as the heat transfer resistance is higher there (Webb, Ralph L. & Kim, Nae-Hyun, 2005). While A can be increased by a factor of 10 to 100, additional thermal resistance occurs along the fins (Baehr & Stephan, 2019). Combined approaches, such as spiral fins, simultaneously increase both A and α, thereby utilizing both effects (Bergmann et al., 2018).

2.2 Additively manufactured structures for enhancing heat transfer efficiency

Several recent studies have explored the potential of additively manufactured structures to optimize heat transfer in heat exchangers (Dixit et al., 2022; Lebaal et al., 2022; Liang et al., 2023; Mahmoud et al., 2023; Sajjad et al., 2022). For instance, ***Lebaal et al. (2022)*** numerically modeled and analyzed octahedron lattice structures. The lattice was designed using *CATIA V5* and optimized by arranging unit cells. The results demonstrated a 70 % reduction in pressure drop and a 7.1 K increase in outlet temperature, significantly improving heat dissipation compared to conventional heat exchangers. Powder bed fusion of metals using a laser beam (PBF-LB/M) was proposed as a suitable additive manufacturing method; however, the component was not fabricated within the scope of this study. ***Mahmoud et al. (2023)*** designed heat exchanger channels utilizing gyroid structures created with nTopology software and analyzed them through computational fluid dynamics (CFD) simulations in ANSYS Fluent. The structures were manufactured using PBF-LB/M. The results confirmed that gyroid designs can significantly enhance the thermal efficiency of heat exchangers. ***Dixit et al.* (*2022*)** investigated a compact, 3D-printed heat exchanger featuring gyroid lattice structures. With a high surface-to-volume ratio (670 m^2/m^3) and turbulence-inducing geometry, the heat exchanger achieved a 55 % higher effectiveness while occupying only one-tenth the size of conventional heat exchangers. The gyroid structure was designed using *SolidWorks*™ and manufactured through stereolithography (SLA). The study highlights that additive manufacturing technologies like SLA enable the creation of lightweight, compact, and highly efficient heat exchangers that are unattainable with traditional methods.

These studies collectively underscore that heat exchangers with additively manufactured structures exhibit improved thermal performance compared to conventional designs. Optimization is primarily based on maximizing the surface area A and/or the heat transfer coefficient α. The targeted selection of specific structural geometries has not yet been systematically investigated but is mostly compared to conventional designs. Additionally, there is a lack of comprehensive consideration that accounts not only for manufacturability but also for compatibility with standardized simulation programs.

3 Case study: optimizing heat exchangers through internal structures

This case study follows a systematic approach: Based on a literature review, a design catalog is created, from which a preliminary selection of suitable variants of internal structures is made. These structures are designed using algorithm-aided design to ensure both simulation and manufacturing feasibility. Subsequently, flow simulations are conducted to evaluate and further refine the selection of structures, which are then fabricated in the final step. Finally, specific recommendations for action are derived.

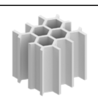
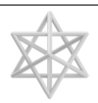
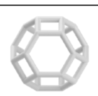
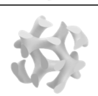
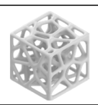
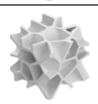
Structure				Main Section			Access Section			
Dimension	Arrangement	Element		#	Example	Figure	Structural	Heat	Biomedical	Objectives and Sources
2D	Periodic	Extrusion	Polygon	1	Honeycomb		x		x	• Enhancement of energy absorption and impact damping (Niu et al., 2022; Xia et al., 2023) • Enhances cell growth and nutrient transport for bone regeneration (Reyes et al., 2022)
3D	Periodic	Strut	Lattice	2	FCC Lattice		x	x	x	• Homogeneous and gradient lattice structures optimize mechanical properties (Khan & Riccio, 2024) • Enhancement of thermal performance while minimizing pressure loss (Lebaal et al., 2022; Sajjad et al., 2022) • Enhancement of the stability and functionality of bone implants through the use of an optimal pore size (Kang et al., 2022; Wang et al., 2023)
3D	Periodic	Strut	Polyhedron	3	Truncated Octahedron			x	x	
3D	Periodic	Mathematical Surface	Thickening	4	Gyroid Surface			x		• Fluid flow within the gyroid structure generates local turbulences that enhance heat transfer (Dixit et al., 2022) • Thin walls increase heat transfer but reduce mechanical stability (Mahmoud et al., 2023) • TPMS structures (Triply Periodic Minimal Surfaces) enhance heat transfer compared to primitive structures (Liang et al., 2023)
3D	Periodic	Mathematical Surface	Separation	5	Gyroid Skeleton			x	x	
3D	Stochastic	Cell	Open-Cell	6	Voronoi Lattice		x	x	x	• Enable flexible porosity and mechanical customization (Castañeda et al., 2023) • The combination of lattice and Voronoi structures optimizes compressive strength and permeability (Han et al., 2024)
3D	Stochastic	Cell	Closed-Cell	7	Voronoi Cells		x	x		

Figure 1. Design catalog for internal structures with classification and application objectives

3.1 Preliminary selection of internal structures based on a design catalog

Additive manufacturing enables the production of internal structures, which can significantly enhance heat transfer efficiency (Wahl et al., 2022). This section presents the preliminary selection of internal structures based on a literature-based design catalog, developed following the methodology based on (Roth, Karlheinz, 2001) and visualized in Figure 1. The catalog classifies structures based on their dimension (2D or 3D), arrangement (Periodic or Stochastic), and element type (Extrusion (Niu et al., 2022; Reyes et al., 2022; Xia et al., 2023), Strut (Kang et al., 2022; Khan & Riccio, 2024; Lebaal et al., 2022; Sajjad et al., 2022; Wang et al., 2023), Mathematical Surface (including Triply Periodic Minimal Surfaces (TPMS)) (Dixit et al., 2022; Liang et al., 2023; Mahmoud et al., 2023) or Cell (Castañeda et al., 2023; Han et al., 2024)). Examples of each structure group are illustrated in the main section, while the access section highlights key objectives and potential applications. The structures are categorized into three primary application areas: structural components, heat transfer, and biomedical engineering. As shown in the catalog, a wide range of structural variations has been applied for heat transfer. From these, three particularly promising structures were selected: “Lattice” and “Polyhedron” from periodic strut structures, as well as “Thickening” from periodic mathematical surface structures.

3.2 Design of internal structures for simulation and manufacturing suitability

While PBF-LB/M enables the production of entirely novel and innovative structures, the tools available in conventional CAD environments are primarily designed for traditional manufacturing methods (Niedermeyer et al., 2024). These tools often reach their limits when creating intricate internal structures, failing to fully exploit the potential of additive manufacturing via PBF-LB/M. Algorithms-Aided Design offers a compelling alternative approach (Müller et al., 2024; Steinnagel et al., 2023; Yao et al., 2024; Zhang et al., 2022).

In this study, *Rhino*® 7, with its integrated *Grasshopper*® visual programming environment, was employed. This tool enables the creation of algorithms specifically tailored to the automated generation of various internal structures. Additionally, its extensive library of third-party plugins enhances functionality to meet specific application requirements. While many existing algorithms and workflows are limited to generating structures as meshes only, this study focuses on creating a closed Boundary Representation (BRep) solid model. This model serves as the foundation for exporting to the universal STEP exchange format, allowing for further processing in external software. Crucially, it ensures compatibility with conventional CFD software and facilitates seamless integration into the specific CFD workflow selected later in this study. To generate the chosen structures, two distinct workflows, illustrated in Figure 2, were employed. These workflows are tailored to address different structure types: mathematically derived surfaces and strut-based designs (Data available at: https://doi.org/10.25835/8eitlrmr).

Strut-based “Lattice” and “Polyhedron” structures are initially created as single unit cells composed of lines using the *IntraLattice* plugin. These unit cells are then arranged in either a rectangular or polar array to conform to the outer pipe geometry. Since the resulting skeleton is not a solid body, the lines must be thickened, which is achieved through two different approaches. The first approach involves thickening the lines with cylindrical elements that are joined by placing spheres at their intersections and using Boolean operations. The second approach employs the “*MultiPipe*” component built into *Grasshopper*® to automatically generate a smooth, continuous subdivision body with integrated joints, which can be seamlessly converted into a BRep body. In contrast, the periodic mathematical structures are created by inputting the corresponding mathematical function into the plugin *Axolotl*, which first generates a volumetric voxel representation. This volume is then converted into a mesh and uniformly thickened to form a sheet. Since BRep bodies are essential for the later employed workflow, the resulting meshes undergo a reconstruction process. This involves quadratic remeshing, subdivision, and final conversion into a BRep format.

For this study, a total of ten structures in various configurations were generated to cover a wide range of design variations. As illustrated in Figure 3, the structures include mathematical surfaces (1–2), struts in a rectangular array with spherical joints (3–6), struts in a polar array with spherical joints (7–8), and struts in a polar array with MultiPipe joints (9–10). All BRep bodies were subsequently combined into a unified geometry for simulation purposes using Boolean operations, with the final assembly enclosed within a pipe body, completing the design. Depending on the structure, the computation time for each script ranges from 2 to 6 minutes, with the majority of the time spent on either the boolean union of individual struts or the quadratic remeshing process and conversion to BRep, respectively.

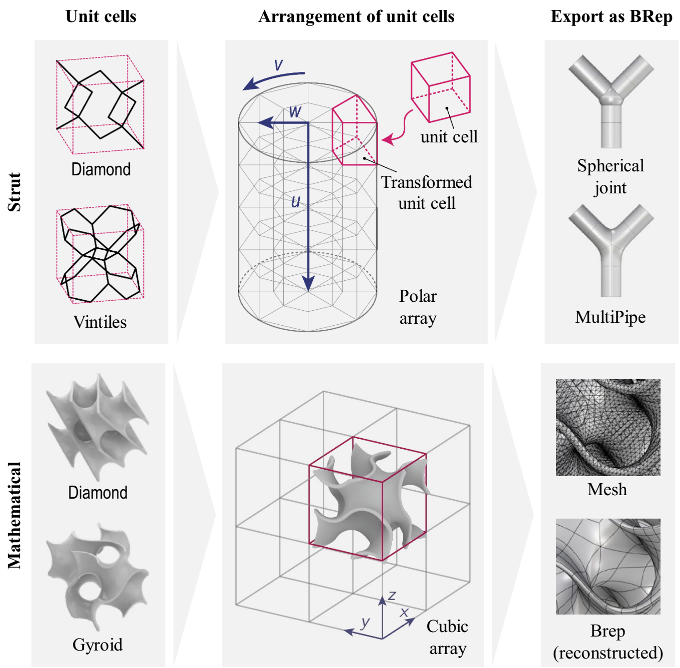


Figure 2. Mathematical and strut-based workflow for generating BRep structures

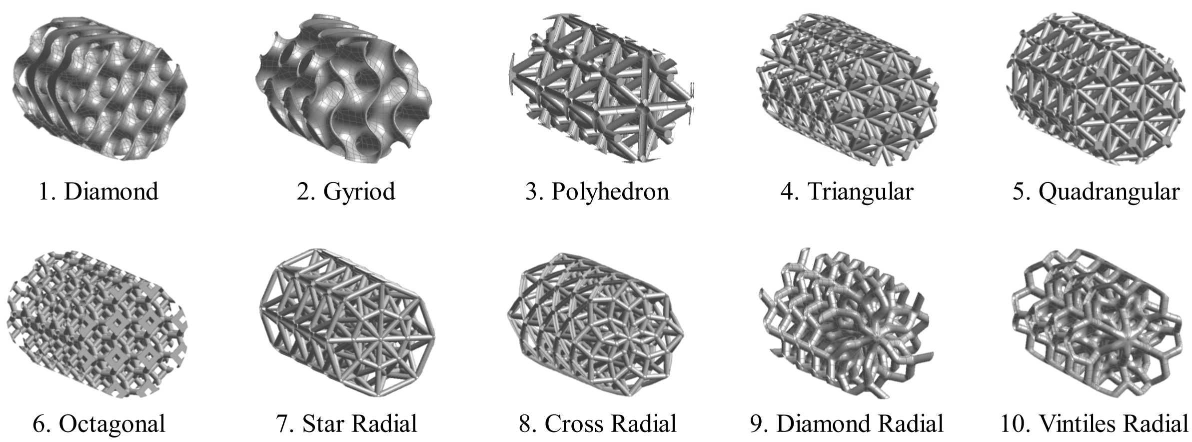


Figure 3. Design of various internal structures for CFD simulation

3.3 Detailed selection of internal structures based on simulation

In this section, a fine selection of the ten structures presented in the previous chapter is made based on CFD simulations in *ANSYS Fluent*®. The boundary conditions of the simulation are defined as cooling of hot air with an inlet velocity $v_{\mathrm{air,in}}$ of 5 m/s and an inlet temperature $T_{\mathrm{air,in}}$ of 700 K, with an outlet pressure $p_{\mathrm{air,out}}$ of 101325 Pa. The heat transfer on the outside of the pipe is modeled as a convective heat transfer coefficient h_{water} of 1200 W/m^{2}K at a free flow temperature $T_{\mathrm{water,free}}$ of 300 K. This corresponds, for example, to a tube in a tube bundle with water flowing around it. To validate the results, a mesh independence analysis was carried out on one of the structures, varying the number of cells (i.e., the mesh resolution) between approximately $3{\cdot}10^6$ and $9{\cdot}10^6$ elements. A suitable number of elements was found to be $5.5{\cdot}10^6$. Further mesh refinement did not result in any change in the transferred heat flux. The settings of this mesh were used for all simulations. The geometry of the simulated tube and resulting temperature and velocity distributions can be seen in Figure 4.

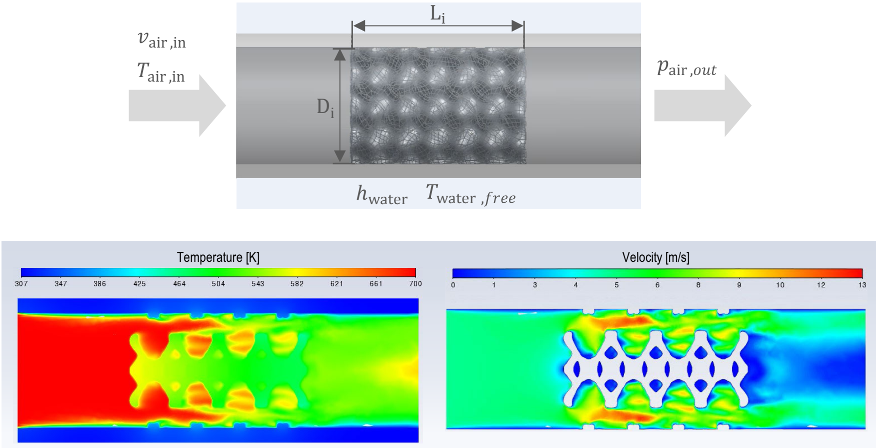


Figure 4. Geometry (Ø25 × 80 mm with D_i = 20 mm und L_i = 30 mm), boundary conditions and exemplary results of diamond radial structure

To evaluate the performance of the structures, the ratio between the resulting heat flow and pressure loss is analyzed using the R-factor (Yilmaz et al., 2005). This factor represents the ratio of the transferred heat flow $\dot{Q}$ and the pump power P_{pump} required to compensate for the pressure loss. A higher R-factor indicates a more efficient heat exchanger.

$$\mathrm{R-factor} = \frac{\dot{Q}}{P_{pump}} \tag{2}$$

Table 1 presents the heat flows transferred within the structured area of the pipe, the pressure losses, and the resulting R-factor for various structures.

Table 1. Surface area, heat flux, pressure drop and R-factor of the simulated structures

Number	Name	Surface area A [m^2]	Heat flux $\dot{Q}$ [W]	Pressure loss Δp [Pa]	R-factor [-]
1	Diamond	0.0082	178.09	131.78	1193.21
2	Gyroid	0.0072	162.60	133.39	1098.33
3	Polyhedron	0.0059	138.78	85.46	1476.26
4	Triangular	0.0097	169.09	157.15	1016.54
5	Quadrangular	0.0076	140.69	107.13	1157.33
6	Octagonal	0.0067	137.68	96.51	1243.91
7	Star Radial	0.0090	150.00	111.05	1213.93
8	Cross Radial	0.0080	147.67	83.59	1567.88
9	Diamond Radial	0.0055	137.16	44.16	2666.74
10	Vintiles Radial	0.0055	136.55	63.66	1830.99

The heat transfer and, in particularly, the pressure loss of the structures differ significantly. The "Diamond" structure (1) achieves the highest heat transfer. In contrast, the centrally oriented "Diamond Radial" structure (9) exhibits the lowest pressure loss. The transferred heat flux of this structure is 23 % lower than the "Diamond" structure, while the pressure loss is 66.5 % lower. Based on these results, the "Diamond Radial" structure can be selected as the optimal choice, as it achieves the highest R-factor and thus offers the greatest potential to enhance the performance of heat exchangers.

3.4 Demonstration of manufacturability: Integration of internal structures into heat exchangers

This section demonstrates the successful manufacturability and integration of internal structures into heat exchangers through practical implementation. For the exemplary demonstration, generated structures were integrated into a double-pipe heat exchanger functioning as a gas cooler using the CAD software *SolidWorks*®. The heat exchanger enables the cooling of a hot gas stream (inner pipe), while cooling water flows through the outer helical jacket and absorbs the heat through the inner pipe wall. The entire heat exchanger (dimensions: Ø46 × 120 mm) is manufacturable using the PBF-LB/M process without the need for additional support structures inside the component. For the fabrication, three exemplary heat exchangers with differently oriented diamond-shaped internal structures were produced from the material 1.2709 maraging steel using an EOS M280 system (laser power: 200 W, scan speed: 1200 mm/s). Figure 5 illustrates the successful fabrication of the design.

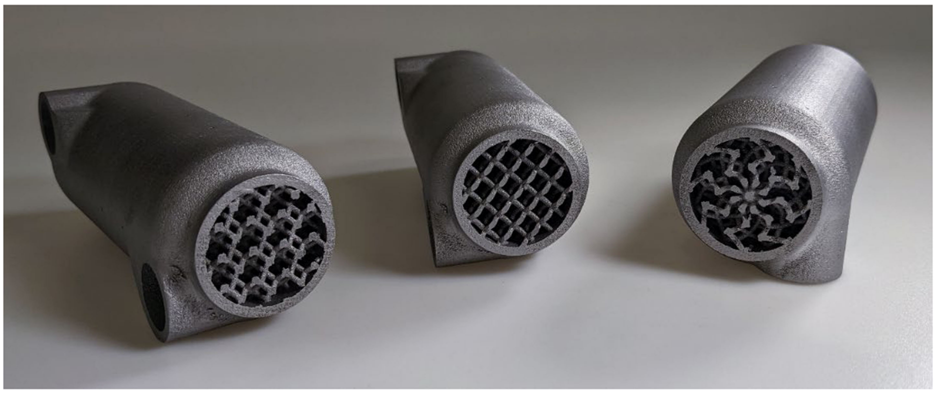


Figure 5. Additively manufactured heat exchangers with different diamond structures

3.5 Derivation of measures and recommendations for action

Algorithms-Aided Design has proven to be a highly promising tool for developing customized workflows for additively manufactured heat exchangers. The methods and workflows employed in this study, including third-party plugins, performed effectively in generating and processing complex geometries. However, the long-term applicability of such approaches depends heavily on the maintenance and support of these third-party tools, introducing a level of risk to future projects. Exporting structures as BRep solids worked well for simulation purposes and manufacturing, but significant challenges were encountered with large data volumes and high computational times in *Grasshopper*® and *Rhino*®, particularly during surface reconstruction. It remains unclear whether the current workflow is scalable to larger full-scale heat exchangers or if there is a practical upper limit to the complexity that can be handled efficiently. The same applies to the analysis with CFD simulations, which become increasingly computationally intensive when applied to complex, complete heat exchanger designs. Despite these limitations, the *Grasshopper*® workflow and associated scripts offer significant potential for future development and customization. For example, the generated structures can be further enhanced by introducing gradation in structure size or by integrating manufacturability considerations into the design process. Such enhancements could include warnings for excessive overhangs, predictions of expected surface roughness, or automated adjustments to improve printability.

4 Summary and outlook

This study focuses on the optimization of heat exchangers through the integration of internal structures enabled by additive manufacturing. A case study demonstrates the successful manufacturing and integration of these structures to enhance thermodynamic efficiency and structural flexibility. Additive manufacturing facilitates the creation of designs with enlarged surface areas for high heat transfer rates, as well as compact and adaptable constructions tailored to various gas and water flow rates. The findings underscore the potential of combining simulation-driven design and additive manufacturing to advance heat exchanger development.

The next step is to experimentally analyze the additively manufactured heat exchangers by measuring their heat transfer and pressure loss characteristics, comparing them with simulated values, and subsequently evaluating the results. This allows for the identification of specific optimization potentials for future designs. Additionally, material variation – such as the use of multi-material components – holds significant potential for making future structures even more efficient and application-specific (Meyer et al., 2023; Meyer, Glitt, et al., 2025; Meyer, Messmann, et al., 2025; Oel et al., 2023). Another promising avenue for research is the use of these structures in hydrogen applications. Topology-optimized and mathematically-defined geometries significantly increase internal surface areas, making them ideal for hydrogen metal hydride storage and gas diffusion layers in polymer electrolyte membrane (PEM) fuel cells (Niblett et al., 2022; Röver et al., 2023). Additively manufactured lattice structures offer superior performance due to their higher surface area and interconnectivity, enhancing hydrogen production and storage (Lei et al., 2019; Mesecke et al., 2025; Ndoye et al., 2021). Finally, comparing additively manufactured lattice structures with conventional designs in terms of their thermal and mechanical properties remains a valuable approach. The presented methods thus offer substantial potential to further optimize existing design and manufacturing processes while setting new standards in the design of internal structures for heat exchangers.

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