TECHNISCHE UNIVERSITÄT WIEN

Master Thesis

Biomimetic materials in the construction industry Development, awareness and potential

carried out for the purpose of obtaining the degree of Dipl.-Ing., submitted at TU Wien, Faculty of Mechanical and Industrial Engineering, by

Martin Rohner
Mat.Nr.: 01440154

under the supervision of

Mag. Dr.rer.nat. Helga Lichtenegger

Institute of Materials Science and Technology, E308

Vienna, November 2022

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Vienna, 30 November 2022

Signature

Acknowledgement

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Abstract

In the present master thesis, a literature review on biomimetic materials for use in the construction industry (CI) was carried out. A state-of-the-art summary of studies on biomimetic materials intended for application in the CI is provided. Results show that the scientific community is working on biomimetic materials intended for a wide variety of applications in the CI. Also, there are products made from biomimetic materials available on the market. They cover a whole range of applications in CI but far fewer applications than the scientific community is currently investigating. A questionnaire survey on the awareness for biomimetic materials for use in the CI was conducted among representatives of the CI of the D-A-CH region (i.e. Germany, Austria, Switzerland). Results show that the concept of biomimetics was not familiar to the majority of these representatives. Also, to date, the use of biomimetic materials for building projects was not considered by the majority of these representatives. It was found that there is a gap between the awareness of biomimetic materials among representatives of the CI in the D-A-CH region and the scientific community working on the development of biomimetic materials. However, after examples of biomimetic materials were shown to these representatives, it was revealed that the majority of them would consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region. Also, the great majority of them agreed that biomimetic materials have the potential to significantly increase the sustainability of the CI in the D-A-CH region. Further, it was found that the great majority of representatives would like to learn more about biomimetics, biomimetic materials and products. Thus, this master thesis shows that promotional measures are urgently needed to increase the awareness for biomimetic materials for the CI in the D-A-CH region. How these promotional measures should look in detail and how they can be successfully implemented, should be the subject of further investigations.

Keywords: Biomimetics, Biomimetic materials, Construction industry, Sustainability, Nature

Zusammenfassung

In der vorliegenden Masterarbeit wurde eine Literaturrecherche über biomimetische Materialien für die Anwendung in der Baubranche durchgeführt. Es wird ein Überblick über den aktuellen Stand der Technik zu biomimetischen Materialien für die Anwendung im Bauwesen gegeben. Die Ergebnisse zeigen, dass die Wissenschaft an biomimetischen Materialien für eine Vielzahl von Anwendungen im Bauwesen arbeitet. Auch auf dem Markt sind Produkte aus biomimetischen Materialien erhältlich. Diese decken eine ganze Reihe von Anwendungen im Bauwesen ab, aber weit weniger Anwendungen, als die Wissenschaft derzeit erforscht. Eine Fragebogenerhebung über das Bewusstsein für biomimetische Materialien für die Anwendung im Bauwesen wurde unter Vertretern der Baubranche der D-A-CH-Region durchgeführt. Die Ergebnisse zeigen, dass das Konzept der Biomimetik der Mehrheit dieser Vertreter nicht bekannt war. Auch die Verwendung biomimetischer Materialien für Bauprojekte wurde bisher von der Mehrheit dieser Vertreter nicht in Betracht gezogen. Es wurde festgestellt, dass es eine Kluft zwischen dem Bewusstsein für biomimetische Materialien bei den Vertretern der Baubranche in der D-A-CH-Region und der Wissenschaft, die an der Entwicklung biomimetischer Materialien arbeitet, gibt. Jedoch nachdem den Vertretern Beispiele für biomimetische Materialien gezeigt wurden, erklärte die große Mehrheit von ihnen, dass sie bei einem ihrer nächsten Bauprojekte in der D-A-CH-Region die Verwendung eines biomimetischen Materials in Betracht ziehen würden. Es hat sich gezeigt, dass die Mehrheit der Vertreter der Meinung ist, dass biomimetische Materialien das Potenzial haben, die Nachhaltigkeit der Baubranche in der D-A-CH-Region erheblich zu steigern. Weiters wurde festgestellt, dass die große Mehrheit der Vertreter gerne mehr über Biomimetik, biomimetische Materialien und Produkte erfahren würde. Somit zeigt diese Masterarbeit, dass Werbemaßnahmen dringend notwendig sind, um das Bewusstsein für biomimetische Materialien in der Baubranche in der D-A-CH-Region zu erhöhen. Wie diese Werbemaßnahmen im Detail aussehen sollten und wie sie erfolgreich umgesetzt werden können, sollte Gegenstand weiterer Untersuchungen sein.

Schlüsselwörter: Biomimetik, Biomimetische Materialien, Baubranche, Nachhaltigkeit, Natur

Contents

List of Abbreviations

Abbreviation	Meaning
CI	construction industry (in this work focusing on the building sector)
D-A-CH	Germany, Austria, Switzerland (i.e. German-speaking countries except Liechtenstein)

1 Introduction

Over billions of years, nature has developed and optimised biological systems. Highly efficient materials and processes with remarkable properties are the result of consistent adaptation to constantly changing environmental conditions. Nature has evolved strategies that clearly outperform many human inventions. Janine M. Benyus [1] describes principles of nature, underlining that nature runs on sunlight, nature uses only the energy it needs, it fits form to function, it recycles everything, it rewards cooperation, it banks on diversity, it demands local expertise, it curbs excesses from within and it taps the power of limits. These principles and their resulting benefits are highly desirable for human inventions. Thus, nature is a great source of inspiration for scientists, engineers and designers to solve problems. Nature provides various models and templates for the development of new and sustainable solutions to the challenges, humanity is facing.

Loss of biodiversity, climate change and resource scarcity are some of the biggest environmental problems we face. Buildings and the CI contribute significantly to these problems. The CI has been recognised as a major driver to loss of biodiversity [2]. It is directly and indirectly responsible for 36% of global energy consumption and 37% of global energy-related CO_2 emissions [3]. Furthermore, the CI is responsible for almost 50% of the global annual resource consumption and waste production [4]. These numbers imply that the CI has significant potential for improvement to reduce its negative environmental impacts or even generate positive environmental impacts. To avoid further damage to climate and ecosystems, radical changes in the way the CI operates are necessary [5]. The 2022 IPCC Climate Change Mitigation Report [6] has shown the importance of climate change mitigation interventions such as low-emission construction materials and highly efficient building envelopes to limit global warming. By adopting sustainable measures, the CI can make an important contribution to mitigating the above mentioned environmental problems and beyond.

Direct impacts of buildings and the CI on the environment result from the production of materials and from the (de-)construction phase; indirect impacts are those that occur during the use phase of buildings, such as power generation for electricity and commercial heat. Material composition and material properties play an important role in these direct and indirect environmental impacts, respectively. For example, material composition influences the greenhouse gas emissions or the carbon capture capacity of materials during their production, material properties influence the heat transition and thus the energy consumption of buildings during their use phase. It is therefore of utmost importance to develop and use sustainable materials with optimised compositions and properties that meet the requirements of the CI. One promising way to increase and accelerate innovation and the development of such required materials is the investigation and learning from nature. Nature provides many examples of resilient and optimised biological materials and systems to achieve excellent properties and sustainable options for the CI [7]. Compared with synthetic, man-made materials, biological materials are remarkably efficient in terms of fulfilling complex requirements using minimal amounts of matter [8].

1.1 Biomimetics

Drawing inspiration from nature, i.e. from biological systems, and applying the acquired knowledge in engineering applications can be described as 'biomimetics'. The International Organization for Standardization (ISO) defines biomimetics as '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' (ISO 18458:2015 First edition 2015-05-15).

Transferring the ability of biological systems to grow, sense, regulate, react, regenerate, clean and heal, into biomimetic materials, could lead to unparalleled properties and performances, including positive environmental and economic benefits [9]. In recent decades numerous biological systems have been investigated under a biomimetic approach. As nature has solved many problems in efficient and sustainable ways, the use of biomimetic approaches for the development of novel engineering materials with better compositions and properties is becoming increasingly important.

1.2 Biomimetics in the construction industry

Through learning from natural forms, functions, processes and systems, the field of biomimetics offers a transformational approach to meet the needs of the CI [10]. While significant progress has been made in areas such as aircraft, automobiles, packaging and others, there are currently comparatively few biomimetic applications for the CI [7]. However, it was highlighted by Ahamed et al. [7] that the application of biomimetic materials in the CI can play a crucial role in making buildings more energy-efficient, more sustainable and more resilient. Thus, there is a great need for more awareness and research on biomimetic materials for the CI. Examples of biological materials which show high potential for the development of biomimetic materials in the context of civil engineering for the CI include teeth, bone, horn, skin, ligament, tendon, silk, seeds, leaves, wood, bamboo, feathers, fur, wool and scales, to name but a few [8].

The range of possible applications of biomimetic materials for the CI is very wide, starting from soil to roof, including for example structural members as well as building envelope and essential components such as windows or floor. Some of the most interesting properties of biological materials to transfer into biomimetic materials are mechanical characteristics such as strength combined with toughness, thermal characteristics such as thermal storage and thermal insulation, adhesiveness and anti-

adhesion, self-cleaning and self-healing characteristics as well as optical properties, biodegradability and recyclability. Implementing these properties into biomimetic materials such as structural members, insulation, paints, coatings, films, adhesives or composites which are lightweight and sustainable could revolutionise the CI [9].
Based on biological characteristics, Imani et al. [11] suggested a classification of biomimetic materials for the CI, shown in Fig. 1. Their literature review suggested that biomimetic materials used in buildings can be grouped into four major categories: mimicking **(1)** structural properties, **(2)** biological processes, **(3)** functions and **(4)** recycling processes observed in nature. Each approach leads to biomimetic materials offering innovative sustainable benefits. Resulting advantages are, for example, the reduction of raw material and/or energy input during production and during the use phase of these materials.

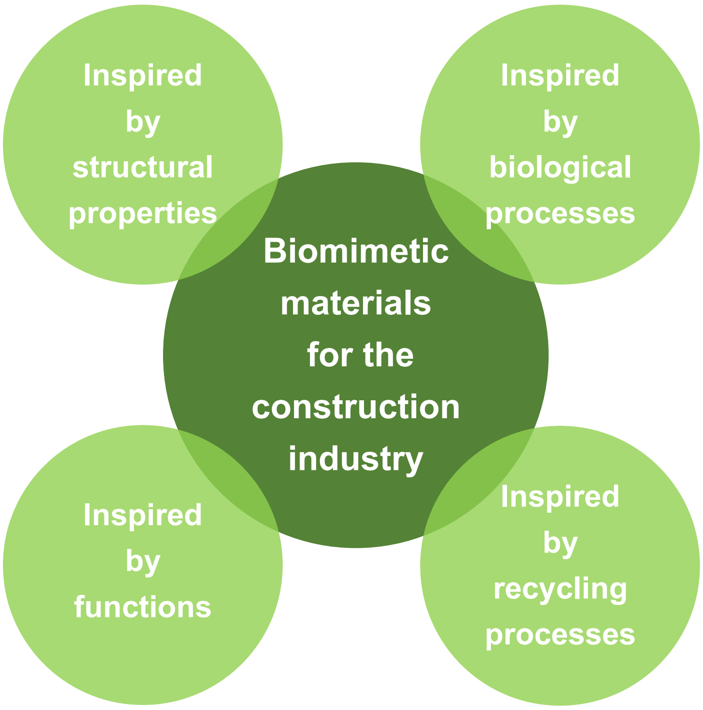

Fig. 1 Classification of biomimetic materials for the CI. Own contribution based on [11].

Mimicking **(1)** nano- micro- or macrostructures of natural organisms results in biomimetic materials with diverse beneficial structural properties. Examples are materials with improved load-bearing or thermal behaviour. Load-bearing behaviour can be optimised through the mimicking of e.g. hierarchical structures or fibre-reinforced composites, both resulting in lightweight materials with high toughness and/or strength. Thermal behaviour can be optimised through e.g. microstructure-mimicking coatings reflecting the energy of the sunlight or through structures of air chambers mimicking morphological patterns, resulting in high thermal insulating foam-based materials. For example, the unique microstructure of polar bear hair offers many advantages. It is non-wettable, lightweight, highly porous and confines a lot of air within the hollow fiber structure, keeping the polar bear’s body warm from low temperatures. Inspired by the microstructure of polar bear hair, Zhan et al. [12] developed a lightweight carbon tube aerogel with impressive thermal insulation properties. Through a simple solution based process the authors were able to fabricate an interconnected tubular aerogel with an extremely low thermal conductivity that outperforms most commercially available thermally insulating materials and even dry air. Additionally, their biomimetic material shows excellent mechanical robustness such as super-elasticity as well as high fatigue resistance. Their presented carbon tube aerogel is of definite interest to potentially replace commercial thermal insulation materials for energy-efficient buildings [13].

Self-organisation in biological systems is a process where the internal components of a system organise themselves without being controlled by external forces. Mimicking **(2)** biological processes for the self-organised growth of ‘living’ materials is still in its infancy and not even close to what is observed in nature [11]. However, the field of biochemistry promises advanced high-performance self-growing and living biomimetic materials for the CI. For example, growth patterns of single-cell organisms and plants show growth characteristics that are of high interest for research. Gruber and Imhof [14] studied the biological growth principles of slime mold, single-cell algae, mycelium, root growth and restricted growth of plants. They transferred qualities present in growth patterns of these organisms, such as adaptiveness or local resource harvesting, into production processes. They developed self-growing structures in form of a mobile 3D printer working with local material. Also, they produced material systems with waste material grown into solid building material made of mycelium. Their results laid new pathways for further research that brings biomimetic materials for the CI closer to biological growth.

A biological function can be described as an adaptation mechanism of living systems. To survive, most living systems have to be able to adapt to extreme environmental conditions. Natural organisms sense and respond to environmental stimuli, their adaption mechanisms are for example self-healing, self-repairing, self-cleaning, self-assembly and self-shaping [11]. These adaption mechanisms observed in nature are highly desirable for biomimetic approaches to generate smart materials for the CI. Such materials are inspired by both **(1)** structural properties and **(3)** biological functions of natural organisms, as their functions are linked to the structural composition of the material [11]. For example, hygroscopic plant structures move in response to humidity changes in the environment without consuming metabolic energy [15]. This is achieved through anisotropic cellular mesostructures and differential swelling and shrinking properties. Natural cones and composite plants open under dry conditions for the release of seeds or pollen and close under wet conditions to keep the seeds or pollen safe. Inspired by the multi-phase motion of e.g. pinecones and the silver thistle, Tahouni et al. [15] presented a method to physically program sequential motion steps in 4D-printed (i.e. a 3D-printed structure with the extended capability to change its shape over time) hygro-responsive structures. They developed multi-layered, multi-material functional bilayers, combining highly hygroscopic active layers with hydrophobic restrictive and blocking layers, printed with bio-composite materials and (bio-)plastics. Their methods open up a range of possibilities such as locking/unlocking in self-assembling structures with possible applications in self-shaping architecture, e.g. in environmentally-responsive facade systems for energy-efficient building envelopes. Also inspired by self-shaping plant tissue structures, Grönquist et al. [16] presented a novel approach for the manufacturing of curved mass timber building components. Through a biomimetic concept of bi-layered composites, the authors developed a smart process to curve wood at large-scale. The process is based on large, programmed material deformations upon controlled moisture content change. It was successfully up-scaled to an industrial manufacturing process. As a proof of concept for application and competitiveness, they realized the 14 m high *Urbach tower*. These curved mass timber structures made of bi-layers open up new possibilities for structural timber engineering with a wide range of curved load-bearing structures.

In nature there is no such thing as waste, natural organisms operate according to a system of nutrients and metabolisms [17]. Carbon, oxygen, hydrogen and nitrogen – the planet's major nutrients – are cycled and recycled. The circulation and recycling of all materials and the interpretation of every matter as nutrient is one of the biggest lessons we can learn from nature. For example, in their biomimetic approach called 'Cradle to Cradle (C2C)', McDonough and Braungart [17] defined two cycles of material flows for our planet, i.e. the biosphere with biological nutrients (biomass) and the technosphere with technical nutrients (synthetic, man-made products). Inspired by **(4)** natural recycling processes, C2C describes the safe and potentially infinite circulation of materials as nutrients, where all constituents are chemically harmless and recyclable. This concept is also attempting to address and solve challenges the CI faces. Traditionally in the CI, resources are consumed in a way they cannot be recycled to an equivalent quality or returned to nature without a negative environmental impact [18]. Further challenges are the energy consumption of a building throughout its lifecycle, soil erosion, water pollution and the impact of a building on its users (e.g. indoor climate). C2C aims to not only reduce these negative impacts but to ensure that buildings have positive environmental impacts, where all materials used in the construction and use phase of buildings become nutrients for the biosphere or the technosphere, with known and healthy material compositions of all building components [18]. Therefore, biomimetic approaches can influence not only the way we design materials in terms of their properties and performance, but also the way we compose, use and recycle them.

1.3 Goals and hypotheses

The goals of this master thesis were

- to provide an overview of the research activities on biomimetic materials intended for application in the CI,
- to identify products made from biomimetic materials available on the market for applications in the CI,
- to assess the awareness of biomimetics and biomimetic materials among representatives of the CI in the D-A-CH region,
- and to assess the potential of biomimetic materials for application in the CI.

This master thesis aims to raise the awareness of biomimetics and to promote the use biomimetic materials in the CI in the D-A-CH region and beyond. The goal beyond this master thesis is to illustrate the beauty of nature and it's sophisticated materials, as well as the capabilities of biomimetics and materials science.

In this master thesis the following hypotheses and corresponding null hypotheses were formulated.

Hypothesis 1 (Scientific community)

H1: The scientific community is working on biomimetic materials intended for application in the construction industry.

H0: The scientific community is not working on biomimetic materials intended for application in the construction industry.

Hypothesis 2 (Construction industry)

H2: The concept of biomimetics is not familiar to the majority of representatives of the construction industry in the D-A-CH region.

H0: The concept of biomimetics is familiar to the majority of representatives of the construction industry in the D-A-CH region.

Hypothesis 3 (Building projects)

H3: To date, the use of biomimetic materials for building projects was not considered by the majority of representatives of the construction industry in the D-A-CH region.

H0: To date, the use of biomimetic materials for building projects was considered by the majority of representatives of the construction industry in the D-A-CH region.

2 Materials and Methods

2.1 Literature review

A literature review was conducted to either verify or reject hypothesis (1) 'The scientific community is working on biomimetic materials intended for application in the construction industry.'

The following databases were searched for the collection of scientific literature: ResearchGate (a large academic social network to share papers), ScienceDirect (a website which provides access to a large bibliographic database of scientific publications of the publishing company Elsevier) and Google Scholar (a freely accessible web search engine for full text or metadata of scientific literature). The search was keyword-based. In each database, search terms were used consistently to search the literature systematically. Different sets of keywords were used, for example 'biomimetic material construction industry', 'bio-inspired building material', 'nature-inspired material buildings'. Also specific types of materials were sought, such as 'biomimetic thermal insulation' or 'self-healing biomimetic material'. Only papers on biomimetic materials with potential application in the CI (more precisely: in buildings) were selected for the emerging review. Further, only papers published from the year 2000 and onwards were selected. The search took place between January and July 2022, approximately half a day per week (i.e. about 65 hours). The literature found was summarised and categorised in Table 1.

In addition to the literature review, the internet was searched for products made from biomimetic materials available on the market for the CI. The search for manufacturers and products was carried out using the most popular search engine Google Search. The search was keyword-based with similar sets of keywords as described above. The products found were summarised and categorised in a Table 2.

2.2 Questionnaire survey

A questionnaire survey was conducted to either verify or reject hypothesis (2) 'The concept of biomimetics is not familiar to the majority of representatives of the construction industry in the D-A-CH region.' and hypothesis (3) 'To date, the use of biomimetic materials for building projects was not considered by the majority of representatives of the construction industry in the D-A-CH region.'

The survey was conducted in the form of a structured questionnaire with ten closed-ended main questions, some additional closed-ended questions and some open questions. Only professionals from the CI operating in the D-A-CH-region were allowed to participate in the survey. Therefore, the survey was conducted in German. The design of the questionnaire was in sections. The first section sought the respondent's awareness of the concept of biomimetics and biomimetic materials for use in the CI.

The second section showed six examples of biomimetic materials for use in the CI (three from scientific research and three from products available on the market), followed by the third section, which asked for the respondents' reaction to the examples shown in the second section. Most of the questions in the first and third section were simple yes or no questions. The fourth and final section asked for background information on the respondents, including their professional affiliation, number of years of experience working in CI, the country in which their company is headquartered, and the country or countries in which their company operates. The detailed questionnaire survey can be found in the appendix. The survey was published on LinkedIn (a business professional networking platform) and sent to representatives of the CI in the D-A-CH region. The survey ran between 20 September and 11 October 2022. A total of 121 responses were collected.

3 Results

3.1 Literature review

In the literature review conducted, a total of 116 scientific papers on biomimetic materials intended for application in the CI were found. The majority of the studies was published between the years 2022 and 2017. The publishing authors and research groups are spread across many countries of the world.

The search for manufacturers and products made from biomimetic materials available on the market for the CI has revealed a total of 18 products manufactured by 12 different companies.

Fig. 2 shows a summary of potential applications of biomimetic materials for the CI that were found during the literature review. Applications for which products made from biomimetic materials are already available on the market are highlighted in green font colour.

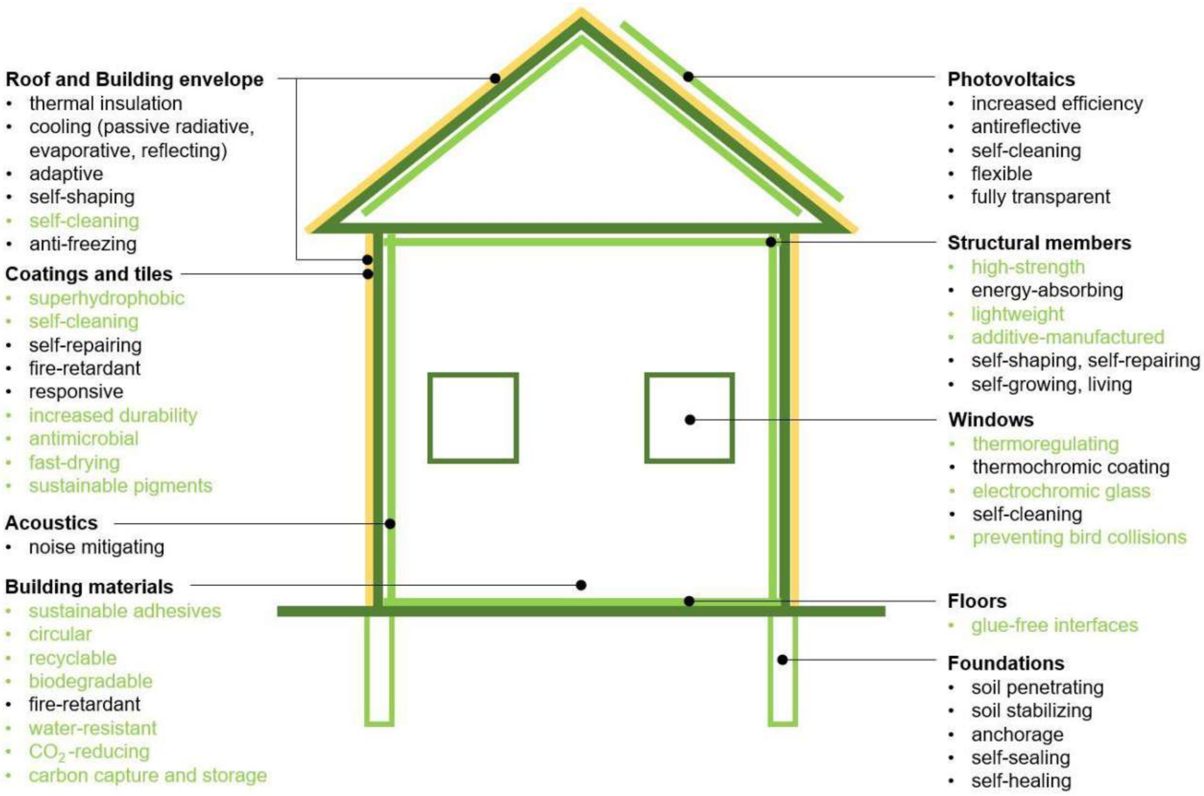

Fig. 2 Potential applications of biomimetic materials for the CI. Applications for which products made from biomimetic materials are already available on the market are highlighted in green font colour. Own contribution.

3.1.1 Scientific research on biomimetic materials

Table 1 lists scientific research on biomimetic materials intended for application in the CI. The table is organised according to the classification described in Fig. 1. The types of material, natural sources of inspiration, mimicked features and corresponding building applications are outlined, as well as references. This summary provides a comprehensive literature review of studies on biomimetic materials intended for application in the CI. The different types of material identified during the work on this master's thesis and listed in Table 1, are graphically assigned in Fig. 3 to their respective classes of biomimetic materials for the CI.

Table 1 A summary of scientific research on biomimetic materials intended for application in the CI.

Classification	Type of material	Natural source of inspiration	Mimicked feature	Application	Ref.
Inspired by structural properties	Thermo-regulating material	Cuttlefish bone, (bird, penguin) feather, silkworm cocoon, water spangles, kapok fibre, (polar bear) skin, (polar bear) hair, insect cuticle sclerotization chemistry, borate cross-linking found in higher plants	Hierarchically organised porous, tubular and/or fibrous structure	Thermal insulation (aerogels, foams, porous ceramics, others) with low thermal conductivity for building envelopes and roofs	[12], [13], [19]–[28]
		Saharan silver ant hair, silkworm cocoon, white beetle scale, long-horned beetle forewing, polar bear fur	Microstructures with high solar reflection and thermal emittance for passive radiative cooling	Passive radiative cooling coating for building envelopes and roofs	[21], [29], [29]–[34]
		(Elephant) skin, (mammals) sweat glands	Porous structures and morphological configurations releasing (and capturing) liquids for evaporative cooling	Evaporative cooling polymers and hydrogels for building envelopes and roofs	[21], [35]–[37]
		Abalone shell (nacre), poplar leaf hair	Multilayer microstructure with high reflectance for reflective cooling	Reflective cooling coating for building envelopes and roofs	[38], [39]
		Moth eye	Tapered nanostructure with optical antireflection properties	Thermochromic coatings for smart windows with improved thermochromism and hydrophobicity	[40]–[42]
		Succulent plants envelopes, animal fur	Surface structures for influencing external air flow characteristics and heat transfer rate within the material	Sculptured concrete tiles with improved thermal insulation for building envelopes	[43]
	Energy-absorbing composite	Abalone shell (nacre), conch shell (crossed-lamellar structure), tree bark, spine of sea urchin, bone, diatom	Deformation mechanisms, hierarchical, mesocrystal or functionally graded structure	Structural members and cementitious materials with increased ductility and toughness; seismic, impact and blast resistance	[44]–[53]
				Steel and metal alloys with increased toughness, crack and fatigue resistance	[54]–[56]

Table 1 continued on next page

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Inspired by structural properties	Additive manufactured material	Various biological organisms such as wood, bone, shell, dactyl club of Mantis Shrimp, exoskeleton of crab, lobster cuticle, fish slace, spine of sea urchin, deep-sea glass sponges, (Caladium bicolor) leaf, etc.	Hierarchical, cellular or graded structures and composites	Structural members and cementitious materials with increased mechanical and damage tolerant properties and/or decreased density or decreased material use	[57]–[64]
	Surface textured material	Moth eye, fly eye, butterfly and beetle wing scale, cicada wing, water fern leave	Nanostructured porous surfaces; surface and internal hierachical structures	Photovoltaics: Antireflecting coatings and thin film solar cells with increased light-harvesting efficiency	[65]–[78]
		(Cyphochilus) beetle exoskeleton	Light scattering effects on nanostructured randomly oriented filaments	White pigment for paints, coatings	[79]
		Snakeskin	Directional structure-soil interfaces	Soil penetration of building foundations	[80]
		Human skin	Hierarchical structure with three levels of gradient in roughness/wetting, strength, and flame retardancy	Superhydrophobic coatings with superior mechanical-chemical-thermal properties for building materials	[81]
		Succulent plants envelopes, animal fur	Surface structures for influencing external air flow characteristics and heat transfer rate within the material	Sculptured concrete tiles with improved thermal insulation for building envelopes	[43]
	Fire-retardant coating	Abalone shell (nacre)	Brick-and-Mortar ordered multilayer microstructure	Fire protection coating for roofs, external walls and/or other building materials	[31], [38], [82]
		Lava	Micro/nano-structured ceramic layer (formed upon exposure to flame)	Fire protection coating for various substrates such solid wood, steel sheets, polyurethane foams and other building materials	[83]
	Lightweight material	Mammalian bone, spine of sea urchin	Multifunctional lightweight composite structure for enhanced mechanical properties	Sandwich composite reinforcement for lightweight pre-fabricated (modular) concrete structures, structural members	[48], [84]
		Wood microstructure	Hierarchical cellular structure and matrix embedded with well-oriented cellulose fibrils	Structural members ('Polymeric woods') with high specific strength, increased thermal insulation properties and fire-retardancy compared to natural wood	[85], [86]

Table 1 continued on next page

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Inspired by biological processes	Growing material	Slime mold, fungus mycelium, swarms	Biological growth mechanisms; adaptiveness; local resource harvesting; autonomously ranging agents	Self-growing structures; solid lightweight building material and building elements from waste products; design and production processes; mobile 3D printing with local material	[14]
	Living material	Protocells, bacteria, slime mold, organs	Embodied, dynamic, responsive systems	Intelligent building materials; lively interfaces with bio/chemical activity, providing infrastructure, e.g. producing heat, filtering water, storing CO_2 in e.g. building envelope or floor, ('architectural organs')	[87]
		Fungal cells; microorganisms on leaves	Surface texture consistency and self-healing mechanism of fungal cells	Durable coatings for wooden facades	[88]
Inspired by functions	Biophotonic material	Moth eye, fly eye, human eye (retina), sea urchin; photosynthesis, natural pigments (e.g. chlorophylls), bio-derived materials such as monosaccharides, cellulose, chitin, lignin, starch, amino acids, proteins, DNA	Light-harvesting mechanism, electron-transfer reactions, spectroscopical, optical mechanical and structural features	Flexible, fully transparent, and/or high-efficient solar cells and windows; bio-derived materials for photovoltaics (third generation PV technologies)	[75], [76], [89]–[91]
	Sound-absorbing material	Moth wings	Sound absorbing mechanism of scales, wing membrane and air movement	Noise mitigating solutions (e.g. coatings) for acoustically reflective substrates	[92], [93]
	Responsive material	Chameleon skin and nervous system; African reed frog, Hercules beetle	Adaptive mechanism of actively controlled absorption or reflection of solar radiation (color changing mechanisms)	Thermoregulation: Electrochromic window material; adaptive building envelope composite	[94], [95]
		Scarabaeid beetle scale	Modification of fluorescence properties in multi-layered structure to enhance or inhibit the emission of certain wavelengths	Photovoltaics with increased light-harvesting efficiency	[96]
		(Mammals) sweat glands	Porous structures releasing liquids for evaporative cooling	Thermoresponsive evaporative cooling polymers and hydrogels for building envelopes and roofs	[21], [35], [36]

Table 1 continued on next page

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Inspired by functions	Self-shaping material	Pine cone scales, Chinese wisteria seed pod, edamame seed pod, wheat awns, stork's bill, silver thistle	Self-shaping mechanisms through bi-layered composite structures as a function of the moisture content	Manufacturing of curved timber building components; hygromorphic adaptive building materials (skins); self-shaping large-scale structures for buildings; self-shaping clay tiles	[15], [16], [97]–[104]
		Plant Root (systems)	Shape-change mechanism, adaptability, morphology	Building foundations (mechanical anchorage, soil stability, soil penetration, prevention of soil erosion)	[105]
	Self-cleaning material	Lotus leaf, water strider leg, mosquito eye, moth eye, duck feather, butterfly wing, cicada wing, water spangles	Water-repellent, super-hydrophobic and self-cleaning mechanisms through hierarchical roughness, hydrophobic wax coating	Self-cleaning windows, exterior paints for buildings, roof tiles, solar panels, water-repellent concrete surface	[25], [32], [40], [69], [77], [78], [106]–[109]
	Self-repairing material	Hemostasis of human spongious bone, human skin, plant root, higher plants	Self-sealing and self-healing mechanisms through delivery and reaction of healing agents; through accretional growth around wounds	Self-sealing and self-healing concrete; cementitious composites; building foundations	[105], [110]–[112]
	Adhesive material	Mussel	Fast curing mechanisms, strong and tough adhesive interfacial interaction with various substrates, moisture-resistant adhesion	Bonding of various building materials such as wood, metal, glass, plastic	[113]–[118]
		Snail mucus, tree frogs toe pads	Interfacial hydrogen-bonding and mechanical interlocking for strong adhesive interaction with various substrates	Strong bonding of fire-extinguishing and fire-retardant polymeric coatings to thermal insulation foams	[119]
	Fire-retardant material	(Matrix mediated) biomineralisation found in various species	Calcification; struvite mineralisation; endothermic decomposition of calcium carbonate; or struvite; as a fire protection agent	Fire-retardant engineered wood products	[120]–[122]
		Succulent plants	Water binding capacity of mucilage, water-loss prevention of cuticle	Fire-retardant sidings	[123]

Table 1 continued on next page

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Inspired by functions	Fire-retardant material	Algae (Cladophora sp.) coated with silica diatoms	Thermal and diffusion barrier to oxygen and dehydration of algal cellulose through silica to carbonaceous layer	Fire protection coating for polyurethane foams	[124]
		Borate cross-linking found in higher plants	Borate cross-linking	Porous cellulose foams for structural materials, sound insulation, thermal insulation with increased mechanical and fire-retardant properties and self-extinguishing behaviour	[28]
		(Human) sweat glands and skin	Heat self-regulation mechanism of sweat glands	Cement-based composite material for improved fire resistance of structural members	[125]
		Wood microstructure	Hierarchical cellular structure and matrix embedded with well-oriented cellulose fibrils	Structural members ('Polymeric woods') with increased fire-retardancy compared to natural wood	[85]
	Antifreeze material	Native ice-binding proteins found in various biological organisms of plants and animals	Ice recrystallization inhibition and dynamic ice shaping activities	Antifreeze polymer for prevention of damage from ice crystal growth in cement paste and concrete	[126], [127]
Inspired by recycling processes	Circular material	Recycling process of nature as a whole	Interpretation of every matter as nutrient	Circular economy with building materials	[17], [18]
	Bio-degradable material	Monosaccharides, cellulose, chitin, lignin, starch, amino acids, proteins, DNA	Biodegradability and sustainable production processes	Biodegradable components for photovoltaics	[89]

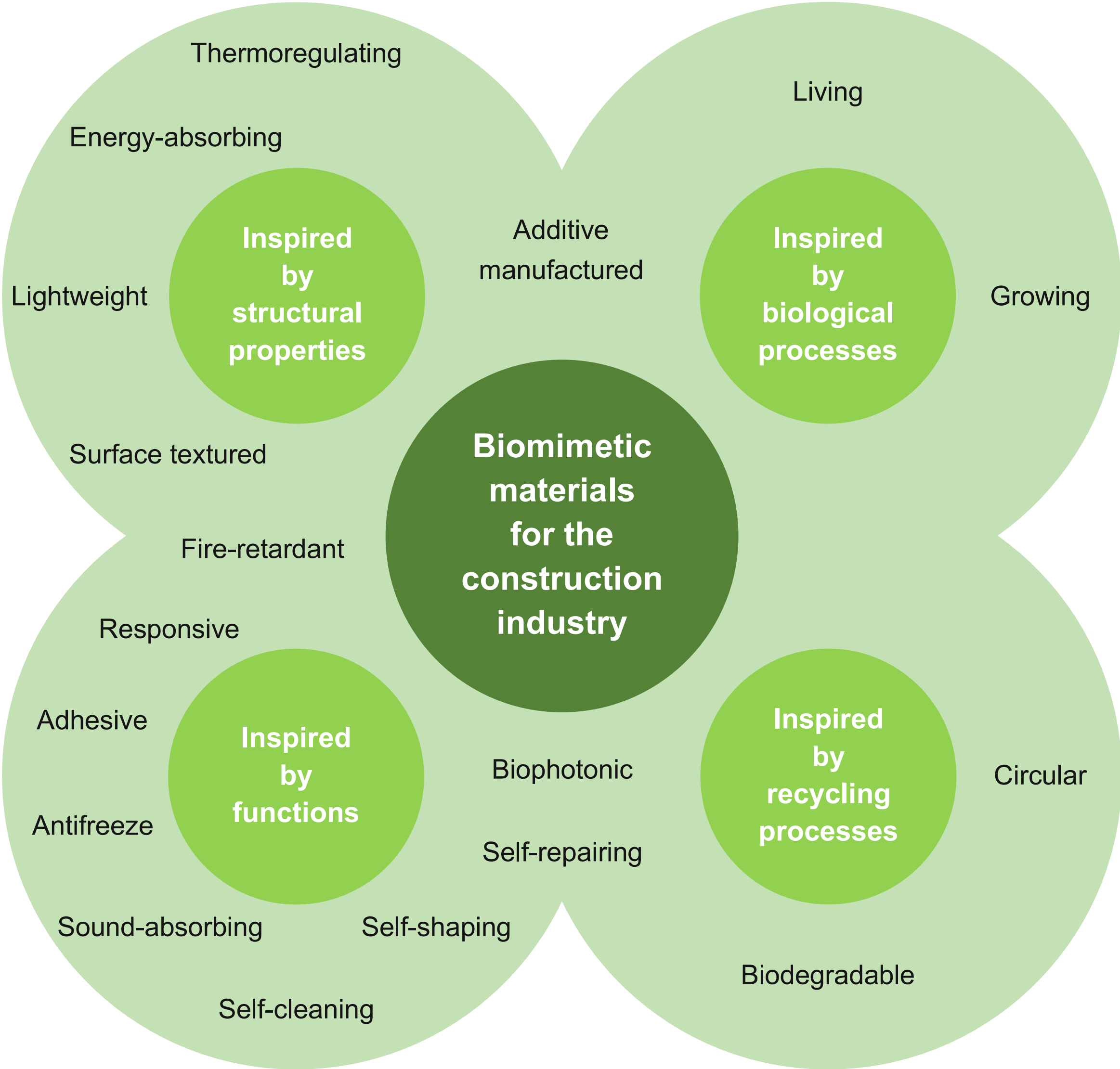

Fig. 3 Different types of biomimetic material assigned to their respective classes of biomimetic materials for the CI. Own contribution. Classification based on [11].

3.1.2 Products made from biomimetic materials

Table 2 lists products made from biomimetic materials available on the market for the CI. The table is organised in the same manner as Table 1, according to the classification described in Fig. 1. The types of material, natural sources of inspiration, mimicked features and corresponding building applications are outlined, as well as references. This summary provides a comprehensive overview of the state of the art products made from biomimetic materials available on the market for the CI.

Table 2 A summary of products made from biomimetic materials available on the market for the CI.

Classification	Type of material	Natural source of inspiration	Mimicked feature	Application	Product (company)
Inspired by structural properties	Surface textured material	Namibian fog-basking beetle	Structured surface with microscopic hydrophilic and hydrophobic bumps	Fast-drying (after rain and dew) facade coating increasing weathering resistance and protection against algae and fungi	StoColor Dryonic® (Sto)
		(Cyphochilus) beetle exoskeleton	Light scattering effects on nanostructured randomly oriented filaments	100% plant-based cellulose white pigment for paints and coatings as substitute product for titanium dioxide	Impossible Materials (Impossible Materials Ltd)
		Orb-weaver spider web	UV-reflection of spider web	UV-reflective glass coating for e.g. windows or facades to prevent bird collisions	ORNILUX® (Arnold Glas)
	Lightweight material	Wood, tree	High specific strength through fiber orientation, density ratios and form	Timber-based structural composites (e.g. timber joints, freeform structural shells) for additive manufactured high strength lightweight structural members	Woodflow™ (Strong by Form)
Inspired by biological processes	Carbon capture and storage material	Biomineralisation, carbonate rock	Permanent carbon capture through mineralisation	Synthetic limestone, aggregate and concrete from waste concrete (upcycling)	Geomimetic® (Blue Planet)
		Marine organisms, coral reef	Permanent carbon capture through ozeanic mineralisation (calcination process)	Supplementary cementitious material, binder or cement with reduced carbon dioxide emissions	ReCarb™, Reactive Calcium Carbonate™ (Fortera)
	Growing material	Marine ecosystem, coral reef	Biological growth of limestone through natural microorganisms in ambient temperatures	Cementitious material preventing carbon dioxide emissions	Biocement® (Biomason)
				Precast tiles for e.g. flooring, walls; preventing carbon dioxide emissions	Biolith® (Biomason)
Inspired by functions	Responsive material	Bobtail squid platelet, hummingbird feather	Adaptive mechanism of actively controlled absorption or reflection of solar radiation (color changing mechanisms)	Thermoregulation: Electrochromic glass for e.g. windows and facades	SageGlass® (Saint-Gobain)
	Self-cleaning material	Lotus leaf	Super-hydrophobic and self-cleaning mechanisms through hierarchical roughness	Self-cleaning facade paints	StoColor Lotusan®, StoColor Lotusan AimS® (Sto)

Table 2 continued on next page

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Inspired by functions	Self-cleaning material	Lotus leaf	Super-hydrophobic and self-cleaning mechanisms through hierarchical roughness	Self-cleaning finish plaster	StoLotusan® K, StoLotusan® MP (Sto)
				Self-cleaning clay roofing tiles / coverings	Erlus Lotus® (Erlus)
	Adhesive material	Mussel	Fast curing mechanisms, strong and tough adhesive interfacial interaction, moisture-resistant adhesion	Soy-based formaldehyde-free adhesive for engineered wood products for buildings	PureBond® (Columbia Forest Products)
		Gecko toe pads	Increased Van der Waal forces through microscopic hair structures	Glue-free interface for joining modular flooring tiles	TacTiles® (Interface)
Inspired by recycling processes	Bio-degradable material	Mycelium	Biodegradation through mycelium which decomposes complex carbon compounds	Recycling process to break down construction and demolition waste materials (such as asphalt or toxic constituents from petrochemical industry) resulting in a renewable by-product for a circular economy	Mycocylce™ (Mycocylce)

3.2 Questionnaire survey

Table 3 reveals the results of the ten closed-ended main questions from the questionnaire survey conducted. The questions asked and the corresponding sum of answers given by the respondents are shown. The last column shows the percentage ratio of the answers within the respective question. The questions and answers consulted for hypotheses 2 (Construction industry) and 3 (Building projects) are highlighted (i.e. no. Q1 and no. Q4, respectively).

From the 121 respondents, 98 (i.e. 81.0%) stated that they were not familiar with the concept of biomimetics. 86 respondents (i.e. 71.1%) stated that they had never considered to use a biomimetic material in one of their building projects in the D-A-CH region. Questions no. Q2 to Q10 were asked after the concept of biomimetics had been explained to respondents in the questionnaire survey.

Table 3 Results of the ten closed-ended main questions Q1 to Q10 from the questionnaire survey conducted.

No.	Question	Sum of answers		Percent
Q1	**Are you familiar with the concept of biomimetics?**	**Yes**	**23**	**19.0**
		No	**98**	**81.0**
Q2	Have you ever heard of biomimetics in the context of the construction industry?	Yes	68	56.2
		No	53	43.8
Q3	Do you know of building projects in the D-A-CH region that have used or plan to use biomimetic materials?	Yes	37	30.6
		No	84	69.4
Q4	**Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region?**	**Yes**	**35**	**28.9**
		No	**86**	**71.1**
Q5	Do you know about scientific work and developments on biomimetic materials for the construction industry?	Yes	31	25.6
		No	90	74.4
Q6	Do you know of biomimetic materials available as products on the market for the construction industry?	Yes	38	31.4
		No	83	68.6
Q7	After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region?	Yes	112	92.6
		No	9	7.4
Q8	Biomimetic materials have the potential to significantly increase the sustainability of the construction industry in the D-A-CH region.	1 = Strongly disagree	0	0.0
		2 = Disagree	5	4.1
		3 = Neither agree nor disagree	20	16.5
		4 = Agree	60	49.6
		5 = Strongly agree	36	29.8
Q9	The development and application of biomimetic materials should be promoted and advertised more intensively in the construction industry in the D-A-CH region.	1 = Strongly disagree	0	0.0
		2 = Disagree	1	0.8
		3 = Neither agree nor disagree	18	14.9
		4 = Agree	49	40.5
		5 = Strongly agree	53	43.8
Q10	Do you want to learn more about biomimetics, biomimetic materials and products for the construction industry as well as for other applications?	Yes	118	97.5
		No	3	2.5

Respondents that answered ‘No’ to question no. Q7 ‘After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region?’ were asked ‘Why wouldn’t you use a biomimetic material in one of your next building projects?’. Their answers (translated into English) are shown in Table 4.

Table 4 Respondents' answers to the question 'Why wouldn't you use a biomimetic material in one of your next building projects?'.

Why wouldn't you use a biomimetic material in one of your next building projects?
Everything still very unknown.
Costs and too little experience regarding durability.
No significant advantage.
We do not yet have a suitable application.
I can only use materials that are officially admitted and reliable.
Not yet practically implementable.
Use as load-bearing elements in structural engineering for classical tasks is not conceivable in the foreseeable future. Mainly used in facades and lightweight pavilions.
No specialist companies as suppliers.
Convincing the clients would be difficult.

The background information on the respondents from the questionnaire survey conducted is shown in Table 5. The information collected and the corresponding sum of answers given by the respondents are shown. The last column shows the percentage ratio of the answers within the respective background information. According to their professional affiliation, the majority of the respondents are architects (14%), followed by construction and project managers (10.7%). Most of the respondents (29.8%) have 5 to 10 years of professional experience in the CI, followed by less than 5 years (27.3%) and more than 20 years (23.1%) of experience in the CI. The majority of respondents work for companies with headquarters in Austria (79.3%), followed by Germany (15.7%) and Switzerland (5.0%). In total, 82.6% of the respondents' companies operate in Austria, followed by 65.3% operating in Germany and 44.6% operating in Switzerland. A total of 51 respondents (42.1%) provided their email address to be informed about the results of this questionnaire survey and master thesis.

Table 5 Background information on the respondents from the questionnaire survey conducted.

Background information	Sum of answers		Percent
Professional affiliation	Architect	17	14.0
	Civil engineer	10	8.3
	Construction manager	12	9.9
	Construction and project manager	13	10.7
	Building physicist	4	3.3
	Building technician	5	4.1
	CEO	5	4.1
	CTO	2	1.7
	R&D	6	5.0
	Innovation manager	8	6.6
	Marketing	4	3.3
	Planner	5	4.1
	Project developer	7	5.8
	Structural engineer	0	0.0
	Sales	5	4.1
	Other C-Level	1	0.8
	Other position in the construction industry	17	14.0
No. of years of professional experience in the construction industry	Less than 5 years	33	27.3
	5 to 10 years	36	29.8
	11 to 20 years	24	19.8
	More than 20 years	28	23.1
Headquarter of the company you work for	Germany	19	15.7
	Austria	96	79.3
	Switzerland	6	5.0
Country or countries in which your company operates	Germany	79	65.3
	Austria	100	82.6
	Switzerland	54	44.6
Please inform me about the results of this survey and thesis at the following email address:	Respondents interested in the results	51	42.1

4 Discussion

4.1 Biomimetic materials for the construction industry

The results from Chapter 3.1 and 3.1.1 show that the scientific community is working on biomimetic materials intended for application in the CI. Based on the high number of topical papers shown in Table 1, hypothesis (1) ‘The scientific community is working on biomimetic materials intended for application in the construction industry.’ was supported by the results. Table 1 also reveals that in each class of biomimetic materials proposed by Imani et al. [11], many different types of materials are being scientifically researched. This is further illustrated in Fig. 3, which highlights that the classes of ‘Inspired by structural properties’ and ‘Inspired by functions’ feature the most diverse types of material. It was found that in the class ‘Inspired by biological processes’ only two main types of material are currently being researched, namely living and growing material. This is in line with [11] who found that the growth of ‘living’ materials is still in its infancy and not even close to what is observed in nature. Also for the class ‘Inspired by recycling processes’ it was found that only two main types of material are currently being researched, namely circular and biodegradable material. However, considering that this class basically includes all materials and material flows that have to do with recycling, circularity or biodegradability, it becomes obvious that this class is no less important than the others. Fig. 3 further indicates that different types of material may also be inspired by multiple classes, for example additive manufactured material, which are inspired by both structural properties as well as biological processes. This was also pointed out by [11], who argued that self-repairing materials, for example, are inspired by structural properties as well as functions.

From Table 1 it can be derived that scientific research on biomimetic materials intended for application in the CI is inspired by a wide variety of natural sources. Plants, insects, animals as well as humans serve for inspiration. Many different natural structures, functions and processes across many different species, length scales and diverse habitats are being investigated. From single-celled organisms or moth eyes to trees or elephant skin, from chemical or physical processes to mechanical properties, from marine organisms to land and flying animals - the versatility is enormous and full of potential.

The features mimicked from nature are very diverse, which can be seen in Table 1. Hierarchically organised structures, nano-, micro- and macrostructures or surface structures are often mimicked to achieve certain structural properties, as well as porous, fibrous or composite structures. Biological growth mechanisms, adaptive mechanisms, self-shaping, self-cleaning or self-healing mechanisms as well as adhesive, cooling and fire protective mechanisms are often mimicked processes and functions. Recycling processes as a general concept for resource utilisation and environmental responsibility are also mimicked very often.

Fig. 2 reveals a wide variety of potential applications of biomimetic materials in the CI. They range from structural components such as roof and building envelope to (load-bearing) structural members, coatings and tiles, windows, floors and foundations. There are also potential applications in areas such as photovoltaics and acoustics. Additionally, sustainable measures such as circularity, recycling, biodegradability as well as reduced CO_2 emissions and carbon capture and storage play important roles for biomimetic building materials. Benefits are being explored in all these potential applications by the scientific community. For some of these applications, products made from biomimetic materials are already available on the market for the CI, also shown in Fig. 2. It can be seen that these products already cover quite a diverse range of applications for the CI, e.g. self-cleaning facade paints or electrochromic glass.

Derived from Table 1 and shown in Fig. 4, it can be seen that most literature on biomimetic materials for the CI was found in the areas of thermal insulation and cooling (38 publications), followed by materials with increased mechanical properties (23 publications), photovoltaics (21 publications), fire protection (14 publications), self-cleaning (13 publications), self-shaping (11 publications), additive manufacturing and lightweight (11 publications), adhesive (7 publications) and self-healing (5 publications) materials. Less but still promising literature was found in the areas of soil penetration and foundation (2 publications), anti-freezing (2 publications), acoustics (2 publications), living (2 publications) and self-growing (1 publications) materials.

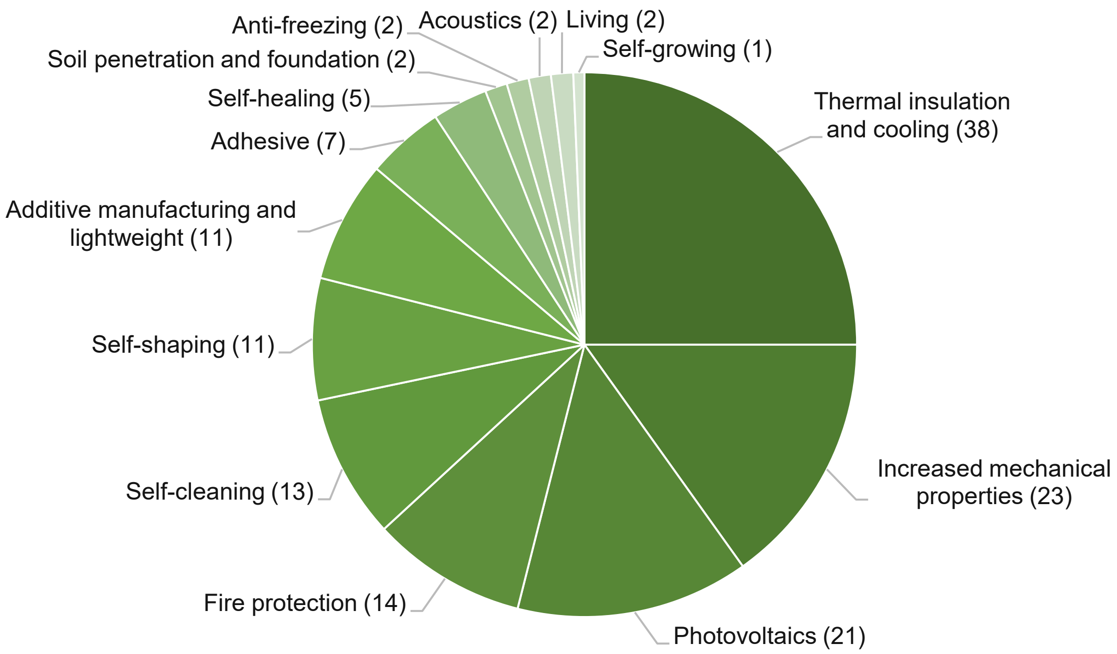

Fig. 4 Areas and numbers of publications on biomimetic materials for the CI found in the literature review conducted. Note: In total, this is more than the 116 scientific papers found in the literature review conducted, as in some cases several areas of application are described within one publication. Own contribution.

These applications and their order of frequency reveal that research activities on biomimetic materials for the CI are very much in the areas of sustainability and climate change-adapted materials. Thus it can be argued that the research on biomimetic materials and their applications in the CI have the potential to make an important contribution to mitigating the above mentioned environmental problems such as climate change and resource scarcity. Findings in areas of application such as thermal insulation and cooling or photovoltaics, fire protection as well as others could significantly boost the adaptation of our building practices to climate change. This is also reflected in the products made from biomimetic materials available on the market for the CI. Similar areas of application areas emerge when comparing the applications from research with the applications of the products available on the market. However, it can also be seen that the number of scientific research (publications) on biomimetic materials for the CI is significantly higher than the number of products made from biomimetic materials actually available on the market. The reasons for this and the challenges for product development or marketability of biomimetic materials for the CI should be further investigated. In the following chapter the awareness for biomimetic materials and their potential for application in the CI is discussed based on the results of the questionnaire survey conducted.

4.2 Awareness of biomimetic materials in the construction industry

Table 5 reveals that the group of respondents from the questionnaire survey is composed of a balanced mix of professional affiliations (shown in Fig. 5), professional experience (shown in Fig. 6) and countries of operation within the CI in the D-A-CH region (shown in Fig. 7). Apart from structural engineers, each of the eligible professions is represented in the survey. It is possible that structural engineers are also represented in the survey but chose the description ‘Civil engineer’ for their professional affiliation instead (due to the fact that structural engineers usually have a degree in civil engineering and ‘Civil engineer’ was further up the list of selectable professional affiliations). In addition, 17 respondents stated that they hold positions in the CI other than those that could be selected in the survey. This makes the mix of respondents’ professional affiliations within the CI even more diverse.

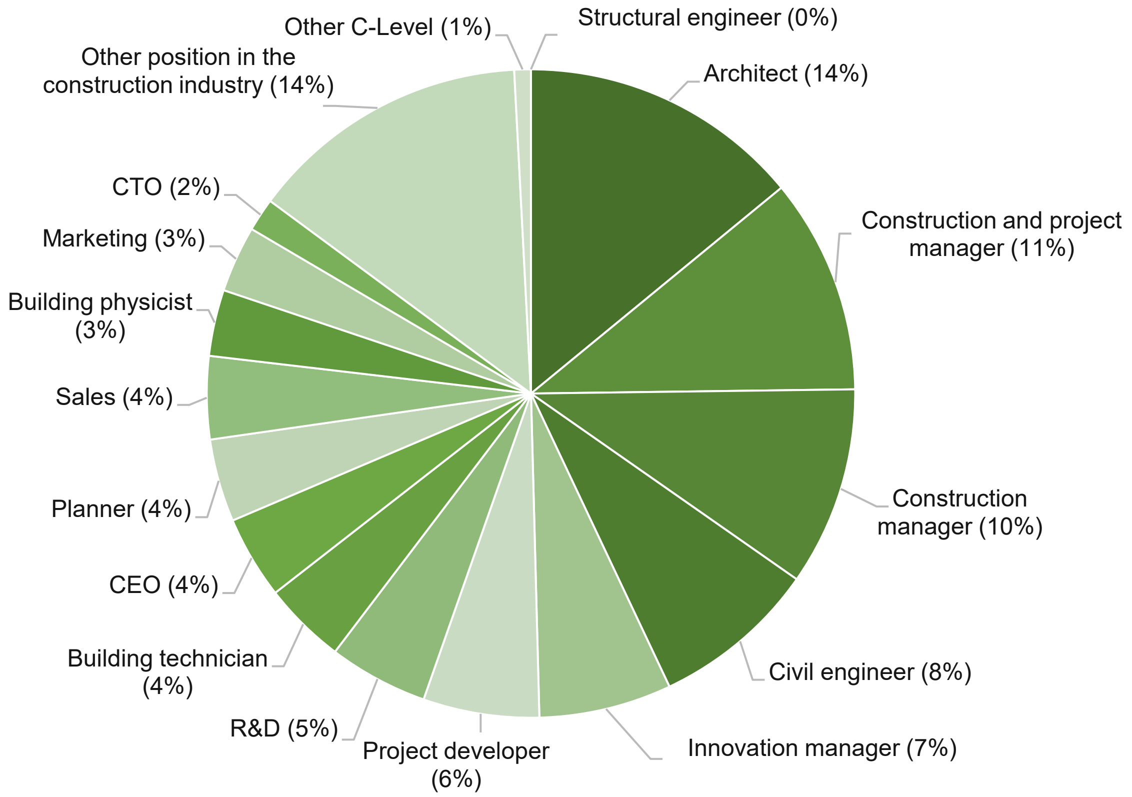

Fig. 5 Distribution (n = 121) of the respondents' professional affiliation in the CI. Own contribution.

The number of years of professional experience in the CI is very balanced among the respondents, with approximately one quarter per selectable option, i.e. from less than 5 years up to more than 20 years of professional experience in the CI.

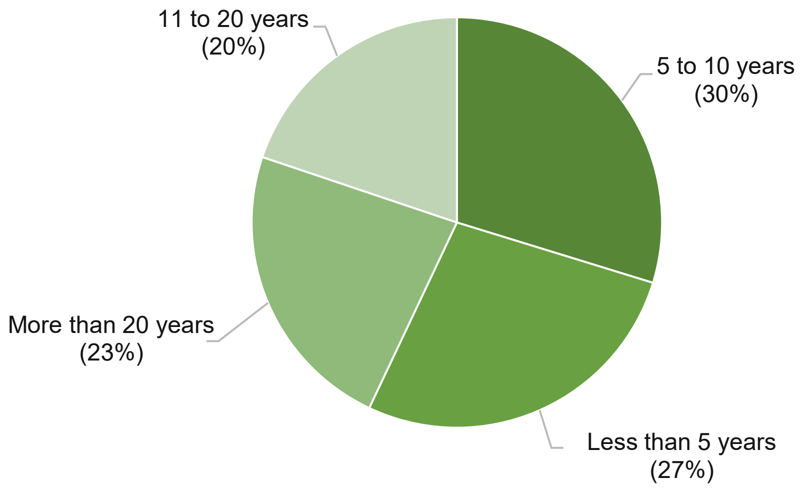

Fig. 6 Distribution (n =121) of the respondents' number of years of professional experience in the CI. Own contribution.

Although the majority of respondents work for companies with headquarters in Austria, many of these companies operate in Germany and/or Switzerland as well, making the D-A-CH region well represented geographically. Based on their background information, it is assumed that the group of survey respondents is sufficiently representing the CI in the D-A-CH region. However, it must be mentioned that the respondents who participated in the survey are probably automatically a more active and interested sample of representatives. It is possible that this has led to a certain bias in the answers and results. For example, it could be that the respondents are to some extent more aware or open to new or innovative topics, such as that of this thesis. However, in the design of the survey, care was taken to limit this bias by intentionally revealing the topic of the thesis and especially the word 'biomimetics' only during the survey and not before. Further, the title of the thesis was intentionally not revealed.

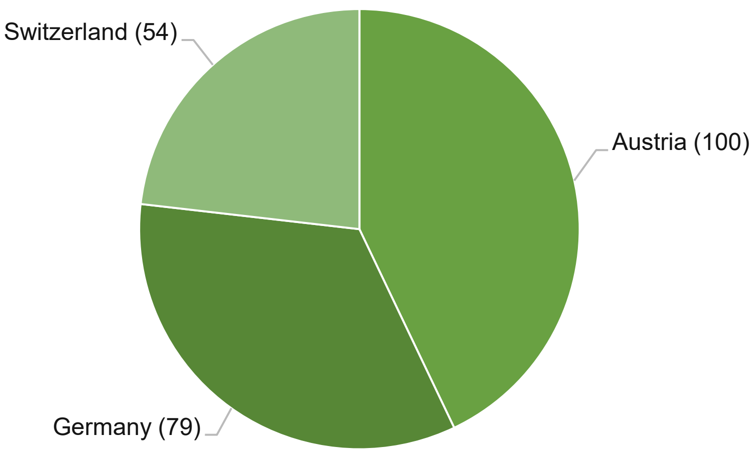

Fig. 7 Distribution of countries (number), in which respondents' companies operate in the CI in the D-A-CH region. Own contribution. Note: This was a multiple choice question.

The results in Chapter 3.2 show that most of the respondents were not familiar with the concept of biomimetics, as illustrated in Fig. 8. Specifically, 81.0% of respondents answered 'No' to the question no. Q1 'Are you familiar with the concept of biomimetics?'. Based on this result and the assumption that the group of respondents is sufficiently representing the CI in the D-A-CH region, hypothesis (2) 'The concept of biomimetics is not familiar to the majority of representatives of the construction industry in the D-A-CH region.' was supported by the results. This is further underlined through the results to questions no. Q3, Q5 and Q6, showing that 69.4% of the respondents did not know of building projects in the D-A-CH region that used or plan to use biomimetic materials (Q3), 74.4% of the respondents did not know about scientific work and developments on biomimetic materials for the CI (Q5) and 68.6% of the respondents did not know of products made from biomimetic materials available on the market for the CI (Q6).

After the concept of biomimetics was explained in the survey, 56.2% of respondents stated that they had heard of biomimetics in the context of the CI (Q2, illustrated in Fig. 8). Therefore, some respondents who previously in the survey stated that they were not familiar with the concept of biomimetics seem to have at least heard about biomimetics (or something that is similar to its definition) in the context of the CI.
71.1% of respondents answered 'No' to the question 'Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region?' (Q4). Based on this result and the assumption that the group of respondents is sufficiently representing the CI in the D-A-CH region, hypothesis (3) 'To date, the use of biomimetic materials for building projects was not considered by the majority of representatives of the construction industry in the D-A-CH region.' was supported by the results. There could be several reasons why the majority of CI representatives have not used biomimetic materials in their building projects in the D-A-CH region to date. One reason might be that the majority of representatives were not aware of the concept of biomimetics (as pointed out above). Further possible explanations could be given with other results from the questionnaire survey conducted. 74.4% of respondents indicated they did not know of any scientific research or developments on biomimetic materials for the CI (Q5) and 68.6% of respondents indicated that they did not know of products made from biomimetic materials available on the market for the CI (Q6).

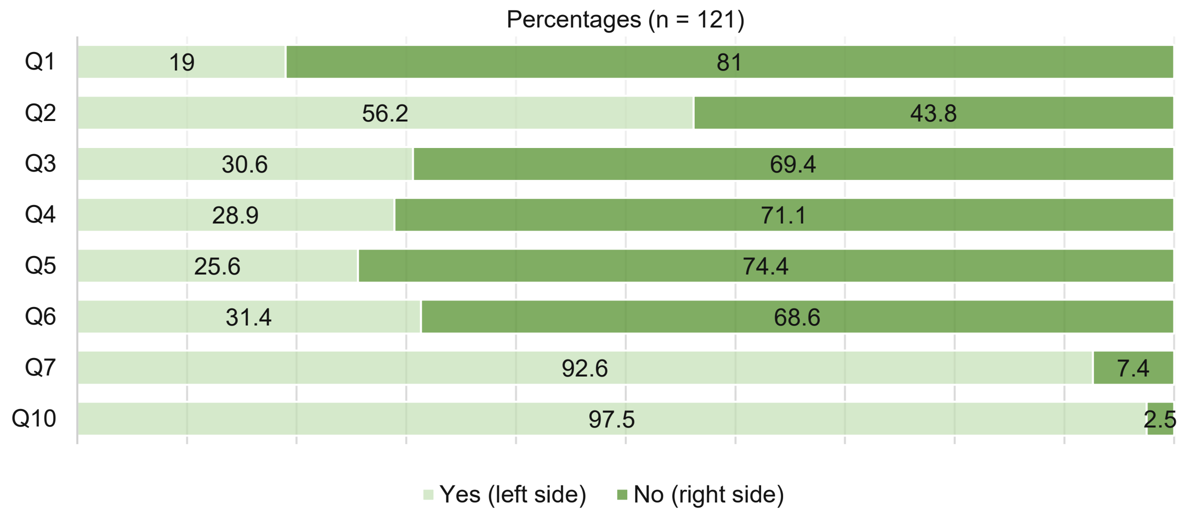

Fig. 8 Results (percentages, n =121) to the questions no. Q1 to Q6 as well as Q7 and Q10 from the questionnaire survey conducted. Q1 = Are you familiar with the concept of biomimetics? Q2 = Have you ever heard of biomimetics in the context of the CI? Q3 = Do you know of building projects in the D-A-CH region that have used or plan to use biomimetic materials? Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Q5 = Do you know about scientific work and developments on biomimetic materials for the CI? Q6 = Do you know of biomimetic materials available as products on the market for the CI? Q7 = After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region? Q10 = Do you want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications? Own contribution.

The results of the survey conducted further show that after the respondents were shown the six examples of biomimetic materials for the CI, 92.6% of them would consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region (Q7, illustrated in Fig. 8). This also speaks in favour of the above-mentioned attempts to explain that the respondents have not used biomimetic materials to date due to their lack of awareness. This lack of awareness for biomimetic materials can also be observed in the answers (shown in Table 4) of the nine respondents from the questionnaire survey conducted, who stated that they would not use a biomimetic material in one of their next building projects. Most of these answers or arguments could probably be rebutted through awareness raising or the provision of information.

49.6% of respondents agree and 29.8% strongly agree that biomimetic materials have the potential to significantly increase the sustainability of the CI in the D-A-CH region, 16.5% of respondents neither agree nor disagree, 4.1% disagree and nobody strongly disagrees (illustrated in Fig. 9). It could be argued that the sustainability of a biomimetic material depends very much on the particular product. However, generally speaking, e.g. Ahamed et al. [7] pointed out, that the application of biomimetic materials in the CI can play a crucial role in making buildings more energy-efficient, more sustainable and more resilient. It can be seen that the opinion of the majority of respondents on the sustainability of biomimetic materials for the CI is in line with the state of scientific knowledge.

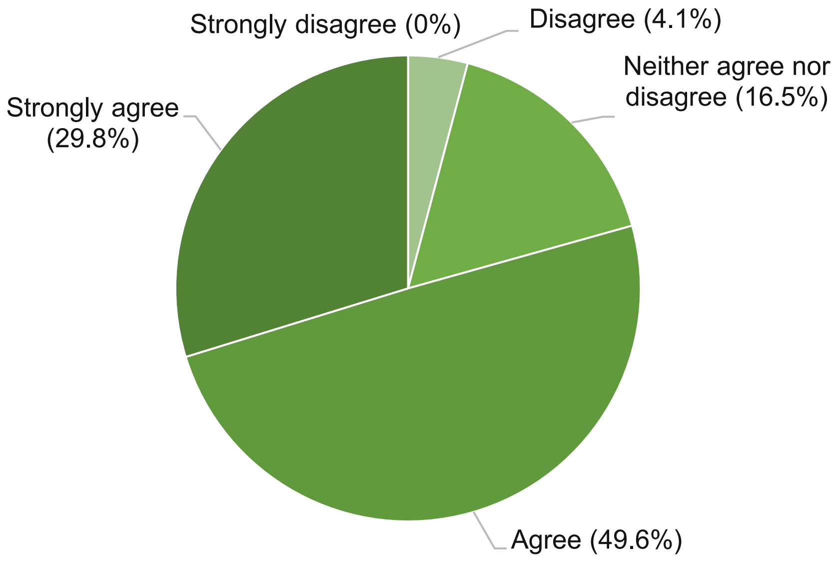

Fig. 9 Distribution of respondents' answers to question no. Q8: Biomimetic materials have the potential to significantly increase the sustainability of the construction industry in the D-A-CH region. Own contribution.

43.8% of respondents strongly agree and 40.5% agree that the development and application of biomimetic materials should be promoted and advertised more intensively in the CI in the D-A-CH region, 14.9% neither agree nor disagree, 0.8% (i.e. one respondent) disagree and nobody strongly disagrees (illustrated in Fig. 10).

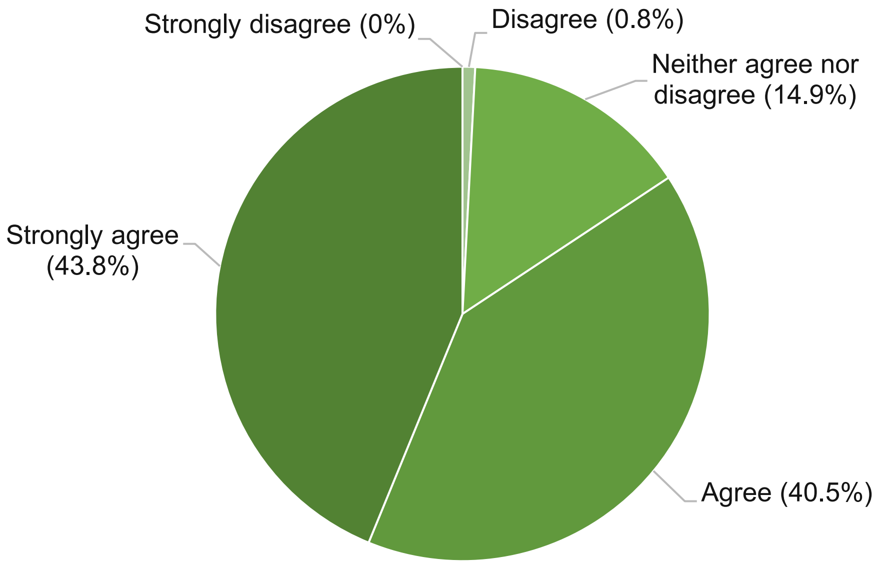

Fig. 10 Distribution of respondents' answers to question no. Q9: The development and application of biomimetic materials should be promoted and advertised more intensively in the construction industry in the D-A-CH region. Own contribution.

The results of the last question from the survey conducted reveal that 97.5% of respondents (i.e. 118 out of 121 respondents) would like to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications (Q10, illustrated in Fig. 8).

No significant difference was found between the groups of professional affiliation with regard to the answers to the main questions no. Q1 to Q10. Fig. 11 and Fig. 12 show the results of the questions consulted for hypothesis 2 and 3 (i.e. Q1 and Q4, respectively), differentiated according to professional affiliation. In all groups of professional affiliation, the majority of respondents stated that they were not familiar with the concept of biomimetics (Q1) and the majority stated that they had never considered to use a biomimetic material in one of their building projects in the D-A-CH region (Q4). Additionally, no significant difference was found between the groups of professional affiliation and the total sample of 121 respondents with regard to the answers to the main questions Q1 to Q10.

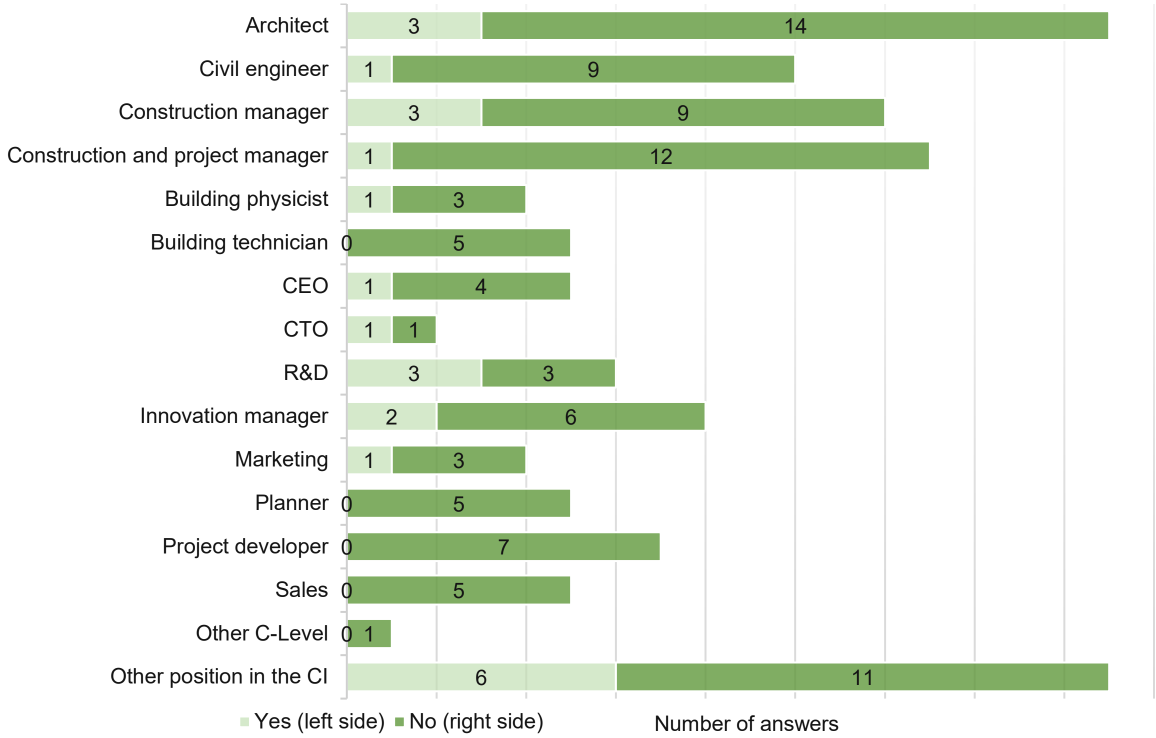

Fig. 11 Results (number of answers) to question no. **Q1** from the questionnaire survey conducted, differentiated according to **professional affiliation**. Q1 = Are you familiar with the concept of biomimetics? Own contribution.

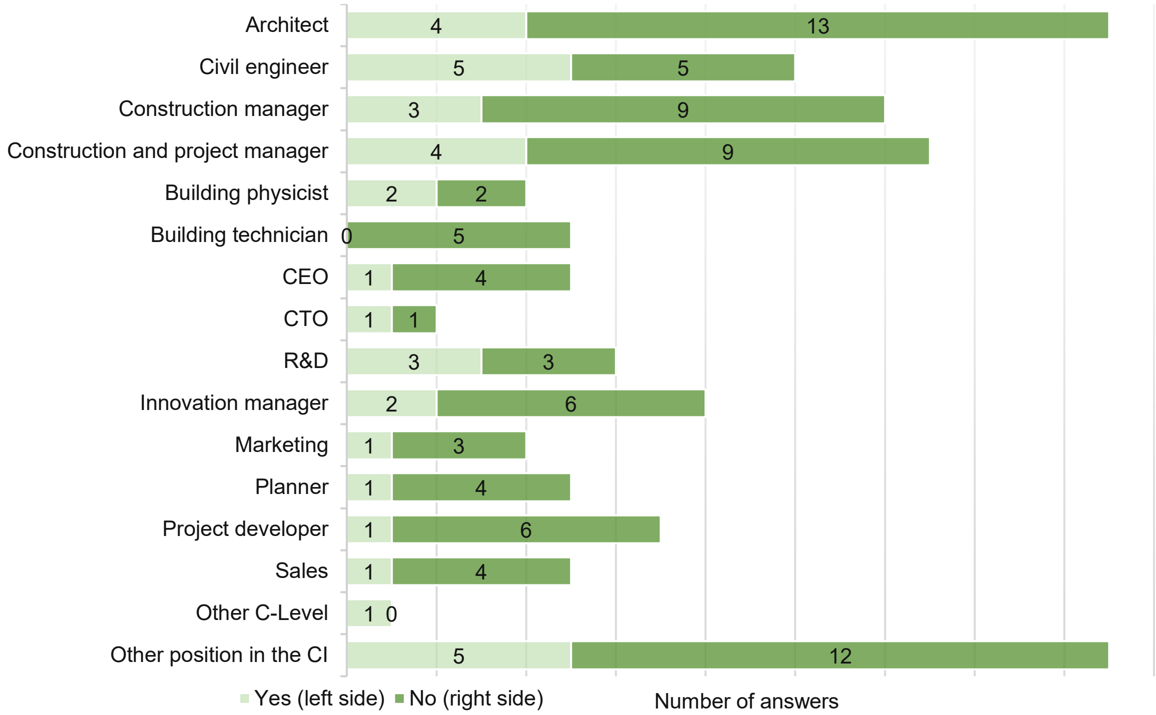

Fig. 12 Results (number of answers) to question no. **Q4** from the questionnaire survey conducted, differentiated according to **professional affiliation**. Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Own contribution.

For the correlation between the number of years of professional experience in the CI and the answers of the respondents to the main questions no. Q1 to Q10, the same statements apply as for the groups of professional affiliation. No significant difference was found between the years of professional experience in the CI. In all groups of years of professional experience, the majority of respondents stated that they were not familiar with the concept of biomimetics (Q1) and the majority stated that they had never considered to use a biomimetic material in one of their building projects in the D-A-CH region (Q4), as shown in Fig. 13 and Fig. 14, respectively. Again, no significant difference was found compared to the total sample of 121 respondents in terms of answers to the main questions Q1 to Q10.

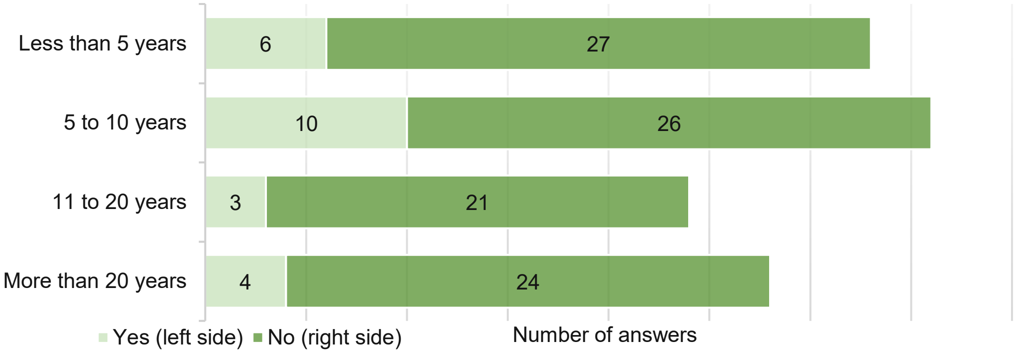

Fig. 13 Results (number of answers) to question no. **Q1** from the questionnaire survey conducted, differentiated according to **number of years of professional experience in the CI**. Q1 = Are you familiar with the concept of biomimetics? Own contribution.

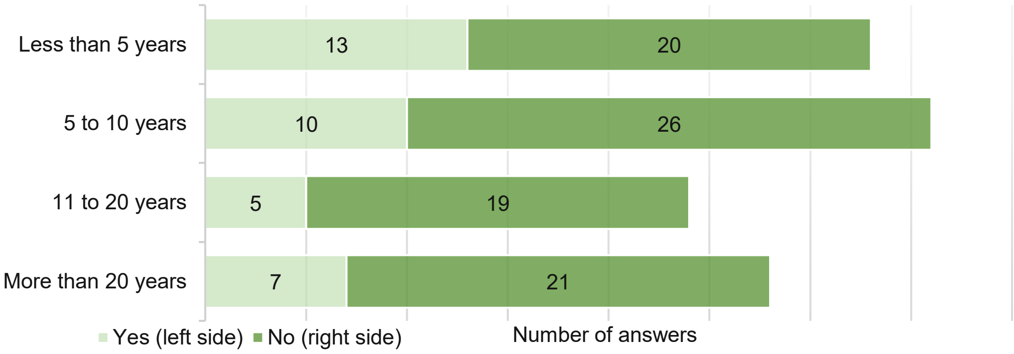

Fig. 14 Results (number of answers) to question no. **Q4** from the questionnaire survey conducted, differentiated according to **number of years of professional experience in the CI**. Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Own contribution.

Also for the correlation between the countries (headquarter and operating) and the answers of the respondents to the main questions no. Q1 to Q10, the same statements apply as above. No significant difference was found in the results differentiated in headquarter and operating countries of the companies the respondents work for. In all groups of countries, the majority of respondents stated that they were not familiar with the concept of biomimetics (Q1) and the majority stated that they had never considered to use a biomimetic material in one of their building projects in the D-A-CH region (Q4), as shown in Fig. 15 and Fig. 16, respectively. Again, no significant difference was found compared to the total sample of 121 respondents in terms of answers to the main questions no. Q1 to Q10.

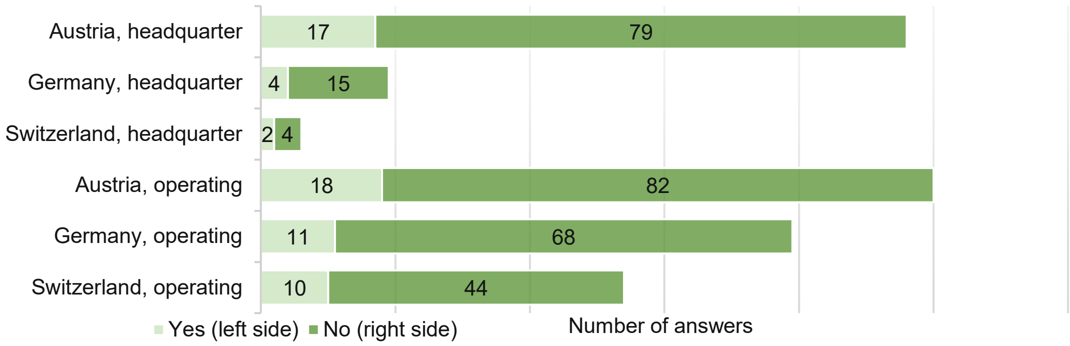

Fig. 15 Results (number of answers) to question no. **Q1** from the questionnaire survey conducted, differentiated according to **headquarter of the company and country or countries in which the company operates**. Q1 = Are you familiar with the concept of biomimetics? Own contribution.

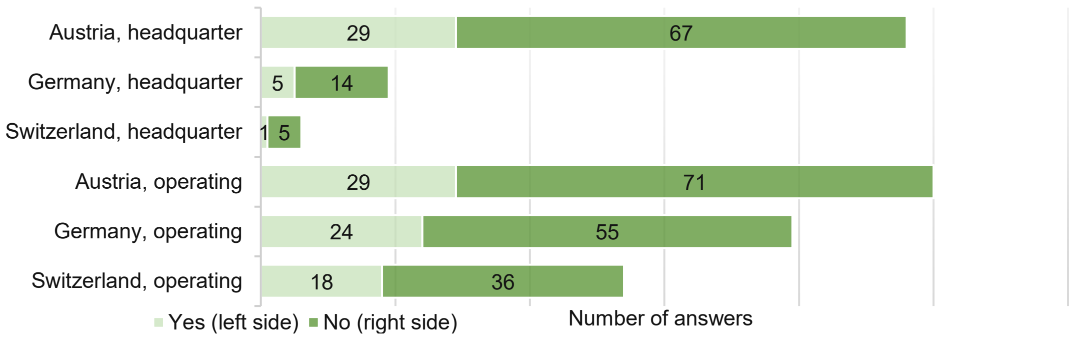

Fig. 16 Results (number of answers) to question no. **Q4** from the questionnaire survey conducted, differentiated according to **headquarter of the company and country or countries in which the company operates**. Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Own contribution.

Thus, among the groups of professional affiliation, the groups of number of years of professional experience in the CI and the groups of countries of the companies (headquarter and operating) no group is significantly more or less familiar with the concept of biomimetics than another group or has considered the use of biomimetic materials significantly more or less than another.

23.5% of respondents, that answered ‘No’ to the question no. Q1 ‘Are you familiar with the concept of biomimetics?’, stated that they have considered to use a biomimetic material in one of their building projects in the D-A-CH region (Q4), shown in Fig. 17.

Furthermore, 49% of respondents who stated that they were not familiar with the concept of biomimetics (Q1) have at least heard about biomimetics in the context of the CI, as they answered 'Yes' to Q2. Also, only 23.5% of them stated that they know of building projects in the D-A-CH region that have used or plan to use biomimetic materials (Q3), only 15.3% of them stated that they know about scientific work and developments on biomimetic materials for the CI (Q5) and 28.6% of them stated that they know of biomimetic materials available as products on the market for the CI (Q6), also shown in Fig. 17. However, it is remarkable that 92.9% of respondents, that answered 'No' to Q1 'Are you familiar with the concept of biomimetics?', stated that they would consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region (Q7), after seeing examples of biomimetic materials during the survey and that 98% of them want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications (Q10), shown in Fig. 17. This shows that the vast majority of these respondents are curious and open to biomimetics, even though they were not familiar with the concept of biomimetics before they participated in the survey.

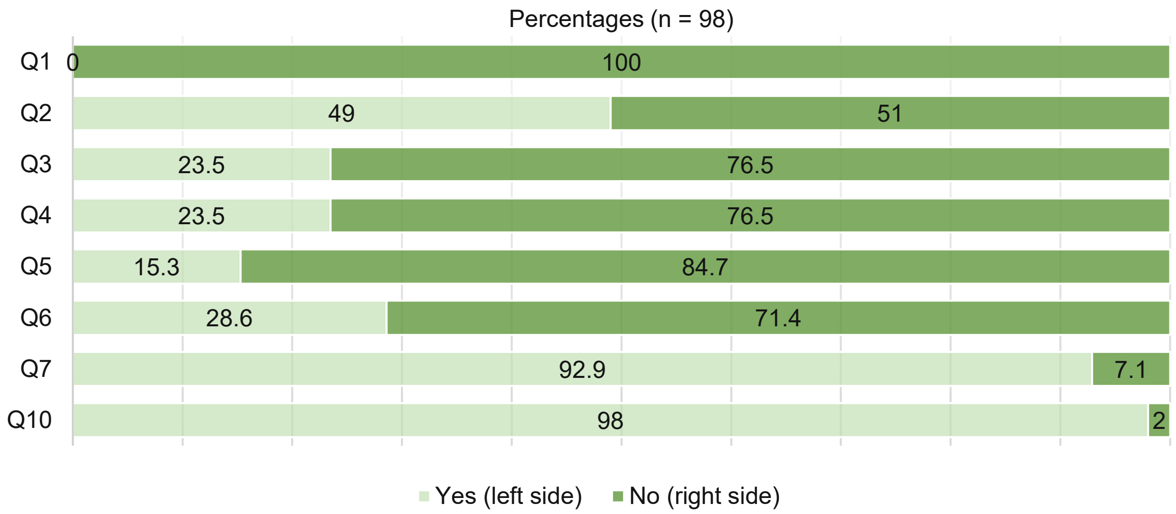

Fig. 17 Results (percentages, n = 98) of **respondents, that answered 'No' to Q1** from the questionnaire survey conducted. Q1 = Are you familiar with the concept of biomimetics? Q2 = Have you ever heard of biomimetics in the context of the CI? Q3 = Do you know of building projects in the D-A-CH region that have used or plan to use biomimetic materials? Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Q5 = Do you know about scientific work and developments on biomimetic materials for the CI? Q6 = Do you know of biomimetic materials available as products on the market for the CI? Q7 = After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region? Q10 = Do you want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications? Own contribution.

Similarly, 91.3% of respondents, that answered 'Yes' to the question no. Q1 'Are you familiar with the concept of biomimetics?' stated that they would consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region

(Q7), after seeing examples of biomimetic materials during the survey and that 95.7% of them want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications (Q10), shown in Fig. 18. This shows that the vast majority of these respondents are curious and want to learn more about biomimetics, even though they were already familiar with the concept of biomimetics before they participated in the survey. However, only 52.2% of respondents, that answered 'Yes' to the question no. Q1 'Are you familiar with the concept of biomimetics? stated that they have considered to use a biomimetic material in one of their building projects in the D-A-CH region (Q4). This might correlate with the fact that only 43.5% of these respondents know of biomimetic materials available as products on the market for the CI (Q6). Nevertheless, 60.9% of these respondents know of building projects in the D-A-CH region that have used or plan to use biomimetic materials (Q3), 69.6% of them know about scientific work and developments on biomimetic materials for the CI (Q5) and 87% of them have heard of biomimetics in the context of the CI (Q2), shown in Fig. 18. Conversely, this means that 13% of respondents, that were familiar with biomimetics, have never heard of biomimetics in the context of the CI.

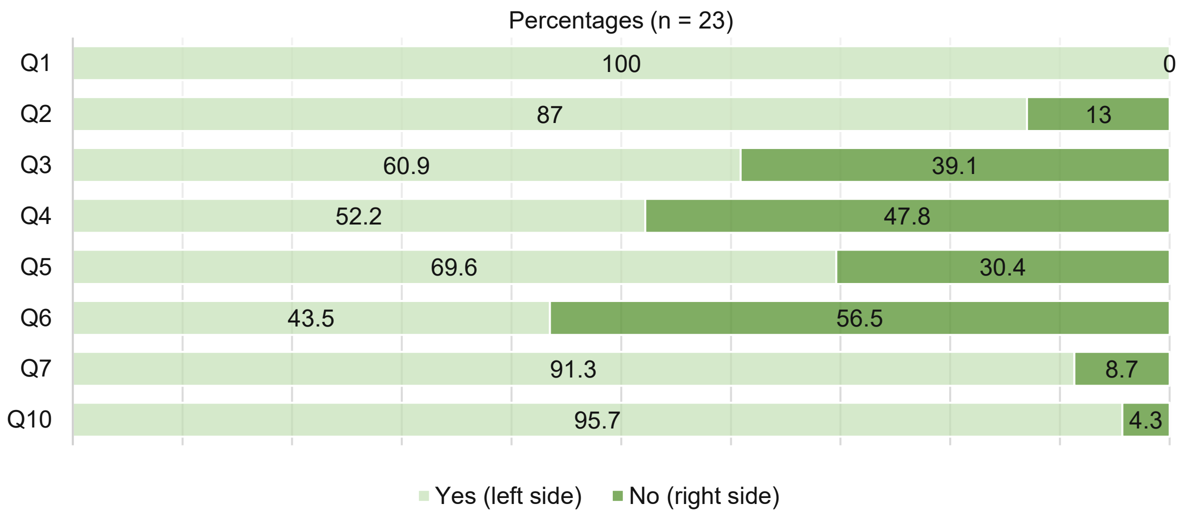

Fig. 18 Results (percentages, n = 23) of **respondents, that answered 'Yes' to Q1** from the questionnaire survey conducted. Q1 = Are you familiar with the concept of biomimetics? Q2 = Have you ever heard of biomimetics in the context of the CI? Q3 = Do you know of building projects in the D-A-CH region that have used or plan to use biomimetic materials? Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Q5 = Do you know about scientific work and developments on biomimetic materials for the CI? Q6 = Do you know of biomimetic materials available as products on the market for the CI? Q7 = After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region? Q10 = Do you want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications? Own contribution.

12.8% of respondents, that answered ‘No’ to the question no. Q4 ‘Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region?’, were familiar with the concept of biomimetics (Q1) and 45.3% of them have heard of biomimetics in the context of the CI (Q2), shown in Fig. 19. However, only 18.6% of them knew of building projects in the D-A-CH region that have used or plan to use biomimetic materials (Q3). Only 16.3% of them knew about scientific work and developments on biomimetic materials for the CI (Q5) and equal few knew of biomimetic materials available as products on the market for the CI (Q6). This low level of awareness among the respondents might explain why they have never considered to use a biomimetic material in one of their building projects in the D-A-CH region.
Nevertheless, it is again remarkable that 91.9% of respondents, that answered ‘No’ to Q4 ‘Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region?’, stated that they would consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region (Q7), after seeing examples of biomimetic materials during the survey and that 96.5% of them want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications (Q10). This once again underlines that the vast majority of these respondents are curious and open to biomimetics, even though they have never considered to use a biomimetic material in one of their building projects in the D-A-CH region, before they participated in the survey.

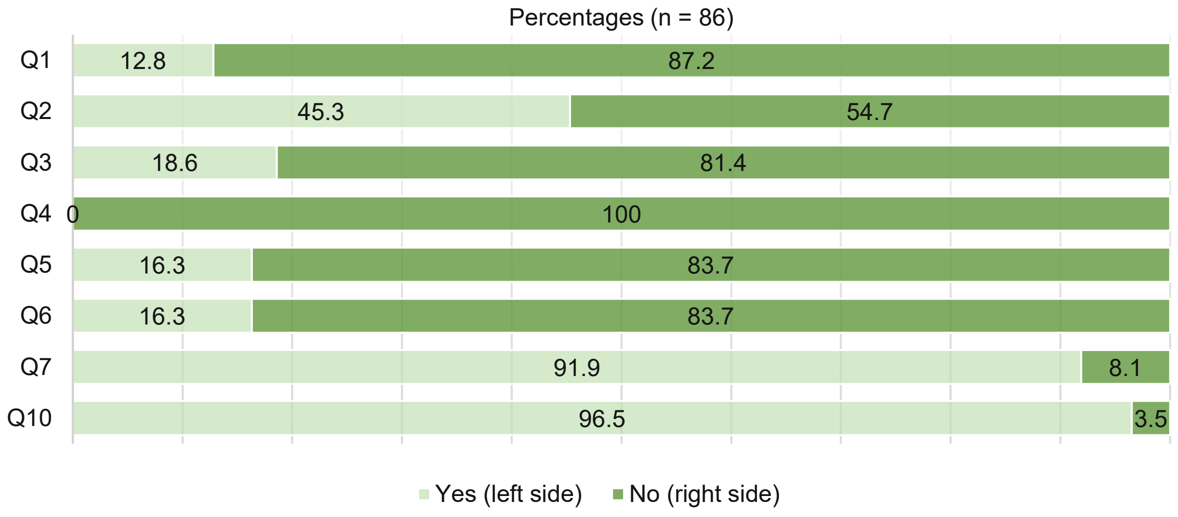

Fig. 19 Results (percentages, n = 86) of **respondents, that answered ‘No’ to Q4** from the questionnaire survey conducted. Q1 = Are you familiar with the concept of biomimetics? Q2 = Have you ever heard of biomimetics in the context of the CI? Q3 = Do you know of building projects in the D-A-CH region that have used or plan to use biomimetic materials? Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Q5 = Do you know about scientific work and developments on biomimetic materials for the CI? Q6 = Do you know of biomimetic materials available as products on the market for the CI? Q7 = After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region? Q10 = Do you want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications? Own contribution.

34.3% of respondents, that answered 'Yes' to the question no. Q4 'Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region?', were familiar with the concept of biomimetics (Q1) and 82.9% have heard of biomimetics in the context of the CI (Q2), shown in Fig. 20. 60% of them knew of building projects in the D-A-CH region that have used or plan to use biomimetic materials (Q3), 48.6% of them knew about scientific work and developments on biomimetic materials for the CI (Q5) and 68.6% of them knew of biomimetic materials available as products on the market for the CI (Q6), also shown in Fig. 20. It can be observed that the level of awareness of biomimetics is higher among respondents that have considered to use a biomimetic material in one of their building projects in the D-A-CH region, than it is among respondents that have not considered it.
94.3% of respondents, that have considered to use a biomimetic material in one of their building projects in the D-A-CH region (Q4), stated that they would again consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region (Q7) and 100% of them want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications (Q10).

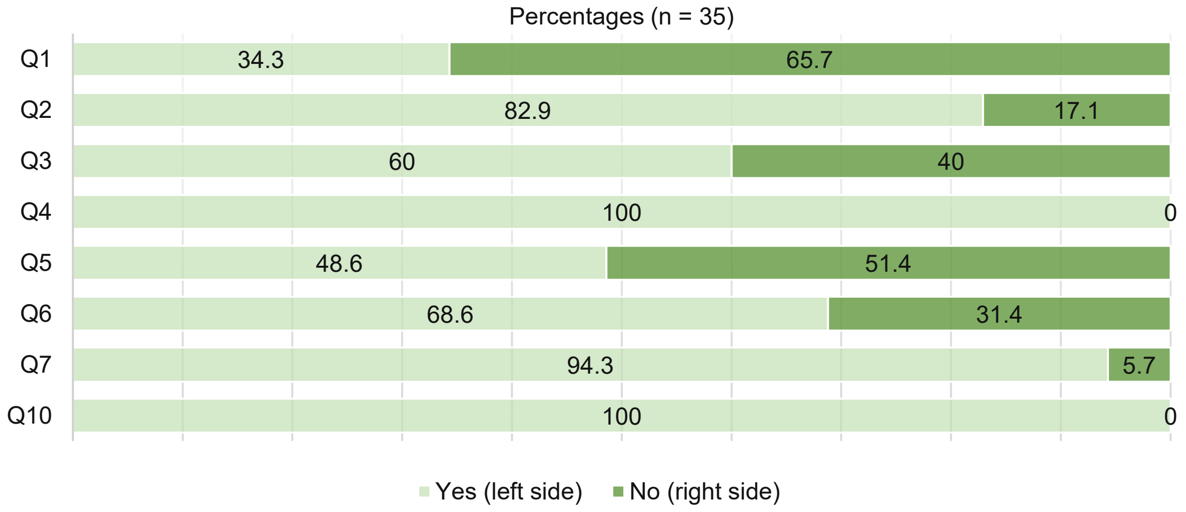

Fig. 20 Results (percentages, n = 35) of **respondents, that answered 'Yes' to Q4** from the questionnaire survey conducted. Q1 = Are you familiar with the concept of biomimetics? Q2 = Have you ever heard of biomimetics in the context of the CI? Q3 = Do you know of building projects in the D-A-CH region that have used or plan to use biomimetic materials? Q4 = Have you ever considered to use a biomimetic material in one of your building projects in the D-A-CH region? Q5 = Do you know about scientific work and developments on biomimetic materials for the CI? Q6 = Do you know of biomimetic materials available as products on the market for the CI? Q7 = After seeing these examples, would you consider using a biomimetic material in one of your upcoming building projects in the D-A-CH region? Q10 = Do you want to learn more about biomimetics, biomimetic materials and products for the CI as well as for other applications? Own contribution.

Considering the added value that the use of biomimetic materials offers to the CI and the environment, as mentioned in the introduction, combined with the discovered lack of awareness on biomimetics and biomimetic materials for use in the CI, it can be deduced that promotional measures on this topic are highly necessary. This is additionally underlined by the willingness of respondents to consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region as well as their interest in learning more about biomimetics, biomimetic materials and products for the CI as well as for other applications. The results from the survey for these two questions (Q7 and Q10) were very high, ranging from 90 to 100 % for all differentiations analysed, demonstrating a strong interest in biomimetic materials across all surveyed groups of representatives of the CI in the D-A-CH region, independent of their professional affiliation, their no. of years of experience in the CI and the country their company is headquartered or operating. How promotional measures for biomimetic materials for the CI in the D-A-CH region should look in detail and how they can be successfully implemented, should be the subject of further investigations.

5 Conclusions

Based on the hypotheses, the following conclusions can be drawn from the results of the literature review and the questionnaire survey conducted. The scientific community is working on biomimetic materials intended for application in the CI. Many different types of biomimetic materials are being scientifically investigated, offering a wide variety of potential applications for the CI. Numerous natural structures, functions and processes across many different species, length scales and diverse habitats serve as inspiration for a wide range of developments. The scientific community reports on promising properties and applications of biomimetic materials that have the potential to make the CI significantly more sustainable and efficient. From the results of the literature research it can be concluded that research activities on biomimetic materials for the CI are very much in the areas of sustainability and climate change-adapted materials. However, it was found that the number of scientific research (publications) on biomimetic materials for the CI is significantly higher than the number of products made from biomimetic materials actually available on the market. Even though the marketable products already cover a whole range of applications in the CI, they cover far fewer applications than the scientific community is currently investigating. From the results of the questionnaire survey conducted it can be concluded that the concept of biomimetics is not familiar to the majority of representatives of the CI in the D-A-CH region. Additionally, the majority of representatives do not know of building projects in the D-A-CH region that used or plan to use biomimetic materials, they do not know about scientific work and developments on biomimetic materials for the CI and they do not know of products made from biomimetic materials available on the market for the CI. As a consequence, the use of biomimetic materials for building projects has not yet been considered by the majority of representatives of the CI in the D-A-CH region. From these findings it can be concluded that there is a gap between the awareness of biomimetic materials among representatives of the CI in the D-A-CH region and the scientific community working on the development of biomimetic materials. The results of the questionnaire survey conducted have further shown that the development and application of biomimetic materials should be promoted and advertised more intensively in the CI in the D-A-CH region. After representatives were shown examples of biomimetic materials, the great majority of them would consider using a biomimetic material in one of their upcoming building projects in the D-A-CH region. The majority of representatives agree that biomimetic materials have the potential to significantly increase the sustainability of the CI in the D-A-CH region, they also agree that they would like to learn more about biomimetics, biomimetic materials and products. This clearly demonstrates the potential of biomimetic materials for the CI in the D-A-CH region. Thus, this master thesis shows that promotional measures are urgently needed to increase the awareness for biomimetic materials for the CI in the D-A-CH region. How these promotional measures should look in detail and how they can be successfully implemented should be the subject of further investigations. Looking beyond the goals of this master thesis, the beauty of nature and it's sophisticated materials, as well as the capabilities of biomimetic materials for the CI were underlined.

6 Register of Illustrations

7 List of Tables

8 References

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9 Appendix

Detailed questionnaire survey conducted

<u>Umfrage Diplomarbeit</u>

Die folgende Umfrage ist Teil meiner Diplomarbeit für das Masterstudium Materialwissenschaften an der TU Wien. Dabei beschäftige ich mich mit einer speziellen Gruppe von Materialien für die Bauwirtschaft.
Ihre Antworten helfen mir dabei, die Bekanntheit und Akzeptanz dieser Materialien einzustufen. Die Beantwortung der Umfrage wird nur ca. fünf Minuten dauern.
Die Umfrage richtet sich ausschließlich an Fachleute aus der Baubranche, die in der D-A-CH-Region (Deutschland, Österreich, Schweiz) tätig sind. Wenn Sie nicht Teil dieser Gruppe sind, bitte ich Sie, nicht an der Umfrage teilzunehmen.
Ihre Antworten sind anonym und werden vertraulich behandelt. Die Auswertung fließt in meine Diplomarbeit ein.
Ihr Mehrwert: Wenn Sie an der Umfrage teilnehmen, bekommen Sie die fertige Diplomarbeit inklusive aller Ergebnisse und einer ausführlichen state-of-the-art Datenbank der untersuchten Materialien und Produkte zugeschickt.
Vielen Dank für Ihre Unterstützung!
Martin Rohner

<u>>> Weiter</u>

Frage 1 von 10: Sind Sie mit dem Konzept der Biomimetik vertraut?

a. Ja
b. Nein

<u>>> Wenn Antwort auf Frage 1 von 10 = Ja, dann:</u>

Sehr gut. Zur Erinnerung hier die Beschreibung von Biomimetik:
Der Begriff Biomimetik leitet sich aus dem Altgriechischen ab: bios = Leben und mimesis = Nachahmung.
Ganz einfach erklärt steht Biomimetik für Lösungen, die von der Natur inspiriert sind.
Laut Definition ist Biomimetik die ‘interdisziplinäre Zusammenarbeit von Biologie und Technik oder anderen innovativen Bereichen, um praktische Probleme zu lösen, durch die funktionale Analyse biologischer Systeme, ihrer Abstraktion zu Modellen und der Übertragung und Anwendung dieser Modelle auf die Lösung’ (DIN ISO 18458:2016-08).

Der Entwicklungsprozess biomimetischer Materialien folgt dem Konzept dieser Definition.
Biomimetische Materialien sind von strukturellen Eigenschaften, biologischen Prozessen oder Funktionen aus der Natur inspiriert, z.B. selbstheilende, selbstreinigende oder selbstformende Materialien.

Zwischenfrage 1: Stimmt Ihr Verständnis von Biomimetik mit der obigen Beschreibung überein?

a. Ja
b. Nein

>> Wenn Antwort auf Zwischenfrage 1 = Nein, dann:

Bitte berücksichtigen Sie die vorherige Beschreibung von Biomimetik für den Rest der Umfrage. Zur Erinnerung:

Ganz einfach erklärt steht Biomimetik für Lösungen, die von der Natur inspiriert sind.
Laut Definition ist Biomimetik die 'interdisziplinäre Zusammenarbeit von Biologie und Technik oder anderen innovativen Bereichen, um praktische Probleme zu lösen, durch die funktionale Analyse biologischer Systeme, ihrer Abstraktion zu Modellen und der Übertragung und Anwendung dieser Modelle auf die Lösung' (DIN ISO 18458:2016-08).

>> Wenn Antwort auf Frage 1 von 10 = Nein, dann:

Kein Problem! Hier die Beschreibung von Biomimetik:

Der Begriff Biomimetik leitet sich aus dem Altgriechischen ab: bios = Leben und mimesis = Nachahmung.
Ganz einfach erklärt steht Biomimetik für Lösungen, die von der Natur inspiriert sind.
Laut Definition ist Biomimetik die 'interdisziplinäre Zusammenarbeit von Biologie und Technik oder anderen innovativen Bereichen, um praktische Probleme zu lösen, durch die funktionale Analyse biologischer Systeme, ihrer Abstraktion zu Modellen und der Übertragung und Anwendung dieser Modelle auf die Lösung' (DIN ISO 18458:2016-08).
Der Entwicklungsprozess biomimetischer Materialien folgt dem Konzept dieser Definition.
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>> Weiter oder wenn Antwort Zwischenfrage 1 = Ja, dann:

Nachdem wir jetzt ein gemeinsames Verständnis für die Biomimetik haben, beantworten Sie bitte folgende Fragen.

Frage 2 von 10: Haben Sie schon einmal von Biomimetik im Zusammenhang mit der Bauwirtschaft gehört?

a. Ja
b. Nein

>> Weiter

Frage 3 von 10: Kennen Sie Bauprojekte in der D-A-CH-Region, bei denen biomimetische Materialien verwendet wurden oder die Verwendung geplant ist?

a. Ja
b. Nein

>> Weiter

Frage 4 von 10: Haben Sie jemals erwogen, bei einem Ihrer Bauprojekte in der D-A-CH-Region ein biomimetisches Material zu verwenden?

a. Ja
b. Nein

>> Weiter

Frage 5 von 10: Kennen Sie wissenschaftliche Arbeiten oder Projekte zu biomimetischen Materialien für die Bauwirtschaft?

a. Ja
b. Nein

>> Weiter

Frage 6 von 10: Kennen Sie biomimetische Materialien für die Bauwirtschaft, die als Produkte auf dem Markt erhältlich sind?

a. Ja
b. Nein

>> Weiter

Beispiele von biomimetischen Materialien für die Bauwirtschaft

Nun werden Ihnen sechs Beispiele von biomimetischen Materialien für die Bauwirtschaft gezeigt. Die ersten drei Beispiele sind aus der Forschung, die restlichen drei Beispiele sind Produkte, die bereits am Markt erhältlich sind. Bitte lesen Sie sich die Beispiele sorgfältig durch.

>> Weiter

Beispiel 1: Von Eisbärhaaren inspiriertes Aerogel für Wärmedämmung

Mehrwert: Wärmedämmstoff mit sehr niedriger Wärmeleitfähigkeit (geringer als jene von handelsüblichen Wärmedämmstoffen und geringer als jene von trockener Luft) sowie hoher mechanische Robustheit (Superelastizität und Ermüdungsbeständigkeit)

Anwendung: Ersatz von kommerziellen Wärmedämmstoffen für energieeffizientere Gebäude

Inspiration aus der Natur: Mikrostruktur vom Haar von Eisbären (dieses wird nicht nass, es ist leicht, hochporös und schließt große Mengen Luft in seiner Hohlfaserstruktur ein)

Forschung: Einfaches Herstellverfahren für ein Aerogel aus Carbon-Hohlfasern mit geringem Wärmeleitkoeffizient

Literatur: H.-J. Zhan *et al.*, 'Biomimetic Carbon Tube Aerogel Enables Super-Elasticity and Thermal Insulation', *Chem*, vol. 5, no. 7, pp. 1871–1882, Jul. 2019, doi: 10.1016/j.chempr.2019.04.025.

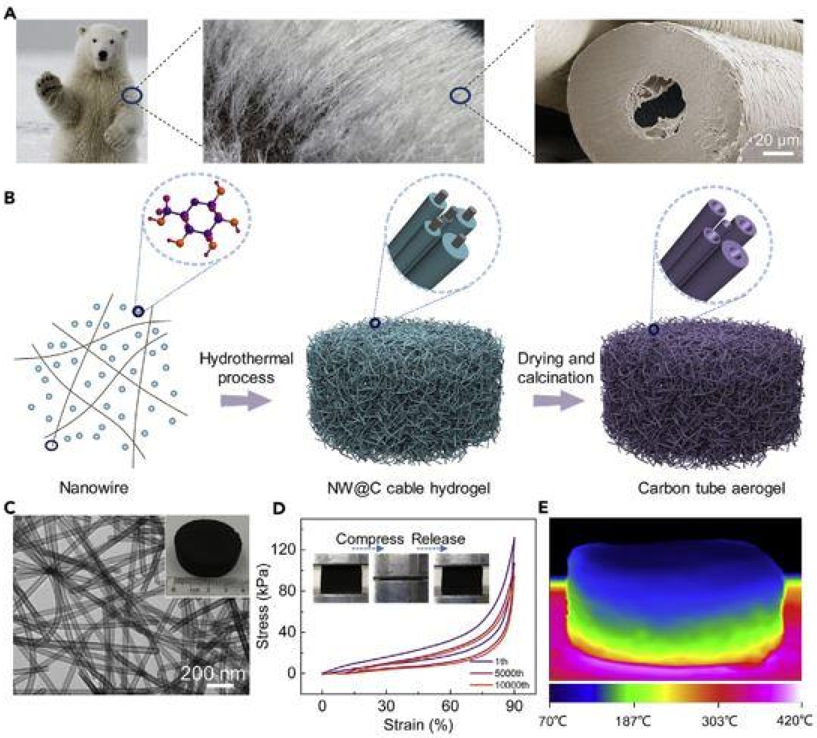


Figure 1. Bioinspired Macroscopic Carbon Tube Aerogel (CTA) Materials
(A) Optical images and SEM image of polar bear hair with different magnification.[15]
(B) Schematic illustration of the bioinspired fabrication processes of the CTA.
(C) A TEM image of the CTA. Inset: the optical image of the CTA.
(D) Stress-strain curves of CTA-25 at 90% strain for 10,000 cycles. Insets: photographs are recording the compress-release process of CTA-25 at 90% strain for the first cycle.
(E) The thermographic image of a cylindrical CTA with a diameter of 4 cm and a height of 2 cm posited on a hot plate which surface temperature maintained at about 400°C.

Quelle: [1] Zhan et al. 2019

>> Weiter

Beispiel 2: Von Kiefernzapfen inspirierte selbstformende Materialien

Mehrwert: Selbstformende Bauteile und Systeme. Einsparung von Energie. Sommerlicher Wärmeschutz

Anwendung: Fassadensystemen für energieeffiziente Gebäudehüllen (Öffnen und Schließen in selbstorganisierenden Strukturen für Verschattung, Sichtschutz, Wetterschutz)

Inspiration aus der Natur: Kiefernzapfen (deren reversible Bewegungsabläufe die keine Stoffwechselenergie zum Öffnen und Schließen der Schuppen benötigen)

Forschung: Methode zum physischen programmieren von Bewegungsschritten in 4D-gedruckten Strukturen. Entwicklung biomimetischer Bilayermaterialien aus Bioverbundwerkstoffen und Biokunststoffen, die sich unter Feuchteänderungen selbst verformen

Literatur: [1] Y. Tahouni et al., ‘Programming sequential motion steps in 4D-printed hygromorphs by architected mesostructure and differential hygro-responsiveness’, Bioinspir. Biomim., vol. 16, no. 5, p. 055002, Sep. 2021, doi: 10.1088/1748-3190/ac0c8e.

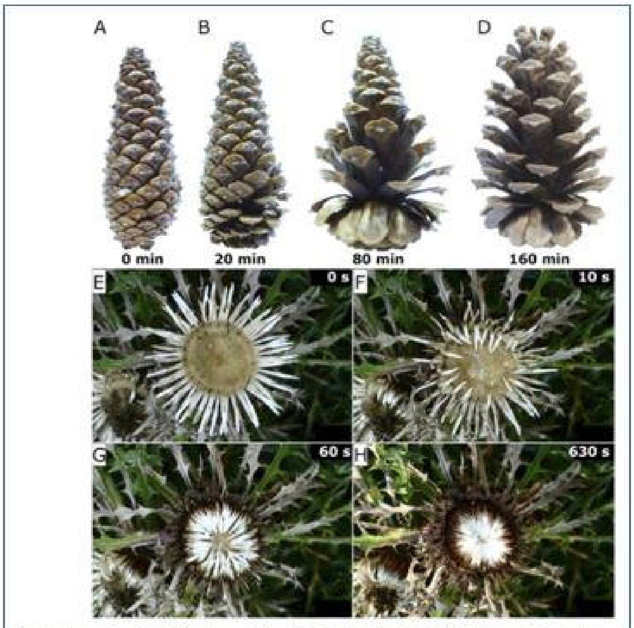


Figure 1. Sequential motion in the pinecone (*Pinus jeffreyi*) and in the silver thistle (*Carlina acaulis ssp. caulescens*).

Quelle: [1] Tahouni et al. 2021

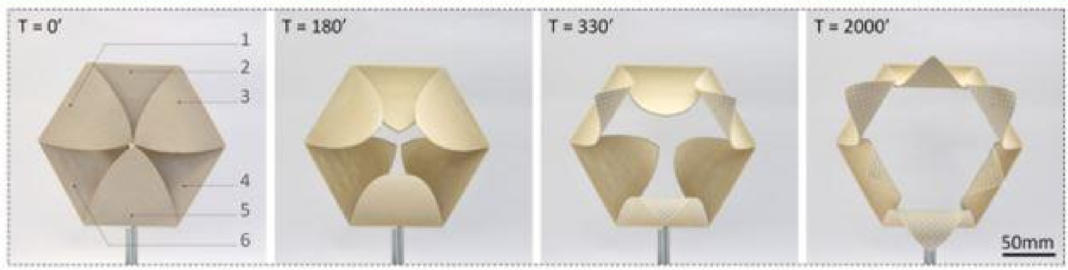


Figure 7. 4D-printed aperture prototype with sequential motion in two stages. The time-lapse images show flaps 1, 3, and 5 complete their motion at $t = 330$ min while flaps 2, 4, and 6 complete at $t = 2000$ min when actuated through drying in 40% RH

>> Weiter

Beispiel 3: Von Lava inspirierte feuerhemmende Beschichtung
Mehrwert: Feuerhemmende dünne Beschichtung die Selbstverlöschen bewirkt
Anwendung: Brandschutz von Massivholz, Stahl, Kunststoff-Schäumen in Gebäuden
Inspiration aus der Natur: Mikrostruktur von Lava
Forschung: Kosteneffiziente mikro-/nanostrukturierte Beschichtung, die im Brandfall eine keramische feuerhemmende (nichtbrennende) Schutzschicht für darunterliegende Bauteile erzeugt
Literatur: [1] Z. Ma *et al.*, 'A lava-inspired micro/nano-structured ceramifiable organic-inorganic hybrid fire-extinguishing coating', Matter, vol. 5, issue 3, pp. 911-932, Mar. 2022, doi: 10.1016/j.matt.2021.12.009

Quelle: [1] Ma et al. 2022

>> *Weiter*

Beispiel 4: Von Bäumen inspirierte Leichtbauelemente

Mehrwert: Holzbasierte Bauelemente, Strukturen und Verbindungen, mit sehr hoher spezifischer Festigkeit (geringe Dichte). Einsparung von Ressourcen. Anschlüsse im konstruktiven Holzbau gänzlich ohne Metall

Anwendung: Leichtbaustrukturen in Freiform sowie leichte, multiaxiale, steife Verbindungselemente

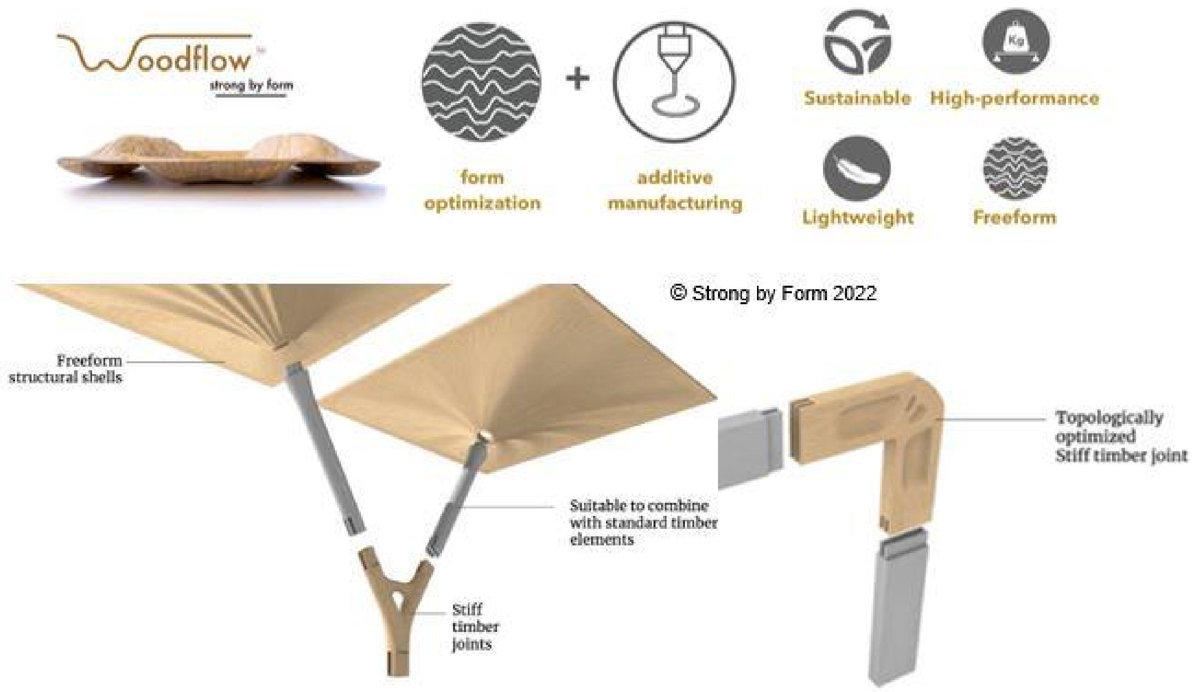
Inspiration aus der Natur: Strukturelle Eigenschaften von Bäumen (deren optimierte Faserverläufe, Dichteverhältnisse und Formen)

Umsetzung: Vollautomatisierter Herstellprozess für holzbasierte biomimetische Materialien, der die Nachhaltigkeit von Holz mit der Performance von Verbundwerkstoffen kombiniert

Unternehmen; Produkt: Strong by Form; Woodflow™

Die unten abgebildete optimierte Schale kann beispielweise mit rund 850g Eigengewicht bei einer Bauteildicke von 5mm eine Masse von über 300kg bei minimaler Durchbiegung tragen

Quelle: Strong by Form



[>> Weiter](#)

Beispiel 5: Von Korallenriff inspirierter Biozement

Mehrwert: Minimaler Energieaufwand für die Herstellung von Zement bei Raumtemperatur. Im Vergleich zu Portlandzement wird pro Kilogramm Biozement ein Kilogramm CO2 eingespart. Normfestigkeit wird bereits nach 72 Stunden (Vgl.: Portlandzement nach 28 Tagen). 100% recyclingfähig.

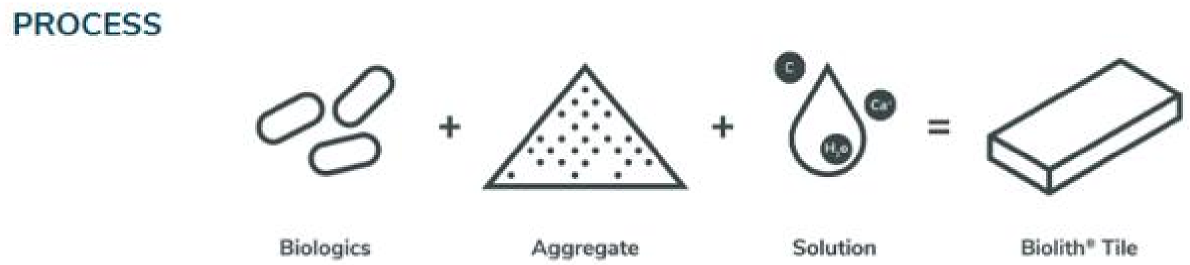
Anwendung: Biozement für Betonfertigteile (z.B. Pflastersteine für Fassaden, Innenwände, Böden, etc.)

Inspiration aus der Natur: Marine Ökosysteme (Wachstum von Korallenriff)

Umsetzung: Biotechnologischer Herstellprozess mit natürlichen Mikroorganismen bei Raumtemperatur aus Recyclingmaterial.

Unternehmen; Produkt: Biomason; Biocement® (Biolith®)

Quelle: Biomason



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>> Weiter

Beispiel 6: Von Lotusblättern inspirierte selbstreinigende Fassadenfarbe

Mehrwert: Fassadenfarbe für reduzierte Haftung von Schmutzpartikeln und Selbstreinigung bei Regen - Schmutz perlt mit dem Regen ab. Natürlicher Schutz gegen Algen und Pilze ohne bioziden Filmschutz. Aktiver, feuchteregulierender Wetterschutz

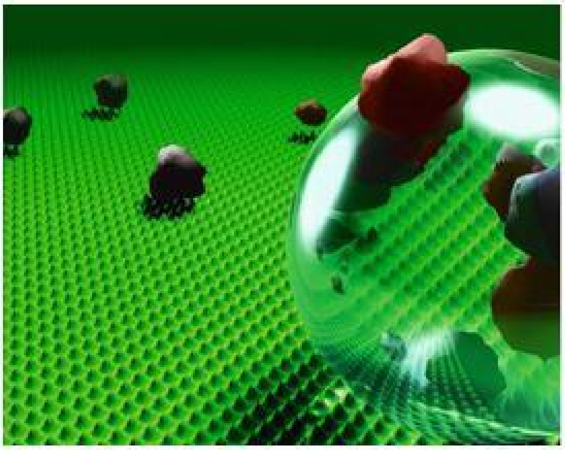
Anwendung: Fassadenfarbe: Anstriche auf mineralischen und organischen Untergründen für die Außenanwendung

Inspiration aus der Natur: Lotusblatt (dessen wasserabweisende, superhydrophobe Oberflächen-Mikrostruktur)

Umsetzung: Lotus-Effekt® Technologie aus/mit nachwachsenden Rohstoffen; als Farbe und Putz erhältlich

Unternehmen; Produkt: Sto GmbH; StoColor Lotusan AimS®

Quelle: Sto GmbH



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>> Weiter

Nachdem Sie die Beispiele gerade gesehen haben, beantworten Sie bitte folgende Fragen.

Frage 7 von 10: Würden Sie die Verwendung eines biomimetischen Materials bei einem Ihrer nächsten Bauprojekte in der D-A-CH-Region in Betracht ziehen?

a. Ja
b. Nein

>> Wenn Antwort auf Frage 7 von 10 = Nein, dann:

Zwischenfrage 2: Warum würden Sie kein biomimetisches Material bei einem Ihrer nächsten Bauprojekte verwenden?

offene Frage

>> Weiter oder wenn Antwort auf Frage 7 von 10 = Ja, dann:

Frage 8 von 10: Biomimetische Materialien haben das Potential, die Nachhaltigkeit der Bauwirtschaft in der D-A-CH-Region signifikant zu erhöhen.

1 = Stimme überhaupt nicht zu
2 = Stimme nicht zu
3 = Stimme weder zu, noch lehne ich ab
4 = Stimme zu
5 = Stimme voll und ganz zu

>> Weiter

Frage 9 von 10: Die Entwicklung und Anwendung biomimetischer Materialien sollten in der Bauwirtschaft der D-A-CH-Region intensiver gefördert und beworben werden.

1 = Stimme überhaupt nicht zu
2 = Stimme nicht zu
3 = Stimme weder zu, noch lehne ich ab
4 = Stimme zu
5 = Stimme voll und ganz zu

>> Weiter

Frage 10 von 10: Möchten Sie in Zukunft mehr über Biomimetik, biomimetische Materialien und Produkte für die Bauwirtschaft sowie für andere Anwendungen lernen?

a. Ja
b. Nein

>> Weiter

Sonstige Anmerkungen
Möchten Sie sonst noch etwas zum Thema oder der Umfrage anmerken?
Offene Frage (freiwillig)

>> Weiter

Allgemeine Informationen

Fast geschafft! Nur noch ein paar allgemeine Informationen zu Ihrer Person

Frage: **Berufliche Zugehörigkeit**

Architekt:in; Bauingenieur:in, Bauleiter:in; Bau- und Projektleiter:in; Bauphysiker:in; Bautechniker:in; CEO; CTO; F&E; Innovationsmanager:in; Marketing; Planer:in; Projektentwickler:in; Statiker:in; Vertrieb; Sonstiges C-Level, Sonstige Position in der Bauwirtschaft

Frage: **Berufserfahrung in der Bauwirtschaft**

Weniger als 5 Jahre, 5 bis 10 Jahre, 11 bis 20 Jahre, Mehr als 20 Jahre

Frage: **Hauptsitz des Unternehmens, in dem Sie tätig sind**

Deutschland, Österreich, Schweiz *(Nur Einfache Auswahl möglich)*

Frage: **Land oder Länder, in dem/denen Ihr Unternehmen tätig ist**

Deutschland, Österreich, Schweiz *(Mehrfachauswahl möglich)*

Frage: **Name des Unternehmens, in dem Sie tätig sind (freiwillig - wir nicht veröffentlicht)**

Offene Frage

>> Weiter

Informationen erhalten

Wenn Sie über die Ergebnisse dieser Diplomarbeit informiert werden wollen, hinterlassen Sie bitte Ihre E-Mail-Adresse (diese wird nicht veröffentlicht) im unteren Feld. Sie erhalten dann die Diplomarbeit mit allen Daten, sobald diese erfolgreich abgeschlossen und verteidigt wurde.

Ansonsten lassen Sie bitte das untere Feld leer.

Bitte informieren Sie mich über die Ergebnisse dieser Umfrage bzw. dieser Diplomarbeit unter folgender E-Mail-Adresse (wird nicht veröffentlicht):

Offene Frage

>> Weiter

Wichtig: Um die Umfrage abzuschließen klicken Sie bitte unten auf Senden.

Danke für Ihre Teilnahme.

Ich bedanke mich bei der WoodRocks Bau GmbH für die Kooperation bei dieser Diplomarbeit.

Sie erreichen mich unter martin.rohner@wood-rocks.com

Mit freundlichen Grüßen,

Martin Rohner

>> Senden

Ihre Antwort wurde gespeichert.