Improving Sustainability in the Building Industry using Biomimetics and Additive Manufacturing

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Abstract (english)

A large part of the global energy consumption and energy-related CO_2 emissions can be attributed to the construction and usage phase of buildings. As one of the largest energy consumers and CO_2 emitters, this industry holds promising potential to contribute to the reduction of global resource consumption and climate-harming emissions through more sustainable construction processes and energy-efficient building techniques.

As the interface between the building interior and the environment, the building envelope significantly influences a building's energy consumption. However, metallic components such as supports and connecting elements of facade systems in the insulation layer create thermal bridges, reducing the energy efficiency of the facade.

Besides the structural and mechanical optimization of components, primarily aimed at increasing material efficiency and reducing resource consumption during manufacturing, the thermal bridge potential of a component can also be influenced by its geometry. Both aspects can lead to opposing optimization goals.

Since biological organisms are usually exposed to various requirements, they are often suitable as model organisms in multi-criteria product development. However, biomimetic solutions often consist of complex geometries that can only be manufactured using additive manufacturing processes. Additive manufacturing enables the cost-effective production of complex component geometries, thus opening up new possibilities for component design and optimization.

Therefore, combining biomimetic design principles with additive manufacturing offers great potential for developing material-efficient and

building physics optimized components for more resource- and energy-efficient buildings.

Abstract (deutsch)

Ein Großteil des weltweiten Energieverbrauchs und der energiebezogenen CO_2-Emissionen sind auf die Bau- und Nutzungsphase von Gebäuden zurückzuführen. Als einer der größten Energieverbraucher und CO_2-Emittenten verfügt diese Industrie über ein vielversprechendes Potential durch nachhaltigere Bauprozesse und energieeffizientere Bauweisen zur Reduzierung des globalen Ressourcenverbrauchs und klimaschädlicher Emissionen beizutragen.

Als Schnittstelle zwischen dem Gebäudeinneren und der Umwelt hat die Gebäudehülle einen maßgeblichen Einfluss auf den Energieverbrauch eines Gebäudes. Metallische Bauteile wie Halter und Verbindungselemente von Fassadensystemen in der Dämmebene führen jedoch zu Wärmebrücken und vermindern so die energetische Effizienz der Fassade.

Neben der strukturmechanischen Optimierung von Bauteilen, welche in erster Linie eine erhöhte Materialeffizienz zum Ziel hat und so zu einem geringeren Ressourcenverbrauch in der Herstellung führt, kann auch das Wärmebrückenpotential eines Bauteils durch dessen Geometrie beeinflusst werden. Beide Aspekte können jedoch zu gegenläufigen Optimierungszielen führen.

Da biologische Organismen in der Regel verschiedenen Anforderungen ausgesetzt sind, sind diese zumeist geeignet, um als Vorbilder in der multikriteriellen Produktentwicklung zu dienen. Bionische Lösungen bestehen jedoch häufig aus komplexen Geometrien, welche nur mithilfe additiver Fertigungsverfahren hergestellt werden können. Die additive Fertigung ermöglicht die wirtschaftliche Herstellung komplexer Bauteilgeometrien und eröffnet dadurch neue Möglichkeiten zur Bauteilgestaltung und -optimierung.

Die Kombination bionischer Konstruktionsprinzipien mit der additiven Fertigung bietet daher ein großes Potential für die Entwicklung materialeffizienter und bauphysikalisch optimierte Komponenten für ressourcen- und energieeffizientere Gebäude.

Introduction

A significant portion of global energy consumption and energy-related CO_2 emissions can be attributed to the construction and operational phases of buildings (Allouhi et al. 2015). According to the 2020 Global Status Report for Buildings and Construction by the UN Environment Programme, this accounts for nearly 40% of energy-related CO_2 emissions and approximately 35% of global energy consumption (UNEP 2020). As one of the largest energy consumers and CO_2-emitters, the construction industry holds promising potential to make a significant contribution to reducing global resource consumption and climate-harming emissions through sustainable manufacturing and construction processes as well as energy-efficient building designs.

Facades

The building envelope plays a crucial role in the energy balance of a building during its operational phase. Serving as the interface between the indoor environment and the external surroundings, it is responsible for heat loss and gain, which in turn influence the sizing of heating and cooling systems and the resulting energy consumption (Knaack et al. 2007).

Systemized facades are predominantly employed in the construction industry, incorporating a range of standardized elements. These standardized solutions facilitate meeting the increasing technical requirements for facades, which demand sophisticated methods for successful execution. In addition to simplifying the design process, they enhance process control by providing a greater predictability (Knaack et al. 2007).

A frequently used facade system is the ventilated facade or rainscreen facade. As illustrated in Figure 1, it comprises an inner wall, insulation, an air cavity and an outer cladding. The cladding shields the building, while the air cavity promotes ventilation and prevents moisture buildup. Insulation enhances thermal performance, and the inner wall provides support. To mount such a facade system, (metal) facade brackets are used (FVHF 2018). To achieve good mechanical integrity, these usually penetrate the insulation layer.

Thermal bridges

However, metallic components such as brackets and connectors that penetrate the insulation layer of facade systems lead to thermal bridges, thereby reducing the energy efficiency of the facade. These components usually result in point thermal bridges, which are included in the design value of the thermal transmittance (U-value) via the point-related thermal transmittance and the necessary number of brackets to be installed per area of the facade (DIN EN ISO 10211:2017).

Optimizing facade brackets is a promising measure to decrease the CO_2 emissions of a building. This can include thermal optimization to reduce the thermal bridge effect and reduce the CO_2 emissions during the use phase of the building, or structural optimization to increase the material efficiency and therefore reduce the necessary amount of material used for the component and the corresponding CO_2 emissions for material processing.

Structural optimization for material efficiency and thermal optimization for a low effective heat conduction can have opposing effects on the part geometry. Structural optimization (e.g. topology optimization) leads to an optimized material distribution within the allowed design space of a part, assigning material only where it is necessary to fulfil the structural requirements (Bendsoe und Sigmund 2004). This results in parts in which the material is usually closely distributed along the main load paths. In contrast, a component optimized with the goal of a low effective thermal conductivity would consist of a rather filigree, porous structure with air inclusions (Pfundstein et al. 2008). Components with such multi-criteria requirements often lead to challenges in product development.

Multi-criteria product development using biomimetics

Using biomimetic design strategies for multi-criteria product development seems to be especially advantageous in such cases. Since organisms in nature compete for available energy resources and must synthesize all needed material with its own metabolic power, evolution fostered energy efficient construction principles that use less energy, less mass and are more durable. However, besides the need for energy efficiency, biological organisms are often exposed to different other requirements depending on their predators and the environment they live in. Since their survival depend on a successful strategy, their structure is inherently designed for

multifunctionality. The similarities of many not closely related species are based on convergent evolution, which means that if a different species faces a new challenge, e.g. colonization of new habitats, successful survival strategies need to be independently re-invented every time, which can lead to different sufficient solutions for similar problems (Wawers 2022; Klein 2013).

Biomimetic design approaches can demand greater efforts compared to established and widely recognized conventional design methods. However, biomimetic designs often exhibit a high degree of innovation (Gralow et al. 2020). Gralow et al. (2020) therefore suggest that biomimetic design approaches are particularly beneficial when conventional methods have not led to sufficient solutions, when there are no other available design tools or initial design ideas for a new design problem, or for complex problems with multi-criteria requirements. The last aspect applies for the redesign of a facade bracket considering sustainability goals.

Biomimetics and additive manufacturing for more sustainable facades

Biological lightweight structures often consist of complex geometries, e.g. the selective use of cavities, lattices and cellular structures (which have an excellent strength to weight ratio) as well as functional growth and adaptation, which often result in complex freeform shapes (Degischer und Lüftl 2009). This can be demonstrated with biological model organisms like the toucan beak, trabecular bone (both consist of a solid and compact outer shell filled with a lattice-like structure), diatom shells and deep-sea glass sponges (Seki et al. 2005; Degischer und Lüftl 2009; Hamm et al. 2003; Fernandes et al. 2021). This high degree of complexity means that such structures are (nearly) impossible to produce using conventional manufacturing technologies because of the associated manufacturing constraints. Additive manufacturing has less manufacturing restrictions regarding component complexity and enables the cost-effective production of sophisticated geometries, opening up new possibilities for component design and optimization, incorporating biomimetic design principles. The most used metal-based additive manufacturing process is laser powder bed fusion (PBF-LB/M) in which metal powder is selectively melted by a laser layer by layer resulting in the required part. Due to the layerwise process and the complete melting of the metal powder, almost fully dense parts (≥

99.5% relative density) can be produced as end products (Gibson et al. 2015; Gebhardt et al. 2019).

Biological principles for thermal insulation often include mechanisms that are based on air inclusions (e.g. realized with with hairy structures, fur, or plumage), besides other anatomical and behavioral adaptation (Gosztonyi 2022; McCafferty et al. 2013).

The identification of biological principles for insulation that mainly rely on geometrical features and that are potentially suitable to serve as inspiration for facade components with a reduced thermal bridge effect is not a research subject in the existing literature, but is one main goal of ongoing research activities within the BMWK-funded AddMamBa project.

Geometrical principles for insulation or restricted thermal conductivity can be classified using the effective thermal conduction. In fractal tree-like branched networks, the effective thermal heat conductivity is always lower than that of a single channel (Xu et al. 2006). This suggests that filigree structures are inherently suitable for structures with the purpose of a low heat conduction. This includes filigree lattice or cell-based structures as a promising construction principle (representing a type of network-like structures and, if designed with a high degree of filigree character, possibly enclosing air and restricting air movement resulting in very less heat convection) and matches with the main characteristics of a lot of biological model organisms for lightweight structures. Examples are illustrated in Figure 1. This makes such structures potentially well-suited for the application in facade brackets penetrating the insulation layer of a facade to effectively reduce the thermal bridge effect of those connecting components. Detailed research on the feasibility and suitability of the described and other biomimetic solutions (yet to be identified), is subject of current activities within the AddMamBa-Project.

Once understood and abstracted, biological principles that have a certain regularity or periodicity can be implemented as parametric CAD-models to easily obtain variant flexible designs that are adapted to the respective requirements. For facade brackets, this can be the case for buildings in regions with differing conditions or for freeform facades which need brackets with individualized geometries.

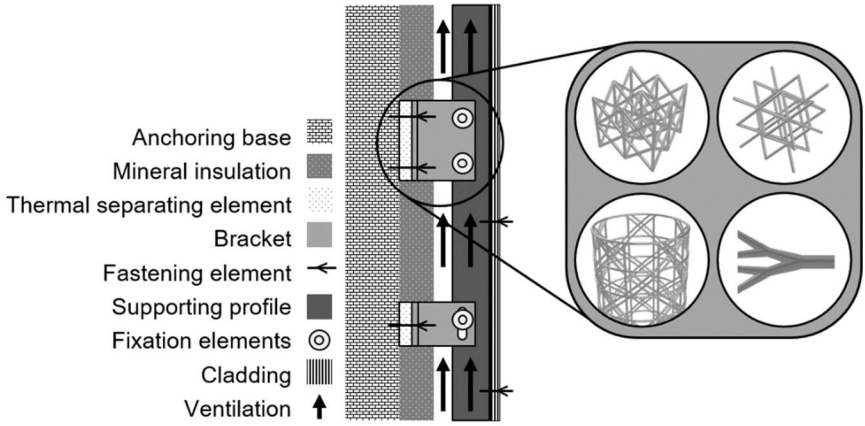


Figure 1: Structure of a ventilated facade and first biomimetic concepts for optimizing the material efficiency and building physics properties of brackets. These include the use of various lattice structures, e.g. based on the deep-sea glass sponge (Euplectella aspergillum), and tree-like branching. The schematic illustration of the facade is based on (FVHF 2018).

Conclusion

The combination of biomimetic principles and additive manufacturing enables the economic realization of improved and more sustainable building components. The use of biomimetic component designs offers great potential for more resource and energy efficient buildings by reducing the amount of material needed for single components and by improving the building physics related component properties. The additive manufacturing technology enables the economic production of the resulting intricate component designs. The combination of both offers a high potential for innovation.

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