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ABSTRACT

Biomimetics as well as additive manufacturing have prominently produced novel design approaches for parts and products independently from each other. The combination of both has resulted in numerous innovative part designs that were unseen before. However remarkable the marketing impact of individual 3D printed biomimetic parts has been, a widespread industrial application is missing to date. This publication, therefore, takes a closer look at how biomimetic design in additive manufacturing is currently pursued and evaluates the different design approaches based on their suitability for industrial application. The assessment reveals that algorithms and thesaurus tools should be preferred in an industrial biomimetic design process. From the various additive manufacturing methods, laser additive manufacturing today is a dominating industrial application when it comes to metal parts. Thus, several case studies of biomimetic designs produced with laser additive manufacturing are presented. On the basis of the selected examples, the added value through biomimetic design is discussed and reviewed critically, raising the question of when a biomimetic design approach is promising compared to conventional design approaches. Based on the review of current use cases and the potentials that the combination of biomimetics and additive manufacturing offer, recommended fields of research are concluded. Finally, the road to industry for biomimetic additive manufacturing design is outlined, taking into account the findings on existing biomimetic design methodologies and tools.

Key words: biomimetic design, laser additive manufacturing, 3D printing

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I. INTRODUCTION

A. Biomimetics: Definition and motivation

1. Definition

Multiple terms, e.g., biomimicry, bionic, bio-inspired, and more, have been coined with regard to taking nature as a role model for technical applications. Although even among the biomimetic community the exact definitions and terminology are still highly discussed,^{1,2} the recently developed ISO standard³ gives a good orientation and shall, therefore, serve as a definition in this publication to set a common ground: *biomimetics* is an interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution.

2. Motivation

Biology offers countless examples to be considered as inspiration during product development or for complex design problems. Approaching and transferring nature's ideas in a structured way is the core task of biomimetics and was standardized in ISO 18458:2015.³ The biomimetic development process is not simple and is ideally supervised by experts in the field. When applied correctly, it has the potential to “lead to a better design faster” and to support the generation of creative new ideas that remain untapped when applying conventional development methods.⁴ The purpose of applying biomimetics lies in the “intended emulation of nature life solutions for solving contemporary challenges. It is based on viewing 3.8 billion years of evolution as a ‘design lab’ and observing its results.”² The efficient use of materials and energy, high tolerances, adaptability, self-regulating capabilities, as well as the

precision and diversity of natural systems⁵ represent only some advantages of natural designs that motivate to take those systems as a role model in order to innovate technical applications.

In addition, nature serves as a model, mentor, and measure for promoting sustainable innovation designs;⁶ however, not all biomimetic products and inventions will automatically be sustainable.⁷ Biomimetic designs offer material-efficient lightweight structures that are interesting use cases for additive manufacturing (AM). These structures often feature complex geometries (e.g., lattice or cell structures), making biomimetic designs hard or even impossible to produce, taking into account the boundaries of conventional manufacturing technologies. With AM, this limitation can be overcome because “complexity comes for free” with this technology.⁸ Furthermore, it offers not only the possibility for complex shapes, but also the realization of material, hierarchical, and functional complexities.⁹ Biomimetics can be the engine of ideas for new technological inventions precisely because the principles of shape, material, hierarchical, and functional complexities as well as their combination can be found in nature in many ways.⁷

B. Laser additive manufacturing technologies

Many experts see AM as one key enabling technology for flexible and digital production that comes along with the industry 4.0 movement.^{8,10,11} The rising interest in AM technologies becomes clear by looking at the continued double digit growth rates of the AM market and the fact that AM is the fastest growing sector of manufacturing at the moment.¹² Most of the applications of AM can be found in aerospace, medical, automotive, tooling, as well as machine building industries.^{8,12,13} More than 80% of turnover is achieved with printing of polymers, but the share of metal printing is increasing.¹² The dynamic development of the AM market has led to the invention of many new AM technologies from which approximately ten can be seen as relevant for the industry.¹⁴ Lasers play a crucial role in these technologies, especially for metals, where the selective laser melting [SLM, also referred to as laser beam melting (LBM)] process is the most commonly used process.^{8,12}

Reasons for the high importance of lasers in AM are their potential to process various different materials with high precision. This offers the possibility to manufacture highly complex parts with a high level of detail and very good mechanical properties.⁸ Table I gives an overview of the most important laser additive manufacturing (LAM) technologies for metals and polymers.

Foundation for the rapid growth of the AM market are the numerous benefits that AM technologies show over conventional manufacturing technologies such as fewer design restrictions, tool-less manufacturing, low material waste, and the fact that they are comparably easy to automate due to the layer-wise manufacturing principle.^{8,19}

In addition to the high design freedom, the circumstance that the complexity of a part does not substantially add to the part costs is one of the main reasons why AM and biomimetic design make a good match.^{10,20} While it is long known that biomimetic design offers great potential for functional integration and weight saving, the complexity of the designs hindered a broad application due to high part costs that come along with conventional manufacturing technologies.¹⁰ One additional relation between LAM and

biomimetics is the circumstance that multimaterial design is a typical “design principle” in nature and some LAM processes are capable of manufacturing multimaterial parts within one step.^{8,21,22}

C. Design for additive manufacturing

Although AM technologies are known to offer a high degree of design freedom, they still possess a number of manufacturing restrictions that need to be taken into account. Furthermore, even if it is possible to manufacture a certain design by AM, the design of the part might still influence processing time and costs. Therefore, specific design guidelines have been developed over the last couple of years with the aim to enable design for AM.^{23–25} Manufacturing restrictions have their origin from different sources, such as the AM machine used, the process principle, material properties, as well as interactions among these sources. Table II gives an overview of important manufacturing restrictions in AM, in addition to addressing potential limitations when using AM to manufacture biomimetic structures.

The overall part size in general is limited by the AM machine's build envelope. Directed energy deposition (DED) processes are mostly flexible in this respect, and the process equipment may be mounted on a robot or gantry system with the desired build space. Wire-based systems are believed to offer the highest robustness when pushing part size limits.²⁹ Powder bed fusion (PBF) processes are more restricted, with powder bed dimensions for LBM typically in the area of 50×50 to 800×400 mm²³⁰ with larger systems under development with up to 1×1 m².³¹

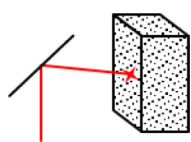
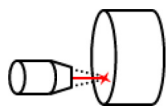
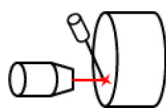
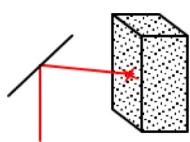
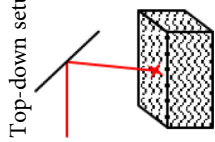
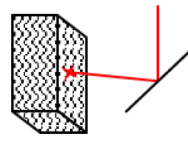
AM processes are also limited in their ability to produce small scale features. When walls or bonelike structures are considered, a minimum wall or strut thickness needs to be respected. The strength and stiffness of each feature need to be high enough to withstand the forces occurring during the process. These typically result from thermally induced stresses (DED, LBM) but may also result from the interaction with the recoater movement (PBF).²³ For DED, they are also regularly a result of the laser and powder focal size or wire diameter. Minimum wall thicknesses in LBM are material dependent but typically in the range of $>400 \mu\text{m}$,²³ while in DED higher wall thicknesses of typically $\gg 1$ mm are needed.^{25,32}

The surface of AM parts in the as-built condition, i.e., without further processing, is typically rather rough compared to conventional manufacturing. While material dependent, DED processes will typically produce a roughness in the range of $R_a = 20 \dots 40 \mu\text{m}$ (LMD, Ti-6Al-4V),³² while PBF will feature a lower roughness of $R_a = 3 \dots 32 \mu\text{m}$ (LBM, Ti-6Al-4V).²³

In biomimetics, this means that surface patterns in the nano- or micrometer range cannot be produced inherently and need to be applied by suitable postprocessing. Additionally, it is also necessary to keep in mind that any surface needing (mechanical) posttreatment will need to persist accessible.²³ This aspect is also relevant for processes with the need of support structures (e.g., LBM). The accessibility for postprocessing will be needed for all surfaces that are touched by supports.

Specifically with PBF processes, powder may be trapped inside enclosed structures such as honeycombs and cells. While the remaining powder is not necessarily detrimental to the mechanical performance of the part, it is usually desirable to remove the

TABLE I. Overview of laser additive manufacturing technologies for metals and polymers (Refs. 8, 12, and 15–18).

	Laser beam melting (LBM)			Laser metal deposition (LMD)		Laser wire-based AM (LWAM)	
Metal	ISO/ASTM Process notation	Powder bed fusion (PBF)	Thin layer of metal powder applied by a recoater. Powder is fused by laser beam. Build platform lowered by one layer thickness	Directed energy deposition (DED)	Metal powder is blown/wire deposited on the substrate. Laser melts and fuses blown powder on the substrate/part.	Directed energy deposition (DED)	Wire deposited on the substrate/part. Laser melts and fuses wire on the substrate/part.
	Accuracy (typical) Surface finish Max. part size	 0.1–0.3 mm 2–15 μm Ra Up to $950 \times 810 \times 300 \text{ mm}^3$		 0.2–1 mm 10–25 μm Ra Up to $4,000 \times 2,000 \times 750 \text{ mm}^3$		 0.2–2 mm 10–20 μm Ra >1 m ³ ; depends on robot/portal system >200 cm ³ /h	
	Build rate Materials ^a	2–100 cm ³ /h Steel (304L, 316L, 17–4PH, 18-Ni300, H13), cobalt–chrome, aluminum (AlSi12, AlSi10Mg), nickel alloy (IN625, IN718), titanium (cp-Ti, Ti-6Al-4V), precious metals, and bronze		10–200 cm ³ /h Steel (316L, H13), carbides embedded in metallic matrices, aluminum alloys (AlSi12, AlSi10Mg), titanium alloys (Ti-6Al-4V, TiAl), nickel alloys (IN625, IN718), copper alloys, and cobalt alloys		Steel (316L, H13), nickel-based alloys (IN625, IN718), cobalt alloys, and titanium alloys (Ti-6Al-4V)	
	Special aspects for Biomimetic Design	High complexity and details possible		Suitable for multimaterial processing		Suitable for multimaterial processing	
		Selective laser sintering (SLS)		Stereolithography (SL)			
Polymer	ISO/ASTM Process notation Manufacturing principle	Powder bed fusion (PBF)	Thin layer of polymer powder applied by a recoater. Powder bed is preheated by IR. Powder is fused by a laser beam. Build platform lowered by one layer thickness	VAT Photopolymerization	Top-down setup	Spatially controlled solidification of a liquid resin by photopolymerization. UV radiation is used for illumination and guided by a scanner to solidify a thin layer. Alternatively, a digital mirror device may be used to illuminate a 2D pixel pattern in the resin (also: Digital Light Projection). Platform moves solidified layers downward (top-down setup, left), or alternatively, light is guided through a transparent plate from the bottom, and the platform moves the solidified layers upward (bottom-up setup, right)	Bottom-up setup
	Accuracy (typical) Surface finish Max. part size Build rate Materials ^a	 0.2–0.4 mm 10–20 μm Ra Up to $700 \times 380 \times 380 \text{ mm}^3$ Up to 1,000 cm ³ /h possible HDPE, HTPA, PA6, PA66, PA11, PA12, PBT, PEK, PEEK, POM, PP, PS, and TPU		 0.05–0.2 mm 1–5 μm Ra Up to $2,100 \times 700 \times 800 \text{ mm}^3$ Up to 100 cm ³ /h Photopolymers			
	Special aspects for Biomimetic Design	High complexity possible		High level of details and good surface quality possible			

^aNonexhaustive list of typical materials used in the respective processes.

TABLE II. Manufacturing restrictions in AM and their potential limitations in biomimetic applications.



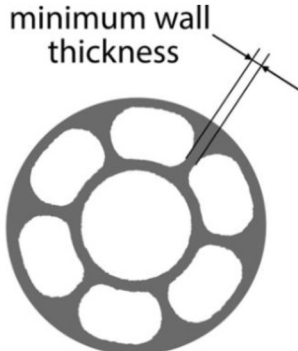
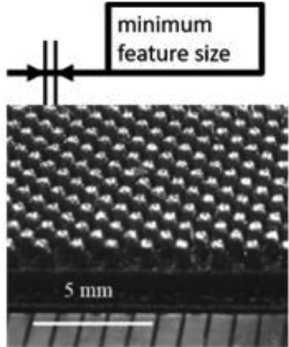
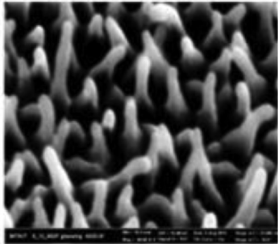
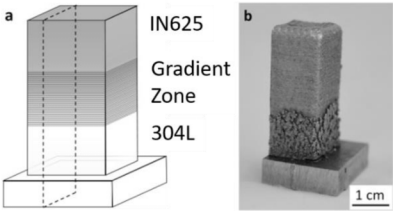

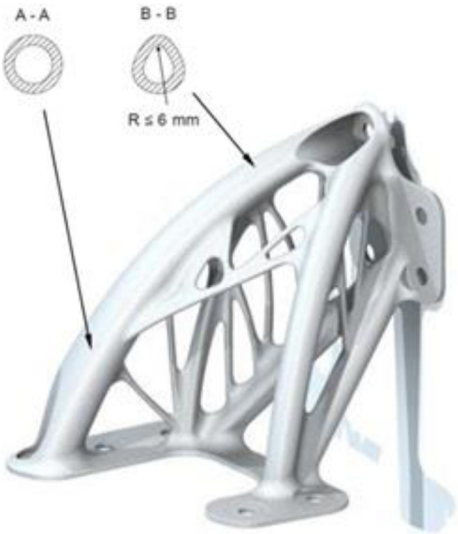
Restriction	Origin and description	AM processes affected	Relevance for biomimetic structures
Maximum size	 <p>Reproduced with permission from Airbus. Copyright Airbus.</p>	<p>AM machine or system</p> <p>The maximum size of the part is generally determined by the build envelope of the machine</p>	<p>LBM, SLS, SL: limited to $<1.5 \text{ m}^3$</p> <p>LMD and LWAM scalable with the positioning system</p> <p>Large structures will still need to be manufactured in several parts and joined together</p>
Minimum wall thickness	 	<p>AM process</p> <p>thermal stresses, stability against deformation</p>	<p>All;</p> <p>typical values: LBM, SL $>100 \mu\text{m}$, SLS $>300 \mu\text{m}$, LMD, LWAM $>1 \text{ mm}$</p> <p>Identified structure not fully scalable</p>
Minimum feature size	 <p>5 mm</p> <p>Example of $\varnothing 400 \mu\text{m}$ pins made by micro SLM</p>  <p>Example of $\varnothing 100 \text{ nm}$ pins on a butterfly wing</p> <p>Left: Reproduced with permission from I. Yadroitsev and P. Bertrand, Proc. of the 21st Int DAAAM Symposium 21, 1 (2010). Copyright DAAAM International 2010. [30] Right: Reproduced with permission from KIT Copyright KIT. [31]</p>	<p>AM machine and powder</p> <p>limited resolution due to powder grain size, layer thickness and focal spot size</p>	<p>All;</p> <p>specific μSLM machines available with feature size down to $1 \dots 10 \mu\text{m}$ but at limited part size in the range of a few cm^3</p> <p>Multiscale structures may be limited</p> <p>Surface patterns and effects cannot be manufactured directly in the AM process</p>

TABLE II. (Continued.)

Restriction		Origin and description	AM processes affected	Relevance for biomimetic structures
Multimaterial	<p>Multi-Material capabilities of LMD</p>  <p>Reprinted from Acta Materialia, 108, B.E.Carroll, R.A. Otis, J.P. Borgonia, J. Suh, R.P. Dillon, A.A.Shapiro, D.C. Hofmann, Z.L. Liu and A.M. Beese, Functionally graded material of 304L stainless steel and Inconel 625 fabricated by directed energy deposition: Characterization and thermodynamic modeling, 46-54, copyright (2016), with permission from Elsevier. [32]</p>	<p>AM process</p> <p>local deposition of several materials needed but not standard in PBF processes</p> <p>multimaterial processing requires compatibility of materials</p>	<p>All;</p> <p>PBF: no commercial systems with multimaterial capabilities available</p> <p>DED: material may be changed at any location, gradient zone necessary</p>	<p>Multimaterial structures are today hardly possible but under development</p>
Powder removal		<p>Geometrical features</p> <p>Powder may be enclosed in structures</p>	<p>PBF processes</p>	<p>Enclosed structures need design modification in terms of a powder outlet</p>
Accessibility for postprocessing		<p>Accuracy and tolerances of the process; need for supports</p> <p>Postprocessing is typically needed to improve surface quality and remove supports</p>	<p>All;</p> <p>LBM surface roughness typically $R_a = 10 \dots 40 \mu\text{m}$</p>	<p>Hollow structures may not be accessible and postprocessing is limited in these areas</p>

powder to reduce the weight of the component. It is, therefore, recommended to avoid such enclosed structures and integrate powder outlets of diameter >3 mm in the design stage.²³

While the materials qualified for AM processes continuously increase, they are typically still limited to the use of a single material per build, i.e., multimaterial approaches are hardly available but under development. DED offers the capability to change the feed material at any location and thus offers multimaterial capabilities for certain material combinations (e.g., steels and nickel-based alloys²⁸). In PBF, the material could in principle be changed at a certain layer.³³ If further design freedom is needed, significant modifications to the process and equipment are unavoidable.³⁴ In any case, multimaterial approaches today are typically restricted to a class of similar materials (e.g., metal alloys). In biomimetics, this significantly limits the manufacturability of structures, which use different materials at locations to alter local properties, which are often found in nature (e.g., structures made of hard and soft materials of a fish scale³⁵). In PBF, local variation of properties may still be achieved by functionally graded structures that vary, e.g., in density or microstructure.³⁶ This is an approach known from nature as well, e.g., in bone structures adapting to loading conditions.³⁷ Here, the high resolution and precision of PBF gives an advantage in manufacturing cellular structures and lattices with small features.³⁸

In summary, manufacturing restrictions of different AM technologies will significantly affect their ability to produce individual biomimetic structures. It is, therefore, recommended to keep this in mind during the entire design process and select the suitable AM process accordingly.

II. BIOMIMETIC DESIGN APPROACHES

In Secs. II A and II B, biomimetic design approaches (BDAs) have been collected. In general, BDAs can be divided into problem-driven and solution-driven types, depending on whether they start with the biological model as initial inspiration or with a detailed engineering problem that is followed by a search for appropriate biological models.³⁹ Since the dominating use case in industrial engineering starts with a distinct engineering problem, search results were narrowed down to problem-driven approaches only. Further, these approaches were subdivided into two categories according to their type: *Design methodologies* and *tools*.

Design methodologies are defined as a collection of tools that in total describe and/or support the entire process of biomimetic design starting from the technical problem definition and ending

with a proposed biomimetic concept design. For design methodologies that in theory meet this criterion but are predominantly centered on one specific tool, it has been decided to categorize the tool only and focus evaluation on the tool itself.

Tools as defined in this publication can be databases, catalogs, digital tools, entire software programs, or paper-based tools—generally speaking, a means to support one or more steps in the biomimetic design process. They have been subdivided according to their type in order to allow a comparison of tool types and their suitability for application in the industry.

The overall biomimetic design process has not yet been standardized when it comes to its single steps; however, first publications that make an effort to find a common step series describing the process are available, e.g., the eight steps shown in Fig. 1.⁴⁰

A. Design methodologies

Over the last two decades, several holistic methodologies have been developed aiming at describing and guiding through the biomimetic design process. Only methodologies that meet the criteria of covering the entire biomimetic process starting with the problem definition and ending with a concept design have been considered. In total, seven holistic biomimetic methodologies (Refs. 41–46 and 2) could be identified from the literature and are briefly described in Table III.

B. Tools

A variety of tools have been developed over time to support users with the tasks along the biomimetic design process. A comprehensive overview over existing tools and databases supporting the individual steps is given by Wanieck *et al.*⁴⁰ Since their list of tools only contains tools supporting the development process in general, for the purpose of this paper it was extended by design-specific tools, which are especially interesting for AM. The optimization tool OptiStruct by Altair (as of August 2019) was added, as a representative for commercially used topology optimization tools, which in the context of AM can be used to their full potential. A database developed by Emmelmann *et al.*,⁴⁸ which supports users with the implementation of biomimetic features into new design concepts, was also added.

For AM, the tools are most useful regarding the search for biological templates and the understanding of structure–function

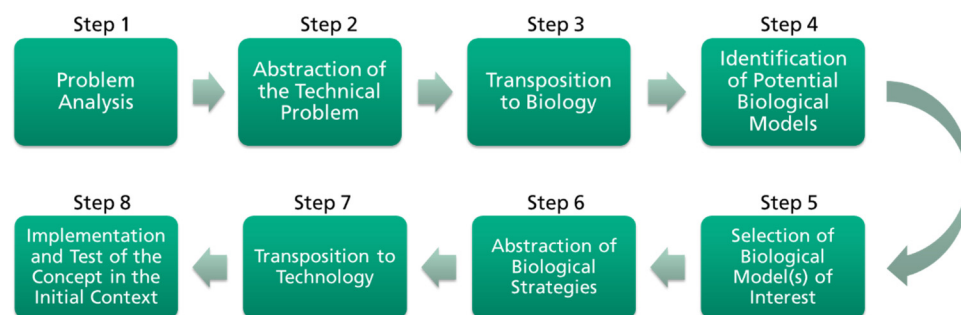


FIG. 1. Biomimetic design process steps as defined by Wanieck *et al.* (Ref. 40).

TABLE III. Identified holistic biomimetic design methodologies and their characteristics.

Methodology	General procedure	Reference
Biomimetic process model	Starting point is the formulation of search terms for a specific problem on an abstract level. ⁴⁷ Next steps include the matching of adequate biological role models, the analysis of their underlying principles, and a check whether these principles can be transferred. A list of 177 technical functions and their related functions and terminologies within biology has been established to support the task.	41
Problem-driven biologically inspired design process	Reframing the search phrases with biological terms is the first step. Four described search techniques based on heuristics help the engineer with the task of finding appropriate biological models. Once biological systems have been identified and understood, the underlying principles are broken down to their key elements and rephrased as neutrally as possible to allow a proper transfer to the “engineering world.”	42
Procedural model for biomimetic design	The model by Lenau and colleagues introduces several feedback loops between steps in order to refine each step further. By showcasing a use case and including practical tips, e.g., which search engines or databases to use, how to formulate search terms etc. offers a little more guidance for individual steps.	43
Eco-innovation by ARIZ and biomimetics concepts	An algorithm for inventive problem solving (Russian acronym: ARIZ) is integrated and offers tools to follow through the design process. Again, a function based problem definition is utilized. The matching of the defined problem to the biological systems and their intrinsic solution is being performed through the formulation of conflicts and suggested strategies to solve these. This is based on the idea that any technical problem can be described by a pair of two conflicting targets.	44
Problem-solving methodology for BID	Tools are introduced in order to make previous knowledge in the biological field obsolete when pursuing biomimetic design, which is highly preferable in an engineering environment. For example: a standardized set of function-related terminology and a correlation matrix help reframing the technical problem with biological terms and the transfer of the principles to a technical product design.	45
BioGen	The methodology revolves around the idea that in nature multiple organisms independently arrive at similar presumably favorable solutions to fulfill a certain function. The principles that initiate the later biomimetic design are broken down into their biophysical-function relations. Categories, e.g., material features, structural features, and environmental conditions, help with the analysis.	46
Structural biomimetic design method	The structural biomimetic design method attempts to support each individual step along the biomimetic design process with respective tools to provide as much guidance as possible. The order and definition of steps is very similar to the one by Refs. 41–43. Relevant included tools include a patterns table, a “Findstructure” database, and a “viable system abstraction model.”	2

relationships. In accordance with Wanieck *et al.*,⁴⁰ the tools were subdivided into following categories:

- *Method*: Usually methods belong to a tool and describe the adequate application of it. Since these methods are automatically assessed with the respective tool, exclusive standalone descriptions (independent from any tool) of a specific procedure are included here. The “Bio-analogous similarity matrix,” for example, is a paper-based tool to compare biological and technical systems, measuring their respective applicability.⁴⁹
- *Algorithm (incl. Optimization methods)*: An automated procedure for solving a certain task in a finite number of steps (paper based or software). Optimization methods were included in this category.

An example is “DANE—Design by Analogy to Nature Engine,” which provides possible biological templates and provides the user with structure–function relations of these templates.^{50,51} Because of their importance to the AM design process, examples of optimization methods are discussed separately below.

- *Database, Static list, Catalogue (DSC)*: A collection of knowledge about biological templates or principles that change only if updated. DSCs usually require little prior biological knowledge and are easy to apply. AskNature^{52,53} is one of the best-known examples. As an online database, it classifies and structures biological templates and related information as well as examples for the successful application of biomimetic principles.

- *Ontology*: Categorizes biological knowledge and abstracts it into descriptive functions. An ontology of biological functions referring to the TRIZ innovation principles is provided by Vincent.⁵⁴ The “BioTRIZ” is partly available as a paper-based and partly as a software tool.
- *Thesaurus*: A type of dictionary, translating biological terms into technological equivalents. As an example, the “BIOPS—Biologically Inspired Problem Solving” web-based tool, developed by Le and Farrenkopf,⁵⁵ supports the search for biological models.
- *Taxonomy*: An orderly scientific classification of principles. For example, “The Biomimicry Taxonomy”⁵² is a paper-based table, which organizes biological models by function and provides abstracted functional principles. This taxonomy can be used in connection with the AskNature database.

Regarding *optimization methods*: In the context of this paper, optimization methods refer to different ways of conducting structural optimization, which describe the process of finding the best possible material distribution for a load-bearing structure.⁵⁶ By this definition, it can be argued that structural optimization problems can also be seen as problems of optimal material distribution.⁵⁷ A differentiation between size optimization, shape optimization, and topology optimization is suggested. All optimization methods rely heavily on computer-aided design (CAD) and the finite element method (FEM). The core of the process is the algorithm used to optimize the CAD model, taking into account the information provided by the FEM analysis. The optimization is an iterative process, resulting in an approximation for an optimal material distribution.⁵⁸

While many numerical optimization algorithms were derived purely mathematically, others have their origin in biology. The efficient usage of resources is an important principle in nature. Lightweight construction saves material and energy. Thus, lightweight structures are a major evolutionary objective and an abundant feature to be found in nature.⁵⁹ At this point, it is noteworthy to mention that topology optimization is used for structural optimization while nature usually optimizes for a combination of structural and other functions. As such, nature produces shapes more similar to the results of topology optimization, when the load-bearing functionality is dominating other functionalities, e.g., silica skeleton of radiolaria closely resembling a truss structure.⁶⁰

A well-known example for topology optimization tools is OptiStruct. Scientists discovered that the structure and microstructure of a human bone develops and adapts itself according to the predominant stresses that the bone has to withstand. The mathematical principles derived from this discovery were implemented into OptiStruct, which became the first commercial solver solution.⁶¹ Other methods such as computer-aided optimization (CAO),^{62,63} computer-aided internal optimization (CAIO),⁶⁴ or soft kill option (SKO)⁶⁵ were derived from biological principles reducing stress peaks, discovered while studying the growth of trees. Another example is the so-called slime mould optimization algorithm.^{66,67} This algorithm is an abstraction of the growth strategy of slime mould and can be applied to structural optimization problems to quickly generate different possible solutions for lightweight structures (also cf. Sec. III B, Table VIII).⁶⁸ The ELISE—Generative Engineering method combines different methods and includes topology optimization and the implementation of predefined

biomimetic features as well as several preparatory steps for 3D printing such as support generation.^{59,69}

III. ASSESSMENT OF BIOMIMETIC DESIGN APPROACHES IN LASER ADDITIVE MANUFACTURING

Section II provides an overview over biomimetic design methodologies and tools supporting the users with the biomimetic development process. This section compares different methodologies and tools, illustrates their advantages and disadvantages, and provides AM related use cases.

A. Analysis of applicability for industrial development processes

1. Design methodologies

It is assumed that the more a methodology is supported by defined tools and/or optimization methods the better the guidance and ultimately the concept design. Hence, the degree of tool usage and the degree of digitalization of the applied tools have been identified (Table IV). Tool usage is defined by how many of the methodology steps are actively supported by tools, while the degree of digitalization is defined by how many of the used tools are available in the digital form—software or web-based.

The degree to which seven methodologies, identified in Sec. II A (cf. Table III), are supported by explicit tools varies. While there is a tendency toward a significantly higher active support through tool usage especially in more recent methodologies, the degree of digitalization generally remains low (<50%). It can be argued that based on existing methodologies, a standard framework for the biomimetic process, covering at least the four major steps (as in Table V) should be formulated and supported with tools in order to offer a baseline for biomimetic design in the industry. Further, the degree of digitalization of biomimetic design tools should be increased to facilitate and speed up the design process.

An analysis of the presented methodologies reveals that the following four steps play a key role in the biomimetic design process: Problem definition, analogy search, analysis or extraction of principle, and transfer to an engineering design. Based on this finding, it was chosen to reduce the degree of detail while maintaining these identified main phases when describing the biomimetic design process. Accordingly, the eight steps by Wanieck *et al.*⁴⁰ have been concised into four major steps that will be referenced from here on (Table V).

2. Tools

The different tools are assessed separately because as opposed to the methodologies some of them only address single steps in the biomimetic development process. The following assessment reveals which steps are already well supported by appropriate tools and for which steps adequate tools lack. To determine the usefulness of a tool category, each was evaluated as follows:

- *User-friendliness* addresses the required expertise of the user to be able to work with the respective tool. Since the assessment below addresses the usefulness of the tools to engineers, the limiting factor is the required biological expertise.

TABLE IV. Assessment of biomimetic design methodologies concerning tools usage and degree of digitalization (high: >75%, bold; medium: 25–75%; low: <25%, italic).

Biomimetic design methodology	Implemented tools	Degree of tool usage	Degree of digitalization	Reference
Biomimetic process model	Association list	(1/5) <25%	(0/1) 0%	41
Problem-driven biologically inspired design process	Solution search heuristics	(1/6) <25%	(0/1) 0%	42
Procedural model for biomimetic design	Databases, (AskNature), Thesaurus function, Template for Cards, Brainwriting	(3/5) <25%	(2/4) 50%	43
Eco-innovation by ARIZ and biomimetics concepts	Eco-efficiency factors, eco-directions, ARIZ tools	(4/4) 100%	(0/3) 0%	44
Problem-solving methodology for BID	NIST functional basis, NIST-BT correlation matrix, Database (AskNature), Set of parameters for preselection, functional causal models, BID guidelines	(5/6) >75%	(1/6) <25%	45
BioGen	Exploration model, analysis table, imaginary Pinnacle, Pinnacle analyzing matrix, Design path matrix	(4/8) 50%	(0/5) 0%	46
Structural biomimetic design method	Function means tree, Patterns table, Databases, Complete viable system model, Ideality tool, Analogy comparison tables	(5/5) 100%	(1/6) <25%	2

- *Digitalization* focuses on the availability and accessibility of a digital user interface. Tools are either paper based or available in the form of software or a web-based application. The access to the individual tools may be limited if it is not publically available, open-source, or commercial. In addition, the share of digitally available tools within each category was determined. The calculated percentage represents the current degree of digitalization.
- *Efficiency* gives a rough estimation of the expected time to first result of the individual tool types and states whether the results produced by the respective tools are reproducible.
- Lastly, *suitability for industrialization* summarizes the results of the previous categories, which are key aspects for a successful industrial application.

To assess the different tool categories, a three-step rating system (low, medium, and high) was used. The following assumptions have been made to define the ideal for each category:

- Since the goal is to enable engineers to use a biomimetic approach, tools not requiring any prior biological knowledge are considered user-friendly and rated as “easy” to use.

TABLE V. Definition of biomimetic design process steps.

Steps according to (Ref. 40)	Steps (in this publication)	Description
1–3	1	Problem definition
4–5	2	Analogy search and preselection
6	3	Analysis and abstraction of biological model
7–8	4	Transfer and product development

- Digitally available tools are assumed to be easier to apply than tools available in the printed form. From a security point of view, software offers a closed solution to companies while a web-based tool is more mobile but at the same time more vulnerable, for which reason software tools were ranked higher considering industrial application. Accessible, well supported, and up to date tools are considered easy to implement in the development process. Therefore, “commercial” access is the preferred option. A “high” degree of digitalization is considered to make this tool category more applicable for industrial applications.
- Time is a critical factor for industrial development processes. Ideally, the required time to generate results with a tool is as “low” as possible. Another important factor is reproducibility. A tool should generate reproducible results with a consistent quality, independent of the respective user. Ideally, the tools get a “high” score in this category.
- Suitability for industrialization is an overall representation of how close each tool category comes to the ideals of the rating system.

The results in each category represent a general assessment of the tool categories by the authors. Individual tools may be rated differently but are rather the exception than the rule. The assessment of different tool types (Table VI) supporting the biomimetic development and design process shows that many tools still require further development for application in the industry sector. The tool type “method” scores lowest on the rating system. The tools in this category are exclusively available in the printed form and usually require prior biological knowledge. Overall, the results of these tools strongly depend on the individual user, which has a negative effect on their repeatability. With only a medium score for expected time to results, the suitability for industrialization can only be rated as low.

DSCs as well as ontologies receive an average rating regarding their suitability for industrialization. Both tool types map the individual templates and deliver additional knowledge, regarding either

TABLE VI. Assessment of tool categories, regarding their suitability for industrialization (close to ideal: bold; far from ideal: italic).

Tools		User-friendliness		Digitalization		Efficiency		Suitability for industrialization
Category	Steps covered	Applicable without biological knowledge	Degree of digitalization	Availability	Accessibility	Expected time to result	Repeatability of results	Overall comparison with ideal
		<i>Hard</i>	<i>Low <25%</i>	<i>Low: print</i>	<i>Low: limited</i>	<i>Slow: weeks</i>	<i>Low</i>	<i>Low</i>
		Medium	Medium	Medium: web based	Medium: open-source	Medium: days	Medium	Medium
		Easy	High >75%	High: software	High: commercial	Fast: hours	High	High
Ideal	—	Easy	High	Software	Commercial	Fast	High	High
Method	1,2	<i>Hard</i>	<i>Low</i>	<i>Print</i>	<i>Limited</i>	Medium	<i>Low</i>	<i>Low</i>
Algorithm (Optimization Methods)	1,2,3,4 (4)	Easy (Easy)	High (High)	Software, print (Software)	Limited (Commercial)	Fast (Fast)	High (High)	High (High)
DSC	1,2,3,4	Easy	<i>Low</i>	Web based, print	Open-source	Fast	Medium	Medium
Ontology	2,3,4	Medium	Medium	Web based, print	Open-source	Medium	Medium	Medium
Thesaurus	3,4	Easy	Medium	Web based, print	Open-source	Fast	High	High
Taxonomy	3	Medium	<i>Low</i>	<i>Print</i>	<i>Limited</i>	Medium	Medium	Medium

the biological principles or possible technical applications. This property lowers their requirement for prior biological knowledge. However, the comprehensiveness of the results depends on the user's experience with the respective tool. While both tool types are well suited to be implemented as web-based applications, the degree of digitalization is still quite low.

Taxonomies are exclusively available in the printed form and only offer limited access, leading to a low degree of digitalization. Usually some biological knowledge is required to apply the tools. This affects repeatability and leads to a medium score in this category. With a low to medium time to a first result, this tool category still requires work for industrial application.

A thesaurus provides clearly structured correlations between technical and biological terms. It is easy to apply even without prior biological knowledge. Some of the tools in this category are available as web-based applications, resulting in a medium degree of digitalization. Since the thesaurus is comparable to a dictionary, the tools receive good scores in the categories repeatability and expected time to results. Overall, this type of tool shows promise for applications in the industry.

Algorithms receive the highest total score. They are mostly available in the digital form and are usually accessible as open-source or commercial software. Since algorithms clearly relate the results to a given input, the tools in this category produce highly repeatable results and are easy to apply without any biological knowledge. Optimization methods are the best example to illustrate, how user-friendliness, repeatability, and degree of digitalization relate to application in the industrial sector. They receive a high score in all these categories and are an

industry standard when it comes to lightweight construction.⁵⁷ For AM, these tools become even more important since reducing part volume directly relates to saving time and money in the manufacturing process.⁷⁰ The expected time to usable results depends on the experience of the user and in the case of optimization methods on the complexity of the simulation. However, in most cases, a good result can be achieved within a few hours to a day.

B. Selected example applications

Today, a number of AM applications using biomimetics can be found in the literature.^{71–73} Topology optimization, as a standard step in design or redesign of parts for AM, was historically inspired by bone growth and can, therefore, be argued to be biomimetic itself.⁷⁴ Interestingly, today most applications focus on structural optimization by biomimetics, and only very few are addressing functional optimization. In the following, several case studies for structural and functional optimization using biomimetics are presented, and for two that are published in detail, the biomimetic design process is described by using the four steps defined in Table V (cf. Sec. III A).

1. Structural optimization using biomimetics

The redesign of aerospace components to benefit from the lightweight design possible through AM technologies is one of the most common application areas.⁷⁵ One example⁷⁶ features a bracket from the Airbus A380 series shown in Fig. 2. It is a part of

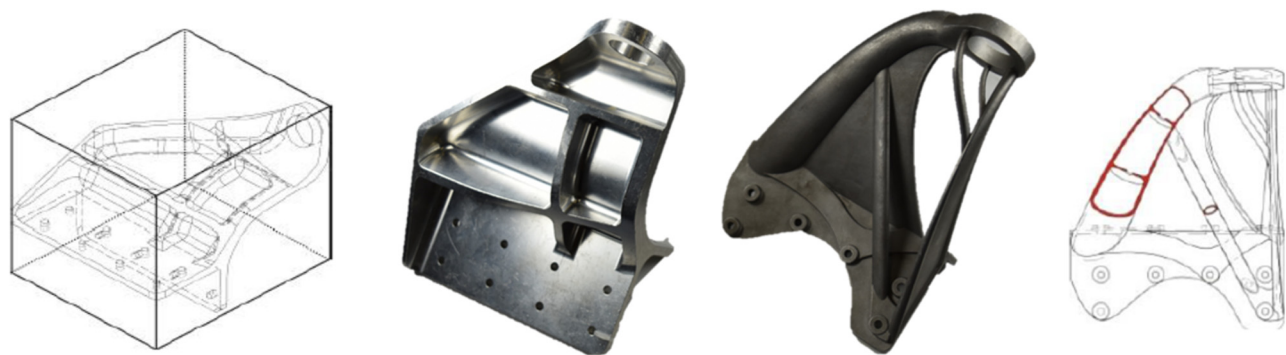


FIG. 2. FCRC bracket in conventional design (left) and AM design (right), with the bamboolike structured section colored in red.

the fixation of the flight crew rest compartment (FCRC) with the primary aircraft hull.

Initially, a topology optimization with commercial software was performed. To increase the stiffness of the hollow beam structure, a bamboolike structure was inserted afterward. The procedure followed in the design phase is discussed in detail in Table VII.

TABLE VII. Biomimetic design process steps followed for the A380 FCRC as presented in Refs. 76 and 77.

Step	Description	Implementation
1	Problem definition	Transfer a spectrum of loads from FCRC to the aircraft structure at minimum weight and in a given design space. The main load case is an 11kN static force (emergency landing scenario). An initial topology optimization result shows an armlike structure on the top (Fig. 2, second image from right), which is subject to bending loads.
2	Analogy search and preselection	Bamboo culm with nodes, which can resist strong lateral forces, e.g., by wind loads.
3	Analysis and Abstraction of biological model	Bamboo is known to have a high bending stiffness due to its hollow, cylindrical structure ² in combination with reinforcements through a local increase in wall thickness at the nodes, which prevent deformation of the cylinder shape.
4	Transfer and product development	The armlike section was redesigned to resemble the features of the bamboo culm. It was designed as a hollow tube, and two “nodes” were implemented for reinforcement.

The part was manufactured from Ti-6Al-4V using LBM, and the AM design proved to be 50% lighter compared to its conventional counterpart. It has to be noted that a later design of the part proposed in Ref. 77 abandoned the hollow features due to concerns about fatigue performance, as the inner structures are hardly accessible for a surface finishing.

To separate the passenger cabin from the galley, a structure called “bionic partition,” shown in Fig. 3, has been developed as an alternative to the current rather heavy non-AM design.⁷⁵ The biomimetic inspiration to the AM design derives from the growth mechanism of the slime mold.⁷⁸ A detailed overview of the biomimetic design process is provided in Table VIII.

Given the dimensions of the partition, it could only be realized as an assembly of a number of sections printed in LBM due to current manufacturing size restrictions (cf. Table II). The final design results in a weight saving of 45% (30 kg) compared to current designs.⁷⁹

Another example for structural optimization using biomimetics is an aircraft spoiler.⁸⁰ The stiffening structure of the spoiler shown in Fig. 4 was inspired by the leaves of a water lily, which is known to be able to carry heavy loads of up to 50 kg while still being light enough to float. The LBM-built metal spoiler saves 30% of the weight in comparison with the original part made of composites.⁸¹

Larger parts with less complexity can be efficiently manufactured using LMD (cf. Table I). An example is the “bionic fuselage,” as shown in Fig. 5. The stiffening structure was derived from topology optimization and inspired by bone growth. In proof-of-concept, the fuselage demonstrator was printed on a plate dimension of $1 \times 0.5 \text{ m}^2$.⁸²

Parts often consist of a number of standard features such as solid bodies, surfaces, struts, and transition areas. Once a biomimetic structure is identified for a certain feature, it can be transferred and scaled to any other feature of the same class. In the example shown in Fig. 6, four biomimetic structures and principles have been identified that can be applied to such features: gyroid structures from butterfly wings for structural optimization of solids, honeycomb structures for structural optimization of surfaces, a plant stem structure for structural optimization of struts, and the method of tensile triangles⁸³ to optimize transition zones. These

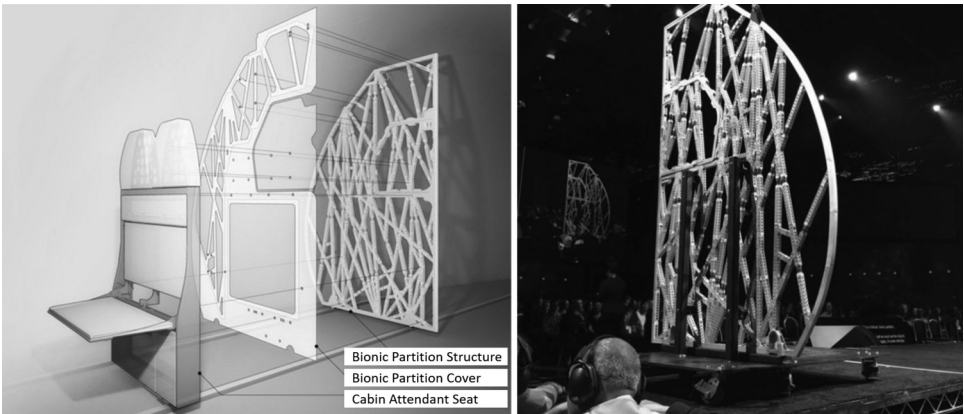


FIG. 3. “Bionic partition” for the Airbus A320, concept (left) and assembled part (right). Reproduced with permission from Airbus. Copyright Airbus.

structures have in common that they can be mathematically described and are comparatively easy to implement into a toolset to allow direct application to features of any dimension.^{84,85}

2. Functional optimization using biomimetics

One of the few examples of using biomimetics for functional optimization is the “bionic handling assistant” (Fig. 7). It was inspired by an elephant’s trunk and its flexibility.⁸⁶ The individual flexible parts are made by SLS out of polyamide. A major improvement in safety during interaction with human operators results from the flexibility of the system. The gripper consists of adaptive elements inspired by the movement of the tail fin of fish. The resilience of the structure improves the function of the gripper especially during handling of sensitive goods.⁸⁷

Biomimetics can also be applied in functional optimization of the LBM process itself by considering treelike structures for the

supports (Fig. 8). The functions of the support structures are including the compensation of mechanical loads, fixation of the part on the platform, and heat dissipation. Tree supports have shown to fulfill these tasks at minimal material usage, thus increasing resource efficiency while reducing cost and build time.^{83,88}

For most of the case studies, only few details are published regarding the biomimetic design process involved. Still, it can be concluded that of the tools described in Table VI mainly algorithms are used, which correlate well with their high suitability for industrialization. Biomimetic design methodologies as presented in Table IV are not yet followed consistently.

C. Benefit of biomimetic design

The examples presented in Sec. III B show that AM and the biomimetic development approach are complementing each other

TABLE VIII. Biomimetic design process steps for the Bionic partition, as presented in Ref. 78 and allocated to the steps defined in Table V.

Step	Description	Implementation
1	Problem definition	Combination of structural challenge of holding a fold-down cabin attendant seat (CAS), need to withstand forces of 16G in crash test, and integration of a removable area to allow for carrying an injured passenger on a stretcher. The solution should, therefore, route forces from the CAS attachment points around obstacles to the support points where the partition is attached to the aircraft structure, at minimal weight.
2	Analogy search and preselection	The slime mold growth mechanism forming material-efficient networks to connect locations where it finds food.
3	Analysis and Abstraction of biological model	The slime mold initially spreads a dense network of connections. It then forms complex networks by reducing the connections to keep only the ones that efficiently link the food sources. The networks are adaptive and redundant so that nutrition transport can be rerouted in case a connection is damaged.
4	Transfer and product development	Initial “dense” network by connecting CAS attachment points, support points, and a number of additional points along the partition boundary. A weight parameter (resembling “food quantity”) is assigned to each vertex and a behavioral algorithm is used to decay the network in order to define the structural pathways connecting the highest “food quantities” for a design iteration. A genetic algorithm is then used to optimize weight while restricting the maximum displacement and the material utilization.

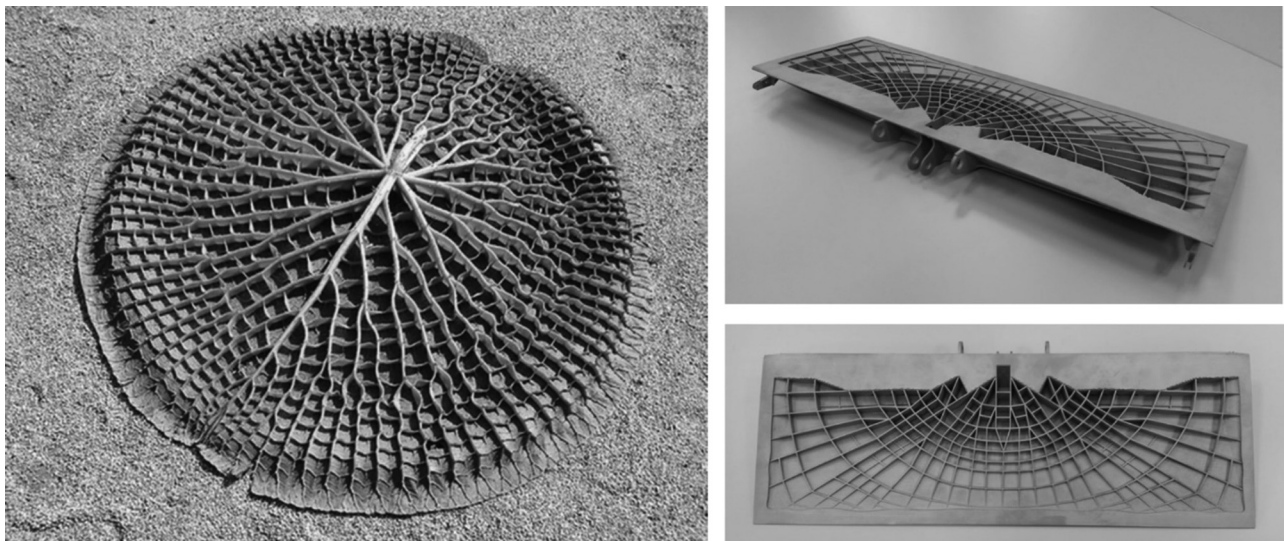


FIG. 4. Aircraft spoiler manufactured by LBM (right) using a biomimetic design inspired by the leaf of a water lily (*Victoria cruziana*, left) to optimize stiffness at lowest weight. Reproduced with permission from Airbus. Copyright Airbus.

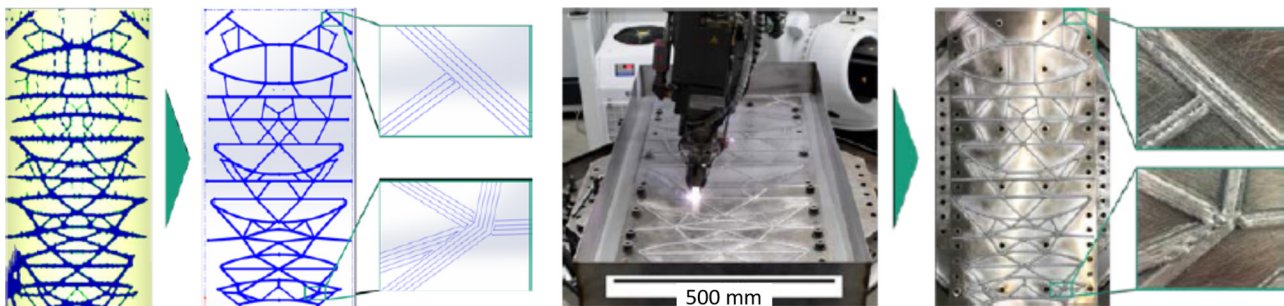


FIG. 5. "Bionic fuselage" consisting of AlSi10Mg stiffening structures manufactured by LMD on top of an AlMg5 sheet. Reprinted with permission from M. Heilemann, J. Beckmann, D. Konigorski, and C. Emmelmann, *Procedia CIRP* **74**, 136–139 (2018). Copyright 2018, with permission from Elsevier (Ref. [82](#)).

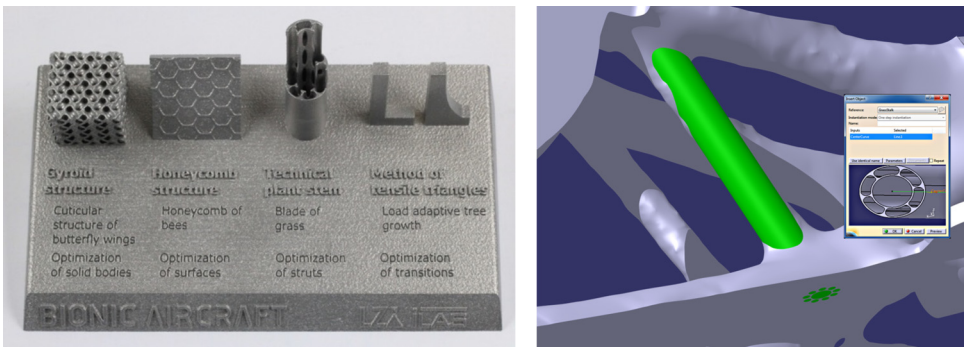


FIG. 6. Biomimetic features (left) integrated into a commercial toolset implemented into a CAD-software environment (right). Reproduced with permission from Cenit AG. Copyright Cenit AG.



FIG. 7. Flexible handling assistant (left) and detail of the gripper (right). Reproduced with permission from Festo AG & Co. KG. © Festo AG & Co. KG, all rights reserved.

well. Structural optimization is standing out as a field of research, where AM enables the realization of new, more complex structures. Nature presents an abundance of such structures, which can serve as templates to accelerate the development of optimized structures.

To evaluate the benefit of the biomimetic development and design approach to the design process for AM in the following, the identified examples were analyzed regarding their innovativeness. A compilation of possible innovation criteria for the evaluation of the innovativeness of a design can be found in Ref. 2. For the purpose of this paper, the examples were evaluated using the following criteria:

- Novelty: Is it a new, original idea or concept?
- Quality: Is the concept feasible and functional?
- Variety: Is there a big solution space?
- Cohesiveness: Is the resulting concept well developed and detailed?
- Generalizability: Is the principle or concept broadly applicable? Does it open new perspectives?

The score was calculated as follows:

Each example was rated in different categories and could achieve a score from 1 to 3. For five categories in total, this means the lowest score is 5 points and the highest score is 15 points. For the final score, biomimetic design ideas and concepts with 13–15 points were rated as highly innovative. Examples with 8–12 points are considered medium innovative and examples with 5–7 points only show low innovativeness.

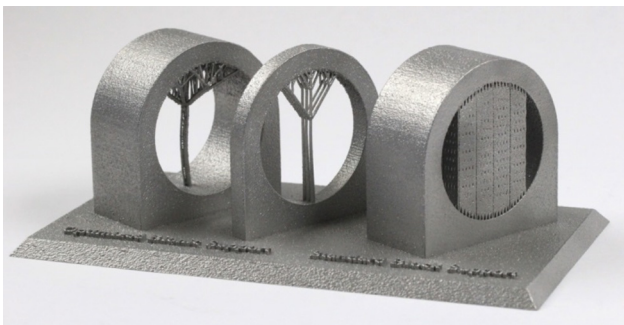


FIG. 8. Treelike support structures in LBM (left and center) compared to conventional block supports (right).

The analysis of the examples (Table IX) shows that all the identified example applications for the biomimetic development process get relatively high scores regarding their overall innovativeness. For all examples, the underlying principles are easily transferable to other applications and concepts, once understood. For structural optimization, the publication of identified principles or preferably their implementation into existing software solutions has the potential to lead to new ideas and the optimization of existing concepts and parts. Current efforts of large software providers such as Dassault Systems (3DEXperience CATIA)⁸⁹ and Siemens (Siemens NX) emphasize the importance of such software solutions. Both companies are working on integrating topology optimization and advanced optimization methods like biomimetic feature catalogs into their CAD-software, offering a single-solution software to cover the complete AM digital process chain.

All examples show that the consideration of biological templates during the development and design process usually leads to a detailed and well developed final concept. These concepts are feasible, when considering AM. Implementation using conventional production such as milling or casting would be very costly for structures with the resulting complex topologies. The desired functionality was achieved for all examples. For structural optimization problems, the weight was reduced up to 50%. Functional optimization could be achieved for both example applications. In case of the flexible handling assistant, a flexible robotic arm, safe for human interaction, as well as an adaptive end effector were developed. Both meet all requirements of a soft robotics design approach.

When evaluating the variety, the solution space for structural optimization can be considered quite limited. Using topology optimization narrows down the possible results to the capabilities of the respective software. But as mentioned above, employing a software-driven process has a positive effect on generalizability. Functional optimization problems usually make use of a bigger solution space. When applying a biomimetic design approach, a variety of different biological templates may be uncovered. Starting with a fresh concept, developers and engineers are not restricted by software but experience full freedom in their designs. At this point, it should be mentioned that in most cases it is poorly documented if and how the biomimetic approach was applied during the development of a concept or product.

Novelty of the individual idea for a concept varies from project to project. Some applications are very common by now for structural optimization such as brackets and connection pieces,

TABLE IX. Assessment of innovation potential of BDAs on the basis of selected use cases (high scores: bold; low scores: italic).

Examples	Novelty	Quality	Variety	Cohesiveness	Generalizability	Score
	New, original idea or concept	Feasibility and functionality	Size of solution space	Detailed, well developed concept	Broadly applicable, opens new perspectives	
Structural optimization						
FCRC bracket	New application?: no	Feasible?: through AM Functional?: 50% lighter	<i>Limited to TO software, different biomimetic features could be considered</i>	detailed, well developed concept	TO and biomimetic feature easy to adapt and transfer	12
Biomimetic spoiler	New application?: yes	Feasible?: through AM Functional?: 30% lighter	<i>Limited to SO software, different biomimetic features could be considered</i>	detailed, well developed concept	SO and biomimetic feature easy to adapt and transfer	13
Bionic partition/ Bionic fuselage	New application?: yes	Feasible?: through AM Functional?: 45% lighter	<i>Limited to SO software, different biomimetic features could be considered</i>	detailed, well developed concept	SO and biomimetic feature easy to adapt and transfer	13
CAD biomimetic features	New application?: biomimetic feature integration in software	Feasible?: through AM Functional?: potential performance increase	Different biomimetic features are considered but standardized	well developed concept implementation of biomimetic features depends on user	TO and biomimetic feature easy to adapt and transfer	12
Functional optimization						
Flexible handling assistant	New application?: yes	Feasible?: yes Functional?: yes	high, different biomimetic templates and different technical solutions possible	detailed, well developed concept	high: principles understood and transferable	15
Biomimetic support structures	New application?: no	Feasible?: yes, through/for AM Functional?: yes	Medium, different biomimetic templates possible, but technical solution generates similar ideas	detailed, well developed concept	high: principles understood and easy to adapt	13

while others are new and have never been tried before such as the biomimetic spoiler. The same is true for functional optimization problems.

The best overall score is achieved by an example for functional optimization problems. The flexible handling assistant receives a perfect score. It encompasses two biological principles, derived from the fin anatomy of a fish and the anatomy of an elephant trunk. Both principles were analyzed, understood, and implemented in a prototype. The principles are transferable, and in case of the fin ray effect, it already has been suggested for other applications.⁹⁰

In conclusion, the analysis and evaluation of the examples show that following a biomimetic design approach delivers superior results. Structural optimization problems are the most common applications. Using topology optimization and the implementation of biomimetic features leads to a significant weight reduction for all presented examples. While the principle of optimal material distribution available through topology optimization is well established and supported by software, other biomimetic principles and their respective biomimetic

features still have to be implemented individually for each selected application. However, applications such as the biomimetic support structures and the software implementation of biomimetic feature catalogues show that the potential of biomimetic designs has been recognized by the industry. Examples for functional optimization problems are less common but show great potential. The selected examples for structural optimization show that the use of software tools makes the design process efficient and leads to good results. Although the examples for functional integration do not benefit from the use of software, they profit from going through the entire biomimetic design process and can, therefore, utilize the complete solution space offered by nature. However, as pointed out in Sec. III A, digitalization is a key aspect for a successful implementation of biomimetic approaches in industrial development processes and makes results reproducible and easier to transfer to other applications.

While the degree of innovation tends to be very high for biomimetic designs in AM, a BDA arguably requires increased effort

compared to established and well-known conventional design approaches. Therefore, a major and provocative question that has not been answered in the literature yet should be addressed when thinking about industrial biomimetic design: Which is the “appropriate” technical problem that potentially yields added value through biomimetic design?

Since there are no systematic investigations available to answer this question, only legitimate assumptions can be drawn at this point and are subject to discussion:

The criteria to determine whether or not a new design approach is suitable have been discussed by Chen and Chen.⁴⁴ These can similarly be adopted for a BDA. Accordingly, BDA should be pursued for technical problems, when

- conventional design approaches do not produce suitable ideas or solutions;
- the problem is new and no other design tools or initial design ideas are available; and
- the problem is complex, e.g., the targeted system expands to a part assembly (supersystem) or the boundary conditions/functional requirements are complex (multitarget problem).

Overall, it is assumed that, especially multicriteria problems, missing conventional solution approaches/or tools and extreme demands on components are a good prerequisite for generating added value with biomimetics at a reasonable cost.

IV. CONCLUSIONS AND OUTLOOK

Looking at today's application of biomimetic, AM-manufactured products, it becomes clear that industrial usage of this combination is still limited. On the one hand, biomimetic design has been used in some of the most advanced LAM use cases (cf. Sec. III B). On the other hand, it has only been applied to a small fraction of products being redesigned for LAM, and predominantly for structural optimization, mostly neglecting other fields of application (e.g., functional integration)—some of which are pointed out as recommended fields of research (cf. Sec. IV A).

From the use cases that have been publicized, it is still obvious that both biomimetic design and LAM can benefit from each other. Biomimetic design often leads to complex structures that can only be manufactured by LAM, while LAM in turn profits from new design ideas that are profitable to manufacture and show a high degree of innovation.

So, while there is clearly a symbiosis, there are still some limitations that need to be overcome in the future to make it a “perfect” match. These limitations refer to the yet missing biomimetic design tools (exceeding structural optimization) that are suitable for industrial application as well as technical limitations of today's LAM technology. Hence, based on the findings from the evaluation of design tools in this publication, the road to industry for biomimetic AM Design is outlined in Sec. IV B.

A. Recommended fields of research

On the side of LAM, the current design restrictions (cf. Sec. I C) are still a major limitation for a broader application of biomimetic design. Obviously, any advancement in LAM to overcome these

restrictions would be beneficial. While the requirements for powder removal openings and accessibility for postprocessing may often be satisfied by simple modifications to the desired geometry, limitations in part dimension, feature size, and multimaterial capability can significantly hinder the technical realization of a biomimetic design approach. Once multimaterial LAM becomes mature (for current advancements see Ref. 91), there will be also the need to integrate multimaterial design approaches into software, e.g., multimaterial topology optimization.

However, even with the current design limitations, there is a high potential to apply biomimetics to functional optimization in new fields of application. Such applications may include, e.g., mechanical damping, acoustic damping and sound design, heat conduction and heat exchange, compliant mechanisms and adaptive structures, as well as pneumatics and hydraulics.

Parts fulfilling several functions in one design require complex multiphysics optimization. The efficient and target oriented coupling of different optimization algorithms may be inspired by biomimetics as well, since each organism in itself has evolved to account for multiple functions at the same time. Identifying underlying algorithms could reveal new approaches for multitarget-optimizations.

B. Road to industry

Major barriers limiting the applicability of BDAs in the industrial environment are missing know-how of engineers on BDAs and respective tools. Additionally, the results depend on the creativity and skills of people applying the BDA. This limits the reproducibility of the results, which is seen as a critical factor for the acceptance of the BDAs by the industry. The need for adequate tools is, therefore, very high, in order to obtain reproducible designs. Existing tools provide some guidance for single steps of the Bionic design process, but there is no holistic methodology that is fully supported by digital tools covering the entire process. Overall, the degree of digitalization among existing tools is relatively poor and, hence, impracticable for the time and cost-sensitive environment as present in the industrial sector.

To overcome these barriers, it is necessary to digitalize and automate the BDAs. This will systemize the design process and make it more accessible and easy to use for the designers. Among the different types of tools, algorithms have shown to be highly recommendable to pursue Bionic design in industrial applications, followed by thesauri.

In case of structural optimization problems, the examples presented in this paper show that commercial software solutions can be used to enable engineers to apply and implement biomimetic principles successfully. The realization of the design principles found in nature as a software tool skips most of the steps of the BDA, jumping directly to the application step (step 8), leading to an abundance of optimized, organic structural designs. In the area of functional integration, examples from the industry are less common, which can be contributed to the fact that identified biological principles for functional integration and optimization are rarely available in a digitalized form.

However, the ongoing development of automated tools (e.g., algorithm or thesaurus) will make it easier to reconstruct the evolution of a specific design result and, therefore, lead to more

acceptance by the industry. As described before, a huge unveiled potential is seen by using the BDAs for complex problems and multicriteria optimizations that usually require a high degree of creativity, especially for the phase of the “concept finding.” To assist the designer in this essential phase and to implement the necessary “creativity” in the tools, artificial intelligence might be a key enabler and should be investigated in more detail.

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