Design approach for additive manufacturing employing Constructal Theory for point-to-circle flows

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A B S T R A C T

Design is crucial for additive manufacturing (AM). Not only does it affect manufacturability and cost but more importantly does it determine the functional performance of a part. Design for additive manufacturing (DFAM) methods consider these aspects and aim to leverage the available design freedom in order to generate functionally optimized parts. The following research work presents a method that is based on design principles from the so-called Constructal Theory. Two design principles are selected form this discipline, which considers design a field of science. The first principle outlines how a fluid flow can be distributed efficiently using a tree-shaped structure. The second principle emphasizes to first create the flow structure and then fit the surrounding solid body around it following the flow of mechanical stress. To demonstrate the approach, a case study of a gear wheel design is presented, which integrates cooling lubricant channels and focuses on minimal part mass. Based on analytical relations, a design concept is generated that provides a mass reduction of 25% and a fluid channel structure with minimal required pumping power. The resulting design serves as starting point for a more detailed simulation-based design optimization.

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1. Introduction

Additive manufacturing (AM) makes complex, functionally optimized parts economically viable and allows lightweight designs as well as functional integration. Examples include lightweight lattice structures and fluid channels for cooling, heating or lubrication. Each function corresponds to a certain flow: lightweight designs are governed by a flow of mechanical stress, whereas thermal convection relies on a fluid flow, and heat conduction on a heat flow. In case of mechanical loading, the part also needs to guide a flow of mechanical stress and requires a material structure. A part facilitates all of these flows through its form, more accurately the material distribution and characteristics. Hence, the part geometry itself has a high impact on the performance of the related part function. This interplay between function, flow, and, form is crucial, especially in the context of additive manufacturing. As the design space is vast compared to conventional manufacturing technologies, the question arises: Which form is suitable to fulfill a given function most efficiently? The presented research approach addresses this question using design principles from the so-called Constructal Theory [1–3] for a large functional performance. A methodology is presented suitable for the specific problem of point-to-circle distribution of flows. After reviewing design for additive manufacturing methods in Section 2.1, an introduction to Constructal Theory is given in Section 2.2. The approach is explained in Section 3 and demonstrated in a case study of a gear wheel design in Section 4. The paper concludes with a discussion and validation, a summary, and an outlook.

2. Fundamentals

2.1. Design for AM

Various design for additive manufacturing (DFAM) methods exist that try to leverage the available design freedom, while considering factors such as functional performance, manufacturability, and cost. Methodologies may be categorized into opportunistic and restrictive rules [4]. An overview over several methods is provided in recent reviews [5,6]. Some DFAM methods follow a process-oriented approach [7,8] providing restrictive rules. Others are based on biomimicry and technical biology employing analogies from nature to develop an opportunistic design solution [6,8].
simulation-driven design is created with tools from computer-aided engineering such as a topology optimization [9]. Another approach is to use a visual worksheet to prevent common design mistakes made by novice users [10]. Moreover, design methods are available to ensure and improve manufacturability along the process chain [11,12]. All in all, a DFAM method should be easily accessible providing a quick generation of a first design concept.

2.2. Constructal Theory

From the viewpoint of Constructal Theory [1–3], the emergence of a design is a physical phenomenon that can be predicted in a deterministic manner.

For a given problem a design is derived mathematically. The approach differs from other fields such as biomimicry, in which a design is observed from nature, or from fractal models, where a geometry arises from a repeating pattern. In 1996, Bejan [13,14] proposed this ‘design as science’ approach together with the constructal law. Stated as a first principle of physics, it describes the evolution of flow configurations in time and follows: “For a finite-size system to persist in time, it must evolve in such a way that it provides easier access to the imposed currents that flow through it.” [14] The derived principles are useful to predict the emergence of a design in nature but serve also as construction rules in a technical context to create efficient system and part designs. A summary of problems, which have been studied within the context of Constructal Theory, is provided by a number of reviews [1–3,15,16] and books [17,18].

A widely studied problem is a point-to-circle flow setup [19–23]. As it is depicted in Fig. 1, the task is to distribute a fluid flow from a source S at a circle center to a number of points N lying on the circle with diameter d. Possible solutions are a radial channel system as well as a channel system with bifurcations. The amount of bifurcations following the channel system is defined as the bifurcation level B. In previous research work [19–23] tree-shaped flow structures were derived as an efficient design for point-to-circle flows.

As an example, Fig. 2 shows three channel networks that distribute a mass flow rate \( \dot{m} \) from a source S at the center to a given number of points N on a circle with diameter d. The tree-structures are denoted with (A), (B), and (C) and have a different number of Y-branches, i.e., bifurcations.

3. Constructal design approach

This research work focuses on point-to-circle flows. In order to facilitate both a fluid flow as well as a flow of mechanical stress creating an efficient design regarding minimal required pumping power and part mass, the proposed approach selects the following two principles from the Constructal Theory: distribution of a fluid flow with a tree-shaped structure (see Section 3.1) in combination with fitting the solid body around the fluid flow (see Section 3.2). The principles’ selected mathematical interdependencies and assumptions are explained as a methodological framework. Section 3.3 describes important design criteria for choosing a sufficient design option. Following the methodology minimizes computational effort to basic calculations leading to an efficient and application-oriented design approach.

3.1. Distribution of fluid flow with a tree-shaped structure

Each design is defined through the angles \( (\gamma_i, \psi_i, \phi_i) \) at every bifurcation and the diameter \( D_e \) of each pipe segment with index \( e \) (see Fig. 2). The required pumping power \( W \) can be minimized under a constrained volume \( V \) of the pipe network [21,22]. In case of laminar flow, the relation between the optimal channel diameter \( D_o \) and the mass flow rate \( \dot{m} \) through channel \( e \) follows \( D_e \sim \dot{m}_e^{1/3} \). If the flow splits equally at a branching, the relation between the diameter \( D_1 \) of the dividing branch with flow rate \( \dot{m}_1 \) and the diameter \( D_2 \) of the two resulting sub-branches with flow rate \( \dot{m}_2 = \frac{1}{2} \dot{m}_1 \) is therefore \( D_1/D_2 = 2^{1/3} \) [21,22]. For turbulent flow in rough channels the corresponding expressions are \( D_e \sim \dot{m}_e^{1/7} \) and \( D_1/D_2 = 2^{1/7} \) [21,22]. Regarding the angles at each bifurcation, it is shown that

![Fig. 1](image1.png)

![Fig. 2](image2.png)
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