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Design processes and multi-regulation of biomimetic building skins: A comparative analysis

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ABSTRACT

Biomimetics is an opportunity for the development of energy efficient building systems. Several biomimetic building skins (Bio-BS) have been built over the past decade, however few addressed multi-regulation although the biological systems they are inspired by have multi-functional properties. Recent studies have suggested that despite numerous tools and methods described in the literature for the development of biomimetic systems, their use for designing Bio-BS is scarce. To assess the main challenges of biomimetic design processes and their influence on the final design, this paper presents a comparative analysis of several existing Bio-BS. The analyses were carried out with univariable and multivariate descriptive tools in order to highlight the main trends, similarities and differences between the projects. The authors evaluated the design process of thirty existing Bio-BS, including a focus on the steps related to the understanding of the biological models. Data was collected throughout interviews. The univariate analysis revealed that very little Bio-BS followed a biomimetic design framework (5%). None of the Bio-BS was as multi-functional as their biological model(s) of inspiration. A further conclusion drawn that Bio-BS are mostly inspired by single biological organisms (82%), which mostly belong to the kingdom of animals (53%) and plants (37%). The multivariate analysis outlined that the Bio-BS were distributed into two main groups: (1) academic projects which present a strong correlation with the inputs in biology in their design processes and resulted in radical innovation; (2) public building projects which used conventional design and construction methods for incremental innovation by improving existing building systems. These projects did not involve biologists neither a thorough understanding of biological models during their design process. Since some biomimetic tools are available and Bio-BS have shown limitations in terms of multifunctionality, there is a need to promote the use of multidisciplinary tools in the design process of Bio-BS, and address the needs of the designers to enhance the application of multi-regulation capabilities for improved performances.

1. Introduction

Building skins are multi-criteria systems that require the control of several environmental factors, such as heat, light, humidity, ventilation and mechanical stress. Their performances highly influence the building total energy consumption, since they filter the environmental constraints [1, Ch. 1]. In order to improve building skins efficiency, academics and industries have explored nature-inspired solutions that are referred to Bio-BS (Bio-Inspired Building Skins).

Biomimetics is an interdisciplinary approach based on the integration of biology and technology, by transferring nature's principles into a technological solution [2,3]. This approach has inspired innovation in diverse fields and had a significant impact in architecture for the design of sustainable built-environments [4–10]. International research has focused on the development of adaptive energy efficiency of building skins where biomimetics was implemented as a sub-research category [11,12]. As a result, ore than seventy case studies and designs of bio-inspired building skins were reported over the last two decades, and this number is rapidly growing across industry and academia [13–18]. However, few of these cases address multi-criterion challenges. Kuru et al. [17] has outlined that only 13.4% of fifty-two published biomimetic adaptive skins (Bio-ABS) control more than one parameter. While Svendsen et al. [19] reviewed eight methodologies and twelve design stage-specific tools that addressed multi-functionality in biological inspired design, it appears that multifunctionality is

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not yet embedded in biomimetic envelopes and needs further development to address multiple contradictory functional requirements [17], [19], [20, Ch. 8], [21]. More generally, these observations converge with recent studies [22–25], showing limited use of existing tools and frameworks to promote the development of multi-functional biomimetic applications.

In order to identify the main obstacles for the design of biomimetic building skins, this study presents a qualitative and quantitative analysis of thirty built bio-inspired building skins (Bio-BS). Their respective design processes were evaluated through a set of questions addressed to the design teams during visits, discussions and written exchanges. Univariate and multivariate analyses were carried out with the collected information, with a strong focus on the integration of biological concepts during the design process, and their impact on the final design of the Bio-BS.

2. Bio-BS design

2.1. Design process

Bio-BS follow different definitions according to ISO 2015:18458 [2]:

- *Bioinspiration*: Creative approach based on the observation of biological systems.
- *Biomimetics*: 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.
- *Biomimicry*: Philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development.

Two main approaches exist in such design processes: 'technology pull' or 'biology push'. The ISO has provided the following definitions: **the technology pull process** is a "*biomimetic development process in which an existing functional technical product is provided with new or improved functions through the transfer and application of biological principles*". **The biology push process** is a "*biomimetic development process in which the knowledge gained from basic research in the field of biology is used as the starting point and is applied to the development of new technical products*" [2]. The generic steps are presented in Fig. 1 for each approach (see Fig. 2).

2.2. Design tools

There exists a wide range of methods and tools in literature to support biomimetic design processes [22]. Nevertheless, due to the interdisciplinary nature of biomimetics designers still tackle certain challenges in the search for, and the selection of appropriate models and strategies [26]. The search for analogies between buildings and natural systems is a common trend to address existing challenges, where seeking different classification categories have emerged, e.g. [5,8,20,27]. Addressing multi-functionality is another challenging topic, where it has been addressed in limited studies only [19], mainly due to its complexity and the need to address multiple contradictory functional requirements at the same time [17,19], [20, Ch. 8]. Existing efforts explore different avenues to develop frameworks that could assist in transferring multi-functionality from nature into biomimetic designs, such as focusing on multi-criteria requirements [28], on the correlation between morphology and environment [26,27] and on hierarchy and heterogeneity [29]. However, these frameworks are still under development and hardly applied in design solutions by the wider community. Therefore, there is a need not only to develop tools that support multi-functional applications but also to promote their use by the wider design community. This work aims to provide a better understanding of the multiple criteria involved in the design process by involving design teams of existing projects in the analysis. For this reason, 30 biomimetic building skins (Bio-BS) were selected for this study.

2.3. Overview of the 30 Bio-BS

Table 2 lists the thirty selected Bio-BS. chose in the scientific literature according to three criteria:

- The designs are above a Technology Readiness Level (TRL) of 6, which means they are either a "*system/subsystem model or prototype demonstration in a relevant environment*" [30]. It excluded student or research projects which had not resulted in a prototype so far. A TRL of 6 ensured that the projects at least have run through the design process enough to provide feedback on the methodological aspects.
- The projects met the definitions of either bioinspiration, biomicry or biomimetics according to [2] Thus, they have different rigor in terms of biological data mining, understanding, and abstraction; however, they all derived from a creative approach based on the observation of biological systems.

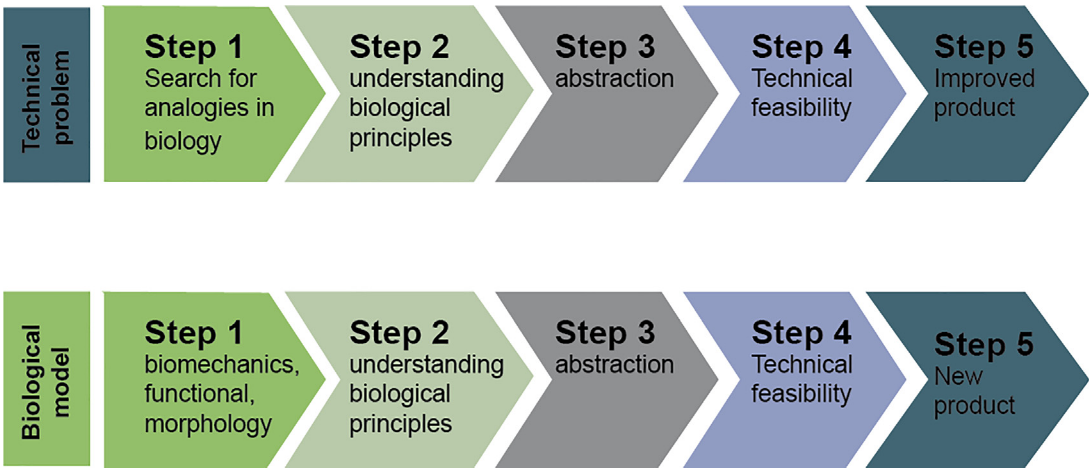

Fig. 1. Biomimetic design process. (a) technology pull, (b) biology push. Adapted with permission from ISO standard 2015:18458 [2].

Fig. 2. Overview of the 30 Bio-BS. With permission from: (1) © PLY Architecture, (2) © DO SU Studio Architecture, (3) © Decker Yeadon LLC, (4) © Tobias Becker, (5) © Art and Build, (6) © SL Rasch, (7) Estelle Cruz CC0 Creative Commons, (8) © Tom Ravenscroft, (9) © Tom Ravenscroft, (10) CC-BY-SA, (11) © Frei Otto, (12) CC-BY-SA, (13) © ARUP, (14) ©Oast House Archive, (15) © Regis L'Hostis, (16–30) © ICD/ITKE University of Stuttgart.

- The bioinspired element of the Bio-BS is embedded at the scale of the building envelope from material, façade component, shading system, wall, fenestration, roof to envelope according to the classification of [31].

Biomimetic research pavilions (TRL = 6) designed by ICD/ITKE at Stuttgart University counted for half of the selection. They resulted from interdisciplinary biomimetic design processes within the collaborative research centre SFB-TRR 141 between the University of Stuttgart (ICD / ITKE research labs), Tübingen and Freiburg (the research group Plant Biomechanics) [32] Although performance of research pavilions highly differs from the building envelopes of public buildings, their biomimetic design processes remained relevant for this study since they were designed beyond the limitations of the real-world constructions. In order to compare the biomimetic design process in several contexts, this study assessed both real-world applications and prototype academic experimentations.

3. Methods

Thirty applications of Bio-BS have been selected according to three selection criteria in order to analyse their design process. Data was gathered throughout interviews of the designers, architects and engineers involved in the design of the Bio-BS. We first compared the Bio-BS using univariate analysis to highlight the main trends, then we compared these applications using multivariate analysis in order to show correlations between them.

3.1. Data collection

To assess the whole design process of the selected Bio-BS, seven categories of qualitative variables were defined. The first two categories provided the context of the Bio-BS (location, climate, etc.) and the biomimetic design process (purpose, main tools, etc.). Then, the following categories corresponded to the five biomimetic design steps according to ISO standard 2015:18458 [2]. These parameters and categories were chosen before identifying the thirty cases based on existing categorisations for building facades [31,33], biomimetic tools [22], and biomimetic facades [17,34]. Table 1 provides an overview of the variables and parameters, and Table 2 presents the 11 variables within the 34 presented in Table 1. They were chosen since they add new knowledge to the field collected during the interviews. A data sheet was created for each case study (Table 2), including the variables listed in Table 1**.** The information was first collected going through literature, then reviewed with the designers for validation. The reviews were conducted as follows (see Table 3):

- digital exchange through online datasheet using comments or direct modifications of parameters from the designers (Ids. 1–3, Table 2),
- phone calls and videoconferences (Ids. 11, 18–22, Table 2),
- face-to-face exchanges, discussions during conferences (Id. 5, 8, 10, 14, 15, Table 2), participant observations (Id. 7 for 10 weeks, Id 13 for 12 weeks, Ids. 16–30 for 2 weeks, Table 2).

3.2. Analysis

Information on the interviews (names/role of interviewees, type and durations of interviews) are given in supplementary data. Overall, 25 of the 30 Bio-BS data sheets received feedback from the designers. The collected data is available in two additional supplementary documents: an excel sheet gathers all results to the variables listed in Table 1 (on request), and an online report provides an overview of each project [103].

Data analysis was conducted through:

- **Multivariate analysis** ($n_{cases} = 30$) using Multiple Correspondence Analysis (MCA). MCA is a descriptive technique to bring to light correlations between variables in a complex dataset. It offers insights on a dataset without beforehand assumptions on variables correlations – it was used as a complementary method to identify typologies of projects by analysing relationships between qualitative parameters (Table 1) and the entire dataset of Bio-BS (Table 2). Information on this tool and results from the MCA analysis are given in supplementary data (section B**. MCA analysis**).
- **Univariate analysis** ($n_{cases} = 19$) – to highlight the trends in the design processes of the analysed Bio-BS through a distribution study of parameter in percentages. The 15 projects of ICD/ITKE/Stuttgart University (Ids. 16 to 30, Table 2) were counted here as 4 projects to obtain more representative results on a global scale. Indeed, they were gathered as 4 clusters defined as listed in Table 2: Hygroscopic façades, Fibrous morphologies, Segmented shells, Compliant mechanisms.

Table 1
Full overview of the variables of analysis clustered in seven categories.

Category	Variable	Parameter
Bio-BS Context	Name	–
	Climate	A (tropical) | B (dry) | C (temperate) | D (continental) | E (polar)
	Continent	Europe | America | Asia | Africa
	City	–
	Country	–
	Year of construction	–
	Surface (m^2)	–
	Cost (€/m^2)	–
	Type of building	Housing (individual or collective) | Pavilion | Exhibition hall | Religious building | Office | Other
	Renovation	Yes **|** No
Biologically-inspired design process	Main motivation of the designers	Energy efficiency | Occupant's comfort | Structure performance | Sustainability
	Outsourced steps	Step 1 (Functional analysis) | Step 2 (Understanding of biological principles) | Step 3 (Abstraction) | Step 4 (Feasibility) | Step 5 (Outcome) | None
	Major constraints	Technical problems | Use of biomimetic tools | Law regulations | Lack of funds | Other
	Use of design framework	No |Yes
Step 1. Identification of biological models	Approach	Biology push | Technology pull
	Definition	Biomimetics | Bio-inspiration | Biomimicry
Step 2. Selection of biological principles	Models' kingdom	Animalia | Plantae | Protista | Archaea | Fungi | Bacteria
	Number of models	Single | Multiple
	Tools for understanding and selection of relevant biological models	Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm | Other | None
	Knowledge	Non-scientific sources | Scientific sources | Created by academics and/or by experimentation during the design process
	Biologists' inputs	Biologists consulted | Biologists integrated in the design process | No interaction with any biologists
Step 3. Abstraction	Abstracted functions of regulation	One function | Two functions | Three functions | More than three functions
	Tools for abstraction	Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm | Other | None
	Level of innovation	Radical | Incremental
Step 4. Technical feasibility	Optimization tools	Quick calculation | CAD/computational tools software | models (mock-ups) | Other
	Design complexity	High | Low
	Construction complexity	High | Low
Step 5. Outcome: improved or new design	Integration scale of bioinspiration	Material | Façade element | Shading system | Wall | Roof | Fenestration | Envelope
	Technology Readiness Level	TRL9 | TRL8 | TRL7 | TRL6
	Comfort	Thermal comfort | Visual performance | Indoor air quality | Mechanical stress resistance | Acoustic quality | Other
	Assessment of energy and structural performances	Yes | No
	Operational state	Still operating | Destroyed | Not yet operating
	Main component	Polymer | Alloys | Concrete | Wood | Textile | Glass fibre
	Adaptation to stimuli	No | Yes
	Adaptable to renovation	No | Yes

Table 2
Full overview of the thirty Bio-BS comparative information collected from literature and interviews. **Type of building**: Public Building (Pub.), Housing (H), Pavilion (Pav.) – **Main motivation(s) of the design teams**: Energy efficiency (EE), Occupant's comfort (Oc), Structure performance (S), Sustainability (Su) – **Approach**: Biology push (Bio), Technology pull (Tech) – **Models kingdoms**: Animalia (An), Plantae (Pl), Protista (Pr), Archaea (Ar), Fungi (Fun), Bacteria (Ba) - **Level of scientific knowledge**: Non-academic sources (nAS),academic sources (AS) , Created by academics and/or by experimentation during the design process (C) – **Abstracted functions**: 1 to more than 3 - **Level of innovation**: Radical (Rad), Incremental (In) – **Construction complexity**: High (H), Low (L) – **Integration scale:** Material (M), Façade element (FE), Roof (R), Envelope (E) – **Assessment of energy performance:** yes, no, na **– Contribution to general building challenges**: Thermal comfort (T), Visual performance (V), Indoor air quality (I), Mechanical stress resistance (Me), Acoustic quality (A), Other (O). Mentions 'na' means not available where the authors could not provide an answer with certainty.

Id	Building envelopes (City, Country, Date) Description of the biomimetic system	Type of building	Main motivation(s) of the design teams	Approach	Models' kingdom	Knowledge	Abstracted function	Level of innovation	Complexity constr.	Integration scale	Energy performance	Comfort impact
1	**Shadow Pavilion** (Ann Arbor, Michigan, USA, 2009) – Pavilion inspired by the concept of phyllotactic to optimize the geometry [35–37]	Pav.	Oc, S, Su	Bio	Pl	AS, nAS	3	rad	H	FE	no	O
2	**Bloom** (Los Angeles, USA, 2011) – Adaptive material inspired by adaptation mechanisms in nature [38–40]	Pav.	EE, Oc	Bio	An	nAS	2	rad	H	M	no	T,V
3	**Homeostatic facade** (NYC, New York, USA, 2012) – Adaptive shading system inspired by mammals' muscles to manage light and thermal comfort [41–43]	Pub.	EE, Oc	Bio	An	nAS	2	rad	H	FE	no	T,V
4	**Breathing Skin pavilion** (Mandelbachtal, Germany, 2015) – Pneumatic façade component inspired by human skin for light, air and thermal regulation [44]	Pav.	EE, Oc	Bio	An	nAS	3	rad	H	FE	no	T,V, I
5	**Pho'liage Façade** (France, Lyon, 2020) – Adaptive shading system inspired by opening and closing of flower petals and plants' stomata [45,46]	Pub.	EE, Oc, Su	Tech	Pl	AS, nAS	2	rad	H	FE	na	T,V
6	**Umbrella Al Hussein Mosque** (Cairo, Egypt, 2000) – Deployable shading system inspired by opening and closing of flower petals [47,48]	Pub.	S	Tech	An	nAS	2	in	H	FE	no	T,V
7	**Sierpinski Forest** (Kyoto & Tokyo 2008, Japan and Tainan, Taïwan 2019) – Sun-shading façade component inspired by the fractal geometry of trees [49–51]	Pub.	EE, Oc, Su	Bio	Pl	AS	2	rad	L	FE	yes	T,V
8	**Esplanade Theatre Singapore** Art Centre (Singapore, 2002) – Shading system of a double roof dome inspired by the skin of the durian fruit for energy efficiency [52,53]	Pub.	EE	Tech	Pl	nAS	1	in	H	FE	na	T,V
9	**ArtScience Museum** (Singapore, 2011) – Building's shape inspired by the shape of the lotus flower to collect and harvest water [54,55]	Pub.	EE, Oc, Su	Tech	Pl	nAS	2	rad	H	E	na	O
10	**Eden project** (Cornwall, UK, 2001) – Greenhouse inspired by soap bubbles for efficient subdivision of space and lightweight stability [56–59]	Pub.	S,Su	Tech	Pro	nAS	3	rad	H	R	yes	Me
11	**West German Pavilion** (Montreal, Quebec, Canada, 1967) – Roof's pavilion inspired by the structure of spider web and biological light structures in general (Frei Otto) [60–62]	Pub.	S	Bio	Pro	AS, nAS,C	1	rad	H	R	no	Me
12	**International Terminal** (Waterloo, UK, 1993) – Façade component inspired by the pangolin scale arrangement to respond to changes in air pressure [63,64]	Pub.	S	Tech	An	AS, nAS	1	in	L	FE	no	Me
13	**Eastgate Centre** (Harare, Zimbabwe, 1996) – Office building envelope inspired by termites' mounds ventilation system and the cactus geometry for energy saving [65–67]	Pub.	EE, Oc, Su	Bio	An	AS, nAS,C	4	in	L	E	yes	T,V,I

(*continued on next page*)

Table 2 (*continued*)

Id	Building envelopes (City, Country, Date) Description of the biomimetic system	Type of building	Main motivation(s) of the design teams	Approach	Models' kingdom	Knowledge	Abstracted function	Level of innovation	Complexity constr.	Integration scale	Energy performance	Comfort impact
14	**Davies Alpine House** (Kew Garden, UK, 2006) – Green house for thermoregulation and passive ventilation inspired by macrotermes termite mounds [68,69]	Pub.	EE, Oc, Su	Tech	An	AS, nAS	3	in	L	E	yes	T,I
15	**Nianing Church** (Nianing, Senegal, 2019) – Church inspired by the ventilation system of termites mounds for passive ventilation [70,71]	Pub.	EE, Oc Su	Bio	An	nAS	3	in	L	E	no	T,I
	ICD Hygroscopic facades - Responsive facade system inspired by opening of pine cone for light and water regulation											
16	**HygroScope** (Orléans, France, 2012) – Responsive wood material within a glass case (in controlled humidity conditions) [72,73]	Pav.	EE, Oc	Bio	Pl	AS	2	rad	H	M	no	T,V
17	**HygroSkin** (Paris, France, 2013) – HygroScope adaptation into a meteorosensitive pavilion in real conditions [74–76]	Pav.	EE, Oc	Bio	Pl	AS	2	rad	H	M	no	T,V
	ICD/ITKE Fibrous morphology pavilions (FB) - Lightweight structure inspired by functional morphology and material properties of arthropods											
18	**FB Lobster research pavilion** (Stuttgart, 2012) – Pavilion inspired by the highly adapted and efficient structure exoskeleton of the lobster [77–79]	Pav.	S	Bio	An	AS, C	2	rad	H	FE	no	Me
19	**FB Spider research Pavilion** (Stuttgart, 2014–15) – Pavilion inspired by the web building process of the diving bell water spider [80,81]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me
20	**FB Elytra I research pavilion** (Stuttgart, 2013–14) – Pavilion inspired by the Elytra, a protective shell for beetles' wings and abdomen [82,83]	Pav.	S	Bio	An	AS, C	3	rad	H	FE	no	T,V,Me
21	**FB Elytra II research pavilion** (London, 2015–16) – Pavilion inspired by the Elytra [84,85]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me
22	**FB Moths research pavilion** (Stuttgart, RP 2017) – Pavilion inspired by functional principles and construction logics of larvae spin silk of leaf miner moths [86,87]	Pav.	S	Bio	An	AS, C	3	rad	H	FE	no	T, Me
23	**FB BUGA Fibre research pavilion** (Heilbronn, 2019) – Load-bearing structure inspired by beetle wings [88]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me
	ICD/ITKE Segmented shell Research Pavilions (SE) - Finger-joints inspired by the sand dollar and sea urchin morphology of their plate structures											
24	**SE Sand dollar I research pavilion** (Stuttgart, 2011) – Pavilion inspired by the high load bearing capacity of the plate skeleton morphology of the sand dollar built exclusively with extremely thin sheets of plywood [89,90]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me
25	**SE Sand dollar II research pavilion** (Stuttgart, 2015–16) – Pavilion employing industrial sewing of wood elements on an architectural scale [91,92]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me
26	**SE LAGA research pavilion** (Stuttgart, 2014) – First pavilion to have its primary structure entirely made of robotically prefabricated beech plywood plates [93,94]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me
27	**SE BUGA Wood research pavilion** (Heilbronn, 2019) – Pavilion built with Co-design (feedback-driven design) ensuring that all segments fit together with sub-millimetre precision like a three-dimensional puzzle [95,96]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me

Table 2 (*continued*)

Id	Building envelopes (City, Country, Date) Description of the biomimetic system	Type of building	Main motivation(s) of the design teams	Approach	Models' kingdom	Knowledge	Abstracted function	Level of innovation	Complexity constr.	Integration scale	Energy performance	Comfort impact
	ICD/ITKE Compliant mechanisms (CP) – Shading façade system inspired by the bird paradise flower and coleoptera to minimize energy for adaptive facade system											
28	**CP Flectofin** (Germany, 2011) – Adaptive hinge less louver system inspired by the opening mechanism of the bird paradise flower [97]	Pav.	EE, Oc, Su	Bio	Pl	AS, C	2	rad	H	FE	yes	T,V
29	**Thematic Pavilion** (South Korea, 2012) – Shading system for the façade of an exhibition hall which adapt the CP Flectofin system [98–100]	Pub.	EE, Oc, Su	Bio	Pl	AS, C	2	rad	H	FE	yes	T,V
30	**ITECH Pavilion** (Stuttgart, 2019) – Adaptive compliant structure inspired by the folding mechanisms of the Coleoptera coccinellidae wings. ITECH 2019 [101,102]	Pav.	EE, Oc, Su	Bio	An	AS	2	rad	H	FE	yes	T,V

Table 3
Variables distribution of category *Context* for the 19 Bio-BS.

Variable	Parameter distribution in percentage
Climate	**68% C (temperate)** | 16% B (dry) | 11% A (tropical) | 5% D (continental)
Continent	**52% Europe** | 16% America | 16% Asia | 16% Africa
Type of building	**37% Pavilion** | **32% Exhibition hall** | 11% Religious building | 11% Office | 5% Others (train station, hospital)
Renovation	**100% No** | 0% Yes

4. Results

4.1. Multiple Correspondence Analysis (MCA) – typologies of projects

The MCA (description in supplementary data **B. MCA analysis**) distinguished a clear disparity between two main groups of Bio-BS: academic and research projects, mainly of the ICD/ITKE/University of Stuttgart, and public buildings. Fig. 3 outlines the distribution of the projects **(a)** and associated weighted variables **(b)**.

Academic projects (on the left of Fig. 3 (**a**) and (**b**) (Ids. 3, 16–30)) presented a strong correlation with biology inputs in their design process; architects, engineers and biologists collaborate closely at an interdisciplinary level. For these projects, the abstraction and then the transfer of biomimetic principles into building constructions have resulted in some radical and incremental innovations, implemented through novel and uncommon manufacturing techniques.

Public buildings (on the right of Fig. 3 **(a) and (b)** (Ids. 1,2,4–15)) were mainly characterised by a scarce involvement of biologists during the design process and no thorough understanding of biological models. The projects used conventional design and construction methods for incremental innovation by improving existing building construction systems. The use of a biomimetic approach was motivated to provide neutral or positive impact design, but only a few of them assessed the final impact of their implemented design.

These preliminary results herald two main approaches for the design process of Bio-BS, with different constraints, context, stakeholders and resources. Data collected from the interviews was then analysed through univariate analysis for each of the 5 design process steps defined in Section 2.

4.2. Univariate analysis

The results of the univariate analysis are presented step by step in the following pages. They are expressed in percentages and discussed in each section.

4.2.1. Context

As presented in Table 3, half of the selected projects are located in Europe and others are equally distributed between America, Asia and Africa. This distribution might be either due to a lack of financial resources in the construction field of less wealthy countries, or to a quieter communication from them in the biomimetic field; some regions might simply use other semantics than what is defined by the ISO standard [2].

Pavilions are the most represented among the selected Bio-BS (37%). Bio-BS with higher TRLs such as exhibition halls count for a high share within the public buildings; this might be explained by their project briefs, usually allowing more creativity, in order to stand out or draw attention to the visitors, more than most other public projects. In line, this could also explain why the authors could not be found Bio-BS for housing, since project contractors would preferably seek conventional building skins configurations, and in short times.

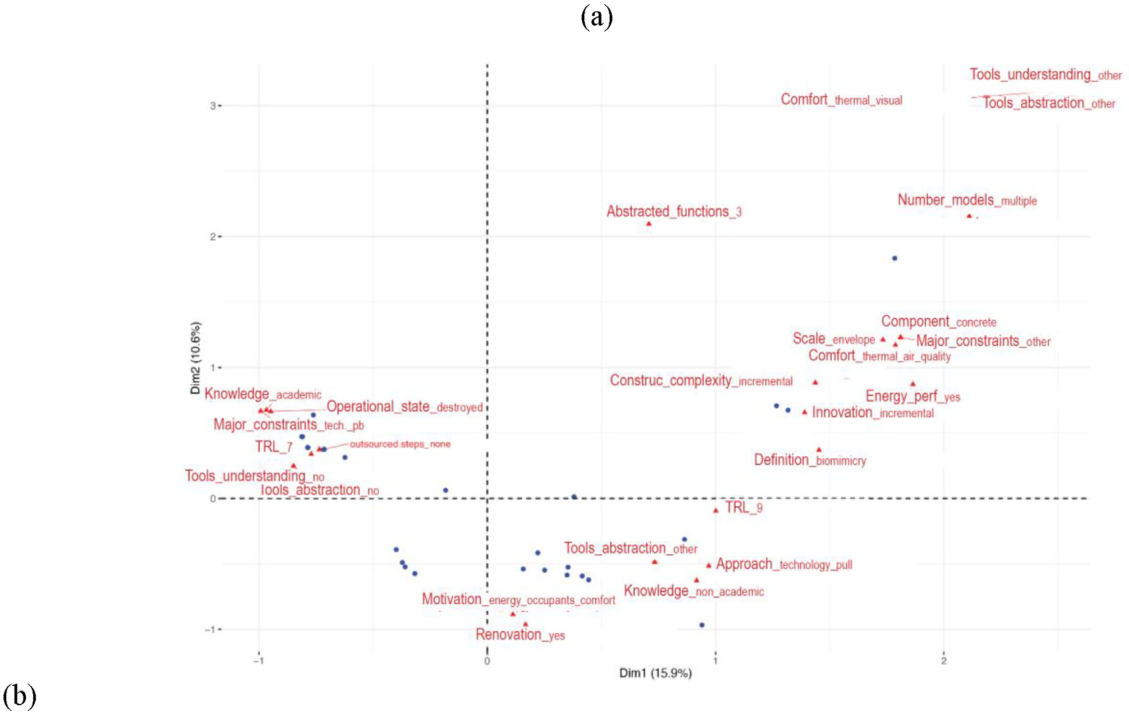

Fig. 3. MCA maps of all Bio-BS (blue points) and the 30 parameters (red triangles) (**a**) with the name of the Bio-BS, (**b**) with the name of the variables. All studied Bio-BS can be summarized in multidimensional spaces: each dimension stands for different variables describing the individuals. The first two dimensions, with here a total eigenvalue of 26.4%, can be considered representative of the correlations between the variables of the dataset. See supplementary data B. MCA Analysis for structuring variables contributing to these dimensions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.). Credits: CC-BY-SA Tessa Hubert

Even if some completions of projects are spread over the last fifty years – the West German Pavilion being the first built of the selected Bio-BS, in 1967 – half of the Bio-BS were completed in the last decade. Surprisingly, none of the latter was designed for the renovation of an existing building, while building renovation is considered as the main challenge over the coming years regarding environmental needs [104].

4.3. Overview of the biomimetic design process

Table 4 presents the variables distribution of the category 'Biologically-inspired design processe' for the 19 Bio-BS. **Main motivation(s) –** This parameter was introduced in order to clarify the design teams' motivation to use biomimetics during their design process. More than half of the interviews confirmed that biomimetics was primarily used to improve the energy performance or occupants' comfort of the Bio-BS rather than to respond to environmental issues [103]. However, the ambivalence of this parameter was highlighted when design teams judged biomimetic skins being more sustainable solutions than traditional ones; improving the Bio-BS energy performances or the comfort of occupants indirectly contributes to environmental issues, by potentially reducing energy demands and use of building materials. Likewise, the ICD/ITKE teams clearly expressed structure performance as the main motivation for biomimetics, and building sustainability as a secondary objective. However, they pointed out that their work was part of a longer process beginning with using less negative impact material for lighter structures, and eventually finding a way to replace them by more sustainable materials. Further investigations must provide a qualitative evaluation of these parameters since biomimetic buildings usually impact energy efficiency, sustainability and occupants' comfort. These novel investigations must be aligned with previous works as carried out by [105,106].

Table 4
Variables distribution of category *Biologically-inspired design process* for the 19 Bio-BS.

Variables	Parameters distribution in percentage
Main motivation(s) of the design teams	**27% Energy efficiency | 27% Occupant's comfort** | 18% Structure performance | 18% Building sustainability Other
Use of design framework	**95% No** | 5% Yes
Main constraints	**24% NA | 20% Technical problems** | 16% Law regulations | 8% Use of biomimetic tools | 4% Lack of funds | 4% Other
Outsources steps	0% Step 1 (Functional analysis) | 0% Step 2 (Understanding of biological principles) | 4% Step 3 (Abstraction) | **28% Step 4 (Feasibility) | 28% Step 5 (Outcome)** | 24% None | 16% NA

Use of design framework – The designation framework covers the contributions describing the whole development process such as process, method and tools. The only followed framework (5%) is the biology push approach provided by the ISO Norm 18458, applied during the ICD/ITKE *Compliant mechanisms* projects (Ids. 28–30). Apart from this exception, none of the interviewees confirmed using or following a framework from literature or peer-learning, and admitted they had not felt the need to use one. It adheres the popular belief that designers usually have their very own ways and habits in their creative processes, even when it comes to biomimetics.

Outsourced steps was defined to evaluate the contribution of external assistance provided outside of the initial design teams. The interviews suggested that the design teams outsourced very little design steps; for medium to large public buildings, most of them took part in steps 1 to 3, steps 4 and 5 being partially or fully assigned to another entity. Note that the authors could not interview all actors involved in the design process, hence some parts are not fully documented.

The identified main constraints were distributed between lacks of adapted biomimetic tools known by the team, the implementation of the biomimetic design in regards with law regulations, and lack of funds or time. Technical problems (such as choosing the right material to make the biomimetic design work, or even scaling the solution) were mostly mentioned when all steps of the design process were covered by the interviewed team, meaning they had to face the whole process by themselves. Rather than giving constraints, researchers from ICD/ITKE/University of Stuttgart admitted they had little limitation in terms of time.

Hence, before a deeper analysis of each step of the Bio-BS design process, the authors made the following observations:

(i) Some answers are not comprehensive: it outlines uncertainties on interpretations from the authors but also points out a lack rigorous methodology or perspective from the interviewed design teams on their design frameworks and encountered limitations.

(ii) These limitations are rather different between the two typologies of projects observed using MCA (**3.1. Main trends**) i.e., academia/research projects and public projects. This is in line with the initial questioning of this study: how does their design process differ to lead to such different design and construction complexities?

The collection of data for step 1 to 5 is analysed and discussed in the next sections.

4.4. Step 1 – functional analysis

Table 5 presents the variables distribution of the category Step 1 - functional analysisfor the 19 Bio-BS. **Definition –** The Bio-BS are equally distributed between bio-inspiration, biomimicry and biomimetics according to the definition provided by [2] Associating semantic to these projects helped dissociate levels of abstractions; biomimetics requires a higher level of abstraction of biological models than bioinspiration. As for biomimicry, it reflected considerations to sustainability when designing a bio-inspired solution.

Approach – Most Bio-BS were designed following a biology-push approach, i.e. starting with the discovery of a biological property then its transfer to a technical solution [105]. These results are consistent with the main trends in bio-inspiration; the absence of systematic selective methodology to identify the relevant biological models results in a practice of biomimetics more driven by a biology-push approach [107]. However, interviews and literature analysis showed that the line between the technology-pull and biology-push approaches is difficult to draw. In fact, designers make permanent back and forth between the two approaches. Their research process is not linear, but rather consists in feedback loops and iterations, as discussed by [108].

Table 5
Variables distribution of category *Step 1 – Functional analysis* for the 19 Bio-BS.

Variables	Parameters distribution in percentage
Approach	**63% Biology-push** | 37% Technology-pull
Definition	37% Bioinspiration | 32% Biomimicry | 31% Bioinspiration

4.5. Step 2 – understanding of biological concepts

Table 6 outlines the variables distribution for the category *Step 2 – Understanding of biological concepts* for the 19 Bio-BS. **Knowledge** and **Inputs of biologists from the design team –** Biologists were not integrated in the design process of public projects: either the architects had a strong sensitivity to biology, or they intended to perform ecological architecture. Bio-BS Pho'liage and Bloom remain an exception, since the architects Steven Ware and Doris Kim Sung have a first-degree in biology (Ids. 2,5). 58% of all design teams (public building projects Ids. 6, 8, 9, 10, 15 and pavilions Ids. 2,4) based their understanding of the living systems on non-academic biological knowledge, i.e. documentary or popular scientific writing. Only Mick Pearce performed experiments himself on the endemic termite mounds *odontotermes transvaalensis* to understand the involved physical phenomenon and then replicate their performance into the Eastgate Centre (Id. 13) (5) [65,109] (Fig. 4.a, and 4.b). However, although the Eastgate is a beautiful example of what bioinspiration or biomimicry can promote, his analysis was eventually proved erroneous [66]. On the other hand, Bio-BS from ICD/ITKE/University of Stuttgart based their transdisciplinary research on existing academic knowledge in biology developed by the scientific community (40% of all cases); most of the inputs from biology were provided by researchers of the University of Tübingen and the Plant Biomechanics Group of the University of Freiburg. When launching new pavilion projects, collaborations starts in the early phases of the design process [101], and according to the interviews, lead to co-discoveries.

Table 6
Variables distribution of category *Step 2 – Understanding of biological concepts* for the 19 Bio-BS.

Variables	Parameters distribution in percentage
Knowledge	**58% Non-scientific sources** | 40% scientific source | 12% experimentation as part of the design process
Inputs of biologists from the design team	**47% No interaction with any biologists** | 31% Biologists integrated in the design process | 21% Biologists consulted
Tools for understanding biological models	**80% NA | 20% none** | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm | Other
Model kingdom	**57% Animalia | 36% Plantae** | 7% Protista | 0% Archaea | 0% Fungi | 0% Bacteria
Number of models	**84% Single** | 16% Multiple

Tools for understanding biological model is a variable entirely based on parameters described in [110] depicting the current biomimetic types of tools in the literature existing to help understanding and selecting relevant of biological models, abstraction, and transfer to a design. The results can hardly be evaluated since the interviewees partially answered to that question. Interviewees from ICD/ITKE, whose projects benefited from the involvement of biologists, explained that biologists are usually much involved at the beginning of their design process, to help understand and select models with designers, then slowly fade away in favour of designers.

Model kingdom (according to the six kingdoms classification of [111]) – As highlighted by Figs. 5 and 6, the distribution of inspiring biological models is not proportionate to the distribution of biomass of estimated and described species on Earth; the species *homo sapiens*, for instance, was used as an inspiration for 15% of the Bio-BS with a 0.01% proportion in the biomass. Although these results convey a propensity by designers to use visible daily life biological inspirations (plants, animals), they could be explained by a problem of scale effect during the design process: the range of sizes of man-made technical devices are different from living organisms, and so are their constraints. This scale effect underpins technical problems mentioned in **3.3**; abstracting biological functions and implementing them into a functional design certainly is a challenge, even more with very small range living systems such as Protista, Bacteria and Archaea.

Fig. 4. Temperature measurements of termite mounds carried out by Mick Pearce (left), CC-SA-BY Licence, Mick Pearce. (b) Heat exchange floor under construction, abstraction of the biological principles of termite mounds, CC-SA-BY Mick Pearce.

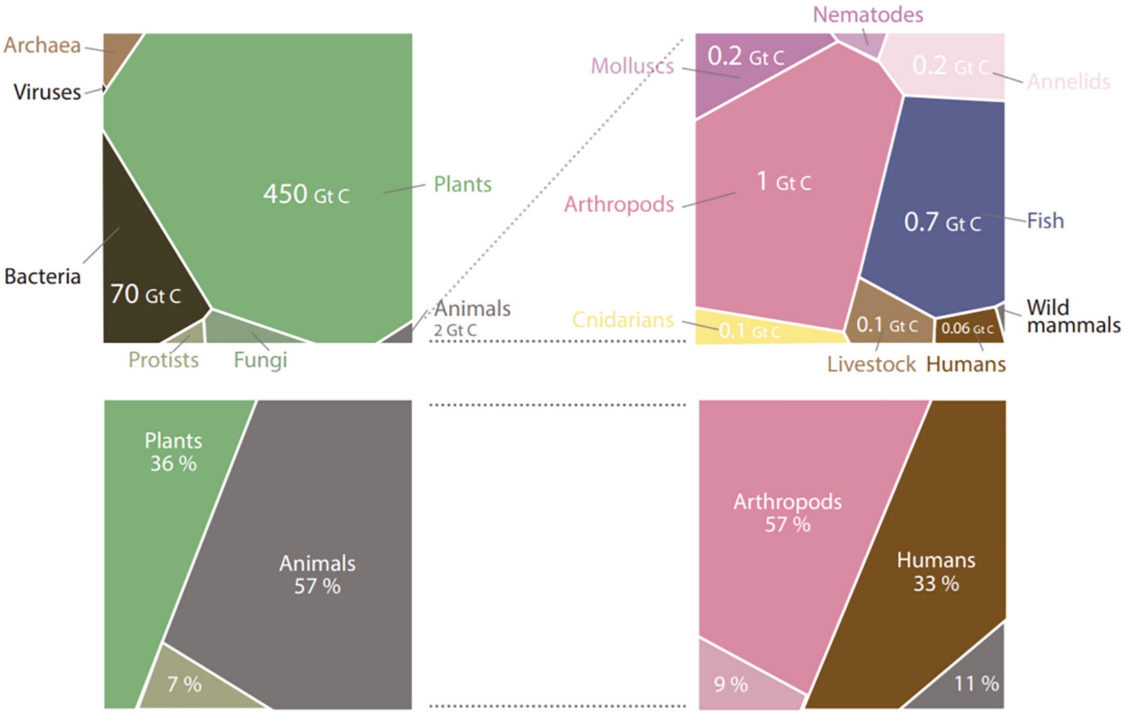

Fig. 5. Compariaison of the 19 Bio-BS with biomass distribution. (A) Distribution of the estimated biomass on earth in gigatons of carbon (GT C), reproduced and adapted from [112](B) Distribution in percentage of the biological models which inspired the 19 Bio-BS. Credits: CC-BY-SA Estelle Cruz

Number of models – 84% of the Bio-BS are based upon one biological model. Only three Bio-BS combined several principles abstracted from several biological systems (Ids. 10, 11, 13).

Combining the results led the authors to the following statements:

(i) The chosen biological models for bioinspiration are often from plant or animal kingdoms. We assume it is either because they are visible in humankind daily life or because other kingdoms present scale effects harder to abstract into designs. Exceptions exist when biologists are involved in the design process.

(ii) The inspiring biological model usually is chosen by instinct or perception when designers have specifications in mind. The use of biomimetic tools to understand or choose biological models seems rare or devolved to biologists. It is hard to tell if that is because the design teams did not express the need to use existing ones, because they could not find suitable ones, or because the biologists actually use these tools and the authors would not be aware. The second explanation is valid when crossed with the lack of biomimetic tools expressed by some projects as a constraint.

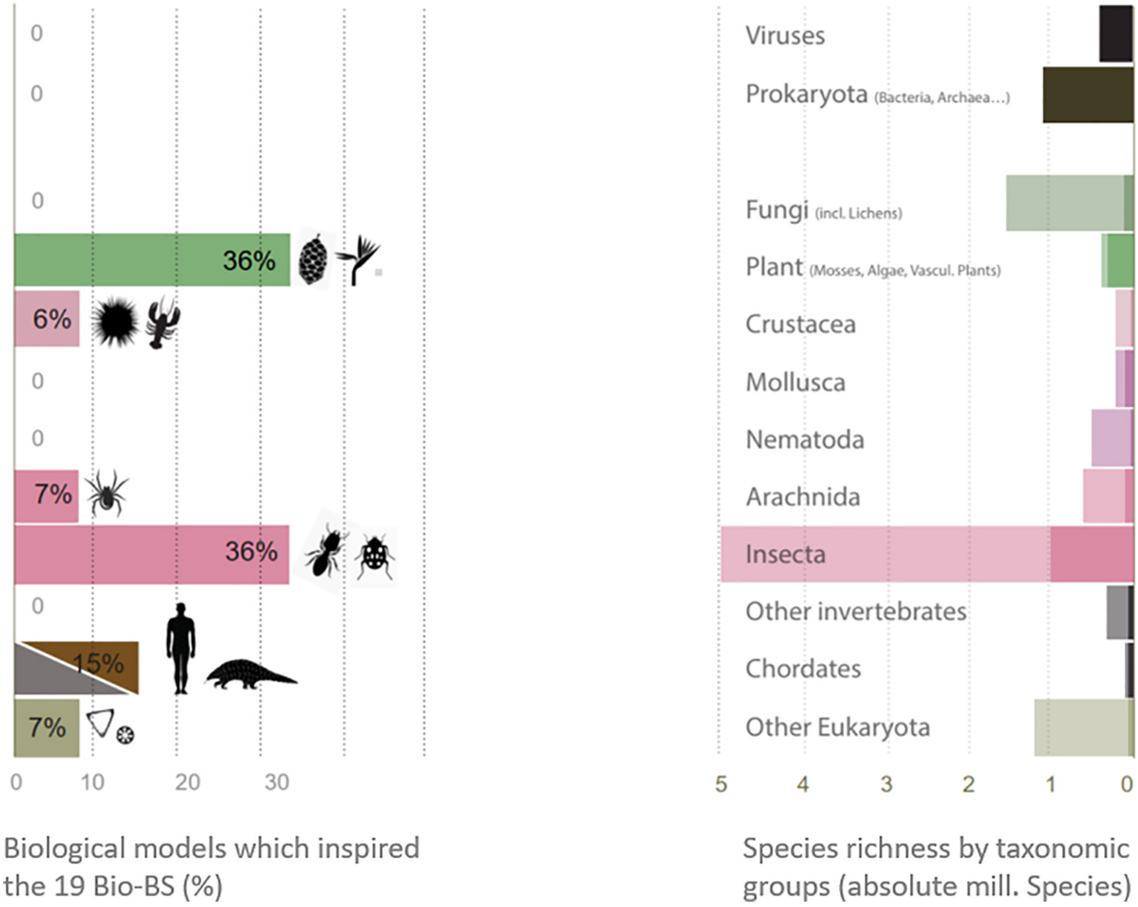

Fig. 6. Distribution of the major groups of biological models which inspired the 19 Bio-BS according to the distribution of estimated species on earth (absolute number of species on the left (grey = estimated number of yet to be described species, black = already described). This figure uses the same colour code as Fig. 5. Reproduced and adapted from [113]. Credits: CC-BY-SA Estelle Cruz

(iii) Interdisciplinary collaborations allow teams to co-discover new properties of living organisms creating mutual benefits between academic research in biology and architecture, and design teams are aware of that; in that sense, an interview from ICD stated that some projects would have hardly gone through without the help of wood experts and biologists (Ids. 16, 17, Table 2).

4.6. Step 3 – Abstraction

Table 7 presents the variables distribution of category *Step 3 – Abstraction* for the 19 Bio-BS. **Tool for abstraction –** The authors received few replies on this variable (n = 5); the interviews did not provide detailed information on this step since most of the designers described the abstraction as a creative step which can hardly be qualified. The few results suggested that none of the design teams abstracted biological principles using biomimetic tools, apart from the Sierpinski Forest (Id. 7, Table 2), which is the result of an opportunity during an abstraction phase [114,115].

Table 7
Variables distribution of category *Step 3 – Abstraction* for the 19 Bio-BS.

Variables	Parameters distribution in percentage
Abstracted functions of regulation	**47% One function** | **30% Two** | 7% Three | 13% more than three functions
Tools for abstraction	**73% NA** | 21% None | 6% Other | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm

Abstracted functions of regulation – Bio-BS mostly abstracted one or two functions. Fig. 7shows the distribution of regulated factors by number of abstracted functions. Almost half of them address mono-regulation, mostly mechanical stress (Ids. 1, 10–12, 18–27, Table 2). Then, multi-functions with light and heat regulations are comprehensively developed (Ids. 2–8, 13–17, 28–30). Only bio-inspired ventilation systems coupled with biomimetic skin provides multi-regulation of more than two factors, since ventilation systems regulate heat, light, humidity and air quality (Ids. 13–15). Among all Bio-BS, thermal comfort and visual performance are the most abstracted functions (see Fig. 8).

The authors found hard to assess the abstraction features since information was scarce. However, this section outlined the following results:

(i) The abstraction phase highly rests on the design team expertise and own creativity process. These results are aligned with recent research that highlighted limited tools to support the abstraction phases [22,116].

(ii) Since the characterization of the biological systems was found mainly mono model in step 2, the abstraction step followed the same trend. Design teams only abstracted one to two features of their inspiring model, often resulting in mono or bi-functional Bio-BS. Also, we noted that both thermal and visual comfort are interdependent and usually simultaneously targeted. There is a need for the development of building envelopes with multi-regulation capacities to address contradictory requirements as highlighted by

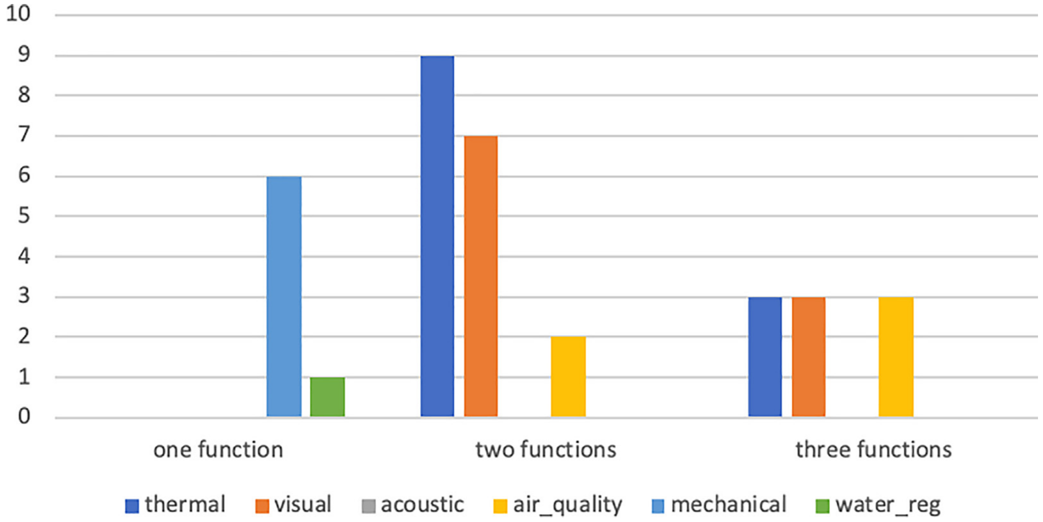

Fig. 7. Distribution of the function of regulation of the 19 Bio-BS according to the number of environmental factors regulated. Credits: CC-BY-SA Tessa Hubert

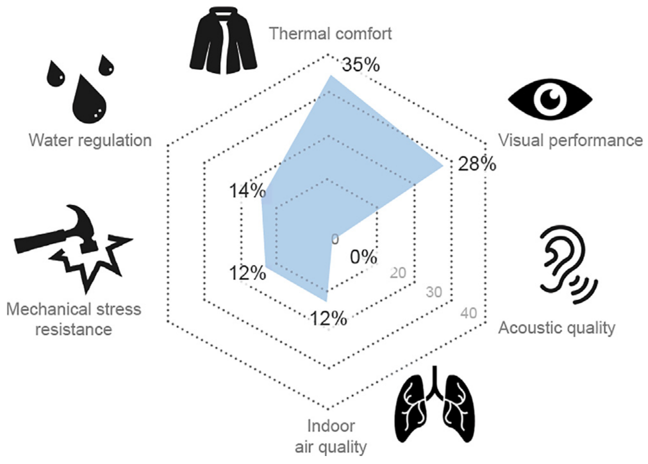

Fig. 8. Distribution of the Bio-BS according to the comfort. Credits: CC-BY-SA Estelle Cruz

[17,20]. For this purpose, several methodologies have been developed such as BioGen by L. Badarnah [26] and Kuru et al. [29]. However, as outlined by the variable 'use of design frameworks' in Table 4, none of these frameworks were used to design the Bio-BS studied in this paper. The interviews confirm that only the ISO Standard 18458 was used for the 5% of Bio-BS that used a biomimetic framework.

These findings encourage to increase the accessibility of biomimetic abstraction tools or to develop adapted tools to increase the development of multi-functional Bio-BS.

4.7. Step 4 – Feasibility and prototyping

Table 8 oulines the variables distribution of the category *Step 4 – Feasibility and prototyping* for the 19 Bio-BS. **Optimization tools** – This variable was defined to give insight about tools used for Bio-BS modelling, prototyping, and design optimization. The answers suggested a frequent use of the following:

Table 8
Variables distribution of category *Step 4 – Feasibility and prototyping* for the 19 Bio-BS.

Variables	Parameters distribution in percentage
Optimization tools	**44% CAD and numerical analyses software** | **44% models (mock-ups)** | 12% quick calculation
Design complexity	53% High | 47% Low
Construction complexity	**68% High** | 32% Low
Level of innovation	**74% Radical** | 26% Incremental

- **CAD and numerical-analysis software** (Ids. 1,2,5,8,10,12,15–30, Table 2): form-finding/scale-finding (Id. 5), Rhinoceros and Grasshopper (Ids. 1,2,8), CATIA (Ids. 2, 10), Revit (Id. 10), AutoCAD (Id. 2), Ecotect (Id. 2), Structural Analysis (Id. 2).
- **Numerical analyses software** (Ids. 2, 10, 15–30, Table 2): Ecotect (Id. 2), FEM (Id. 10), Heliodon (Id. 15), unspecified software such as programming languages (Ids. 15–30).
- **Prototyping** (Ids. 1, 2) before final construction.

Design complexity – The authors distinguished whether the Bio-BS resulted from high or low design complexity. Applied to buildings, the 3D-modeling using parametric programs such as Grasshoppers or Rhinoceros was considered as high design complexity (Ids. 1,2,9,16–30, Table 2). On the other hand, low design complexity applied to construction refers to the use of conventional design methods and software (Ids. 11–15, Table 2).

Construction complexity – The construction complexity was introduced to assess the ease of implementation of the biomimetic solution. High construction complexity refers to the use of novel and uncommon manufacturing techniques, materials or technology in contrast to low construction complexity. 68% of the Bio-BS which resulted in high construction complexity are mostly research pavilions. For instance, the ICD/ITKE fibrous morphology research pavilions (Ids. 18–22, Table 2) are an exploration of a novel robotic fabrication process coupled with computational design.

Level of innovation – Radical and incremental describe two different types of technological process innovations. Radical innovations refer to fundamental changes that represent new changes in technology whereas incremental innovations are minor improvements or adjustments in current technology according to [117]. The results show that the number of radical innovations is twice higher for research pavilions than for public buildings.

The distribution of these four variables led to the following observations:

(i) Public building Bio-BS projects tend to use conventional design methods. Likewise, the induced design outcomes usually require common construction techniques only. The analysed projects were mostly designed using classic CAD modelling, and the technological transfer resulted in the design implementation through well-known construction systems (Ids. 6, 8, 12–15, Table 2).

(ii) The teams of Bio-BS research pavilions undertook the technological transfer using highly complex design and construction systems. Their research context led towards a high design complexity requiring advanced modelling tools for parametric design, and high construction complexity exploring new manufacturing methods using robotic assistance. More generally, the construction complexity naturally increases when the design materials are non-usual for building skins (e.g., fibreglass, carbon fibre, hygroscopic wood) and are not necessarily suited for real-world construction.

(iii) Biomimetic projects can benefit from internal *and* external collaborations, whatever level of innovation (incremental or radical). As explained during interviews with ICD/ITKE teams, new projects in their labs take less and less time because knowledge and technology add-on. There is little communication with biologists or scientific entities in public buildings projects (see section **4.5. Step 2**), hence scientific grounding or technological opportunities would be a worthwhile consideration to push forward further development in biomimetic architecture.

4.8. Step 5 – Outcome: Improved or new design

Table 9 outlines the variables distribution of category *Step 5 – Outcome: improved or new design* for the 19 Bio-BS. **Spatial scale** (classification according [118]) – Some Bio-BS were found hard to classify since the biomimetic system is both embedded in the roof, wall and fenestration (Ids. 9–11, 18–30). These projects were classified as “envelope”.

TRL – The concept of TRL was defined by the ISO standard 16290:2013 [30]. This concept is widely used in all fields of engineering in order to measure the maturity level of a particular technology.

Table 9
Variables distribution of category *Step 5 – Outcome: improved or new design* for the 19 Bio-BS.

Variables	Parameters distribution in percentage
Integration scale of bioinspiration	**31% Shading system | 26% Façade element** | 11% Material | 11% Roof | 21% Envelope | 0% Fenestration | 0% Wall
Technology readiness level – TRL	**30% TRL9** | 27% TRL8 | 23% TRL7 | 20% TRL6
Comfort	**35% Thermal comfort | 28% Visual performance** | 12% Indoor air quality | 12% Mechanical stress resistance | 14% Other | 0% Acoustic quality
Assessment of energy and structural performances	**63% No** | 16% Yes | 21% NA
Operational state	**74% Still operating | 21% Destroyed** | 5% Not operating yet
Main component	**26% Polymer | 26% Alloys** | 21% Concrete | 11% Wood | 11% Textile | 5% Glass fibre
Adaptation to stimuli	**53% Yes** | 47% No
Adaptable to renovation	**58% No** | 42% Yes

Assessment of energy and structural performances – This variable specifies if the performance of the Bio-BS, from an energy and structural point of view, was assessed. Very few quantitative assessments of the Bio-BS were found and they were all carried out for public building projects (hygrothermal performance assessment for Ids. 10,13,14 and structural assessment for Id. 23, Table 2).

Comfort – The distribution of targeted performance is shown on Fig. 8. Thermal and visual comfort were simultaneously addressed since most of the Bio-BS were shading systems. This result is consistent with previous studies [17].

Operational state – This parameter provided a qualitative evaluation of the biomimetic systems’ performance after the building completion. Most of the research pavilions have been destroyed after completion, except BUGA Wood and Fibre pavilions exhibited in Germany in Heilbronn, and the Laga pavilion (Ids. 23, 26–27). Note that their destruction allowed the research teams to test technical performances such as tensile and compressive strength.

Adaptation to stimuli – Almost half of the Bio-BS (47%) can adapt over time in response to external stimuli to improve the overall building performance. Referring to the definition of Loonen *et al.*, their adaptation was mostly extrinsic – *adaptation which implies first information retrieving and processing and then, actions to be taken* – rather than intrinsic – *self-adjusting automatically triggered by environmental stimuli* (Ids. 2, 5, 16–17) [118].

Main component –Polymer material and metal alloys, used on half of the Bio-BS, were mostly used for adaptive use, as they can more easily adapt their shape to respond to stimuli.

Adaptable to renovation – None of the Bio-BS were applied to new buildings. However, half of them can easily adapt to existing buildings. For instance, the shading components and adaptive materials could be applied to retrofitted building.

Cost – The cost of the solutions was specified for 7 Bio-BS, as shown in Table 10. Results show a wide disparity of costs among office building Bio-BS, i.e. from 900 €/sqm up to 11 k €/sqm while building cost average in Europe varies from 960 €/sqm in Moscow, 2 400 €/sqm in Paris and over 3 350 €/sqm in London [119]. These strong price variations can be explained by the innovative manufacturing process and use of new technologies for Bio-BS. In order to compare and quantify the cost of bioinspiration, further research will have to assess the details of the distribution of costs during the design process (staff time, resources, etc.), during the construction (materials, manufacturing technics) and afterwards (maintenance, renovation, cost of HVCA, etc.).

The distribution of these variables led to the following observations:

(i) There is a lack of qualitative data on the Bio-BS. It probably does not help the promotion of biomimicry as a lever to environmental and energy performance challenges. Since public authorities have no tangible data, they are not driven to advocate or encourage (e.g., by grants) public procurement to apply biomimetic approaches. Hopefully, with the current biomimetics emergence, more effort will be made in the future to provide performance assessments (in terms of life cycle assessment, comfort, etc.) when designing Bio-BS.

(ii) Thermal and visual comfort/performance are the most targeted performances, largely implemented into shading systems, while other regulation parameters are not ensured by the biomimetic design. There is a need for more multifunctional designs for the building skin, covering functions that also have a strong impact on the comfort and the energy efficiency of the building.

Table 10
Costs of construction ranked in ascending order of cost / floor area according to project use.

Id	Bio-BS	Building use	Floor area (sqm)	Cost (k€)	Cost/floor area (€/sqm)
1	Shadow Pavilion	Pavilion	20	18	900
13	Eastgate Building	Private (office)	55 k	30 M	545
8	Esplanade theatre	Public (museum)	5.5 k	5.5	1 000
15	Nianing church	Private (church)	457	1 M	2340
9	Art Sciences Museum	Public (museum)	350 k	75	4 655
10	Eden project	Public (green house)	23 k	239	10 391
14	Davies Alpine House	Public (green house)	70	800	11 430

(iii) There was no case of renovation: it implies that possibilities of already existing designs are not considered enough by renovation stakeholders. This may be linked to points (i) and (ii); possibilities of multifunctionality are little-known, applied, and assessed.

5. Discussion

Some joint efforts between research media and public procurement could lead to new development in biomimetics. For public building projects where the available time is fairly often an irreducible constraint, biological progress such as the generation of knowledge, the creation of structuring tools and biological data mining, may considerably help biomimetic design process.

Selecting and abstracting the accurate biological model for a biomimetic solution is intricate. Even trained biomimetic practitioners, such as researchers of Stuttgart, need a preselection of groups of organisms with the involvement of biologists to help focus the research project. This approach has shown to stimulate co-discoveries, beneficial for technological breakthroughs and contribution in biological data. Therefore, it would be interesting to apply this multidisciplinary work specifically with a focus on several taxonomic groups at a time, and to assess the effects of hybridization of biological strategies on the design of a biomimetic envelope element with multi-regulation targets and specifications.

As seen in this study, the methodologies and tools used in thein bioinspiration design process are diverse, and yet, the number of projects in the literature reaching a TRL of 6 is low. Despite a high potential for product development, the implementation of Bio-BS elements in practice is challenging. During abstraction and technical feasibility steps, designers have to take into account market specifications, but they should also retrieve feedbacks and experience from the users afterwards, to allow scalable and repeatable models, and avoid successful but unique-application biomimetic designs.

In addition, we suggest that addressing multi-regulation requires mechanisms in the early-stage of the design process, assisted with data exploration and structuring tools. Further research from the authors is ongoing and focusing on the development of tools to access to biological data during the design process and help combine different biological strategies.

6. Conclusions

The presented study has given an overview of Bio-BS and their design process. Thirty built Bio-BS were analysed using two complementary methods: a univariate analysis to highlight the main trends of biomimetic design process and a multivariate analysis (MCA) as a complementary analysis to outlined main variables discriminating the different types of Bio-BS. Although recent studies have provided comparative analysis of adaptive biomimetic building skins, an overview, which assesses the correlation between the design process and the final result has been lacking so far. This study is the first qualitative and step-by-step evaluation of the biomimetic design process of existing Bio-BS.

Results from the multivariate analysis (MCA) - outlined two main types of Bio-BS where the final design highly depends of the context in which they were designed. The two main groups go as follow:

(A) **Academic projects** which present a strong correlation with the biology input in their design process; architects, engineers and biologists collaborate closely at an interdisciplinary level. The abstraction then the transfer of biomimetic principles into building constructions have mostly resulted in some radical innovations.
(B) **Public building projects** are mainly characterised by a scarce involvement of biologists during the design process and no thorough understanding of biological models. The projects used conventional design and construction methods for incremental innovation by improving existing building construction systems. The use of a biomimetic approach was motivated to provide neutral to positive impact design towards environmental issues, but almost none of them assessed the final impact of their implemented design.

The results demonstrated that the integration of biological knowledge has a strong influence on the following design steps and the final result since academic projects resulted in radical innovation whereas public buildings in incremental. These two main groups highlighted the gap between academic research and building applications as discussed by [120] as “the valley of the death”.

Results from the univariate analysis showed that Bio-BS have limitation in:

(i) Being precisely described for the biomimetic design process.
(ii) Integrating scientific biological knowledge during the design process since inputs from biology are mostly based on knowledge for general public (58%). 82% of biomimetic projects are inspired by a single biological organism which belongs to the kingdoms of animals (53%) and plants (37%) kingdoms which represent a small part of the diversity of species on earth.
(iii) Addressing multi-regulation since 47% of the Bio-BS one function and 30% two functions. When the Bio-BS addressed more than one function, it is mostly thermal comfort and visual performance, which are correlated functions. Very few Bio-BS meet contradictory requirements.
(iv) Being evaluated with numerical analysis to quantify energy performances (thermal, visual, acoustic, mechanics). The authors founded quantitative data for only 16% of the Bio-BS.

CRediT authorship contribution statement

Estelle Cruz: Conceptualization, Investigation, Formal analysis, Visualization, Writing - original draft. **Tessa Hubert:** Conceptual-

ization, Investigation, Formal analysis, Visualization, Writing - original draft. **Ginaud Chancoco:** Investigation. **Omar Naim:** Investigation. **Natasha Chayaamor-Heil:** Investigation, Writing - review & editing. **Raphaël Cornette:** Methodology, Formal analysis, Writing - review & editing. **Lidia Badarnah:** Conceptualization, Resources, Writing - review & editing. **Kalina Raskin:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Fabienne Aujard:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. None of the sponsors or the co-authors of this research have been closely or remotely involved in the design or construction of the thirty analysed Bio-BS.

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Appendix A. Supplementary data

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