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1 Design processes and multi-regulation of biomimetic building skins: a 2 comparative analysis

3 4 **Abstract**

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

28

29

30 **1. Introduction**

31

32 Building skins are multi-criteria systems that require the control of several environmental factors,
33 such as heat, light, humidity, ventilation and mechanical stress [1], [2]. Their performances highly
34 influence the building total energy consumption, since they filter the environmental constraints [3, Ch.
35 1]. In order to improve building skins efficiency, academics and industries have explored nature-
36 inspired solutions that are referred to Bio-BS (Bio-Inspired Building Skins).

37 Biomimetics is an interdisciplinary approach based on the integration of biology and technology, by
38 transferring nature's principles into a technological solution [4], [5]. This approach has inspired
39 innovation in diverse fields and had a significant impact in architecture for the design of sustainable
40 built-environments [6]–[12]. International research has focused on the development of adaptive
41 energy efficiency of building skins where biomimetics was implemented as a sub- research category
42 [13], [14]. Both living systems and building envelopes have to filter simultaneously several changing
43 environmental factors to maintain their physical integrity [15]. More than seventy case studies and
44 designs of bio-inspired building skins were reported over the last two decades, and this number is
45 rapidly growing across industry and academia [16]–[21]. However, few of these cases address multi-
46 criterion challenges. Kuru *et Al.* [20] has outlined that only 13.4% of fifty-two published biomimetic
47 adaptive skins (Bio-ABS) control more than one parameter. More generally, these observations
48 converge with recent studies [22]–[24], showing limited use of existing tools and frameworks to
49 promote the development of multi-functional biomimetic applications.

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

56 **2. Bio-BS design**

57

58 **2.1. Design process**

59 Bio-BS follow different definitions according to ISO 2015:18458 [4]:

60 - *Bioinspiration*: Creative approach based on the observation of biological systems.

61 - *Biomimetics*: Interdisciplinary cooperation of biology and technology or other fields of innovation
62 with the goal of solving practical problems through the function analysis of biological systems, their
63 abstraction into models, and the transfer into and application of these models to the solution.

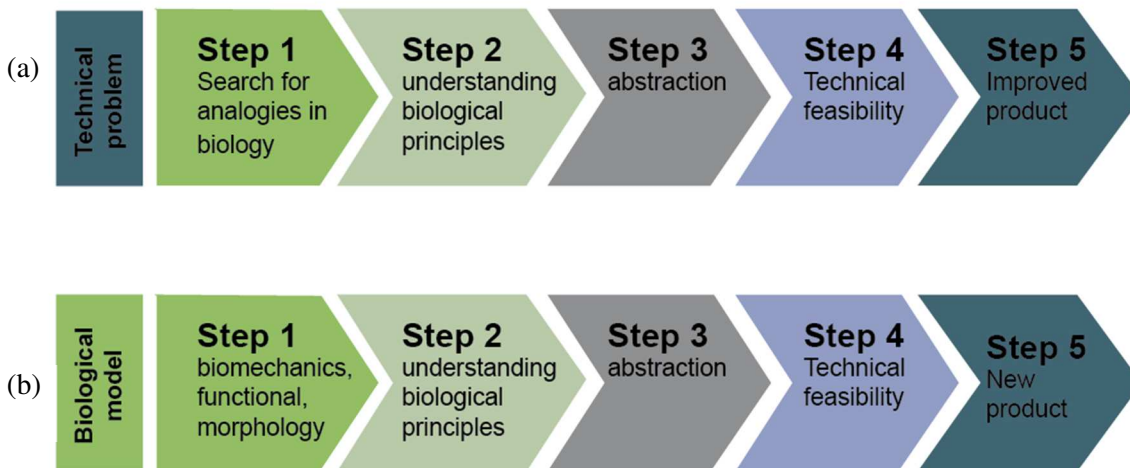
64 - *Biomimicry*: Philosophy and interdisciplinary design approaches taking nature as a model to meet
65 the challenges of sustainable development.

66

67 Two main approaches exist in such design processes: ‘technology pull’ or ‘biology push’. The ISO
68 has provided the following definitions: **the technology pull process** is a “*biomimetic development*
69 *process in which an existing functional technical product is provided with new or improved functions*
70 *through the transfer and application of biological principles*”. **The biology push process** is a
71 “*biomimetic development process in which the knowledge gained from basic research in the field of*
72 *biology is used as the starting point and is applied to the development of new technical products*” [4].

73 The generic steps are presented in Figure 1 for each approach.

74



75

76 **Figure 1.** Biomimetic design process. (a) technology pull, (b) biology push. Adapted with permission from ISO
77 standard 2015:18458[4]

78

79

80 2.2. Design tools

81 There exists a wide range of methods and tools in literature to support biomimetic design processes
82 [22]. Nevertheless, due to the interdisciplinary nature of biomimetics designers still tackle certain
83 challenges in the search for, and the selection of appropriate models and strategies [25]. The search
84 for analogies between buildings and natural systems is a common trend to address existing challenges,
85 where seeking different classification categories have emerged, e.g. [2], [26]–[28]. Addressing multi-
86 functionality is another challenging topic, where it has been addressed in limited studies only [29],
87 mainly due to its complexity and the need to address multiple contradictory functional requirements at
88 the same time [20], [2, Ch. 8], [29]. Existing efforts explore different avenues to develop frameworks
89 that could assist in transferring multi-functionality from nature into biomimetic designs, such as
90 focusing on multi-criteria requirements [30], on the correlation between morphology and environment
91 [27], [31] and on hierarchy and heterogeneity [32]. However, these frameworks are still under
92 development and hardly applied in design solutions by the wider community. Therefore, there is a
93 need not only to develop tools that support multi-functional applications but also to promote their use
94 by the wider design community. This work aims to provide a better understanding of the multiple
95 criteria involved in the design process by involving design teams of existing projects in the analysis.
96 For this reason, 30 biomimetic building skins (Bio-BS) were selected for this study.

97

98 2.3. Overview of the 30 Bio-BS

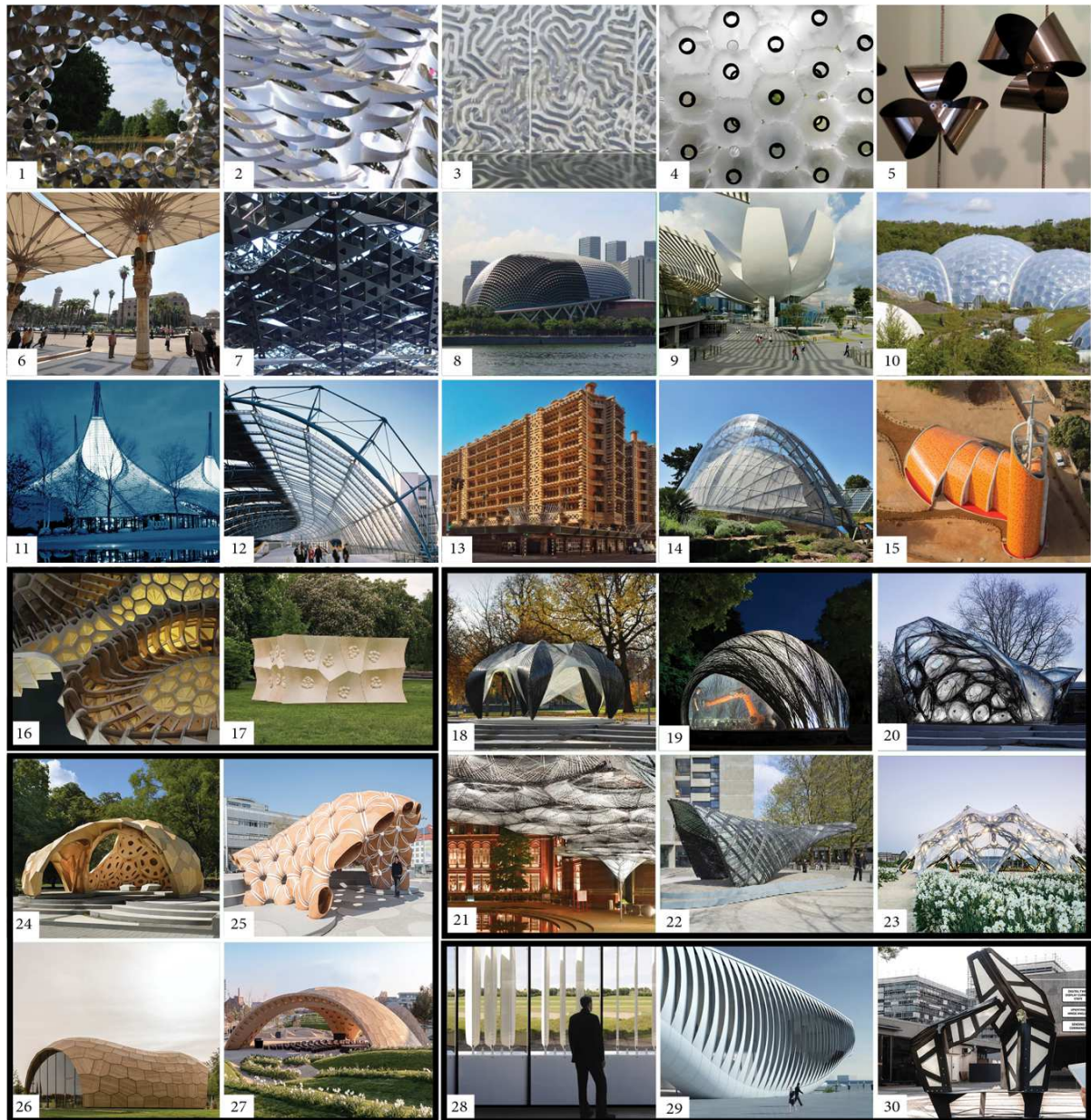
99 **Table 2** lists the thirty selected Bio-BS. Thirty cases of Bio-BS were chosen in the scientific literature
100 according to three criteria:

- 101 • The designs are above a Technology Readiness Level (TRL) of 6, which means they are
102 either a “*system/subsystem model or prototype demonstration in a relevant environment*”
103 [33]. It excluded student or research projects which had not resulted in a prototype so far. A
104 TRL of 6 insured that the projects at least have run through the design process enough to
105 provide feedback on the methodological aspects.
- 106 • The projects met the definitions of either bioinspiration, biomimicry or biomimetics
107 according to [4] Thus, they have different rigor in terms of biological data mining,
108 understanding, and abstraction; however, they all derived from a creative approach based on
109 the observation of biological systems.
- 110 • The bioinspired element of the Bio-BS is embedded at the scale of the building envelope from
111 material, façade component, shading system, wall, fenestration, roof to envelope according to
112 the classification of [34].

113

114 Biomimetic research pavilions (TRL = 6) designed by ICD/ITKE at Stuttgart University counted for
115 half of the selection. They resulted from interdisciplinary biomimetic design processes within the

116 collaborative research centre SFB-TRR 141 between the University of Stuttgart (ICD / ITKE research
 117 labs), Tübingen and Freiburg (the research group Plant Biomechanics) [35] Although performance of
 118 research pavilions highly differs from the building envelopes of public buildings, their biomimetic
 119 design processes remained relevant for this study since they were designed beyond the limitations of
 120 the real-world constructions. In order to compare the biomimetic design process in several contexts,
 121 this study assessed both real-world applications and prototype academic experimentations.
 122



123
 124 **Figure 2.** Overview of the 30 Bio-BS. With permission from: (1) © PLY Architecture, (2) © DO SU Studio
 125 Architecture, (3) © Decker Yeadon LLC, (4) © Tobias Becker, (5) © Art and Build, (6) © SL Rasch, (7) Estelle
 126 Cruz CC0 Creative Commons, (8) © Tom Ravenscroft, (9) © Tom Ravenscroft, (10) CC0 Creative Commons
 127 Licence, (11) © Frei Otto, (12) CC0 Creative Commons Licence, (13) © ARUP, (14) © Oast House Archive,
 128 (15) Regis L'Hostis, (16-30) © ICD/ITKE University of Stuttgart.

129 **3. Methods**

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

135

136 **3.1. Data collection**

137 • To assess the whole design process of the selected Bio-BS, seven categories of qualitative
 138 variables were defined. The first two categories provided the context of the Bio-BS (location,
 139 climate, etc.) and the biomimetic design process (purpose, main tools, etc.). Then, the
 140 following categories corresponded to the five biomimetic design steps according to ISO
 141 standard 2015:18458 [4]. These parameters and categories were chosen before identifying the
 142 thirty cases based on existing categorisations for building facades [34], [36], biomimetic
 143 tools [22], and biomimetic facades [20], [37]. **Table 1** provides an overview of the variables
 144 and parameters, and Table 2 presents the 11 variables within the 34 presented in Table 1.
 145 They were chosen since they add new knowledge to the field collected during the interviews.
 146 A data sheet was created for each case study (**Table 2**), including the variables listed in **Table**
 147 **1**. The information was first collected going through literature, then reviewed with the
 148 designers for validation. The reviews were conducted as follows: digital exchange through
 149 online datasheet using comments or direct modifications of parameters from the designers
 150 (Ids. 1- 3, Table 2),

151 • phone calls and videoconferences (Ids. 11, 18-22, Table 2),

152 • face-to-face exchanges, discussions during conferences (Id. 5, 8, 10, 14, 15, Table 2),

153 participant observations (Id. 7 for 10 weeks, Id 13 for 12 weeks, Ids. 16-30 for 2 weeks,
 154 Table 2). **Table 1**. Full overview of the variables of analysis clustered in seven categories

155

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

156 **Table 2.** Full overview of the thirty Bio-BS comparative information collected from literature and interviews. **Type of building:** Public Building (Pub.), Housing (H),
 157 Pavilion (Pav.) – **Main motivation(s) of the design teams:** Energy efficiency (EE), Occupant’s comfort (Oc), Structure performance (S), Sustainability (Su) – **Approach:**
 158 Biology push (Bio), Technology pull (Tech) – **Models kingdoms:** Animalia (An), Plantae (Pl), Protista (Pr), Archaea (Ar), Fungi (Fun), Bacteria (Ba) - **Level of scientific**
 159 **knowledge:** Non-academic sources (nAS), academic sources (AS) , Created by academics and/or by experimentation during the design process (C) – **Abstracted functions:** 1
 160 to more than 3 - **Level of innovation:** Radical (Rad), Incremental (In) – **Construction complexity:** High (H), Low (L) – **Integration scale:** Material (M), Façade element
 161 (FE), Roof (R), Envelope (E) – **Assessment of energy performance:** yes, no, na – **Contribution to general building challenges:** Thermal comfort (T), Visual performance
 162 (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
 163 answer with certainty.
 164

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 [38]–[40]	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 [41]–[43]	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 [44]–[46]	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 [47]	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 [48], [49]	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 [50] [51]	Pub.	S	Tech	An	nAS	2	in	H	FE	no	T,V
7 Sierpinski Forest (Kyoto & Tokyo 2008, Japan and Tainan, Taiwan 2019) – Sun-shading façade component inspired by the fractal geometry of trees [52]–[54]	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 [55], [56]	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 [57], [58]	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 [59]–[62]	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) [63] [64] [65]	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 [66], [67]	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 [68]–[70]	Pub.	EE, Oc, Su	Bio	An	AS, nAS, C	4	in	L	E	yes	T,V,I
14	Davies Alpine House (Kew Garden, UK, 2006) – Green house for thermoregulation and passive ventilation inspired by macrotermes termite mounds [71], [72]	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 [73], [74]	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) [75], [76]	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 [77]–[79]	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 [80]–[82],	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 [83], [84]	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 [85], [86]	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 [87], [88]	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 [89], [90]	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 [91]	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 [92], [93]	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 [94], [95]	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 [96], [97]	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 [98], [99]	Pav.	S	Bio	An	AS, C	1	rad	H	FE	no	Me

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 [100], [101]	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 [102]–[104]	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 [105], [106]	Pav.	EE, Oc, Su	Bio	An	AS	2	rad	H	FE	yes	T,V

165 3.2. Analysis

166 Information on the interviews (names/role of interviewees, type and durations of interviews) are given
167 in supplementary data. Overall, 25 of the 30 Bio-BS data sheets received feedback from the designers.
168 The collected data is available in two additional supplementary documents: an excel sheet gathers all
169 results to the variables listed in **Table 1** (on request), and an online report provides an overview of
170 each project [107].

171 Data analysis was conducted through:

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

185

186 4. Results

187 4.1. Multiple Correspondence Analysis (MCA) - typologies of projects

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

192

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

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

204

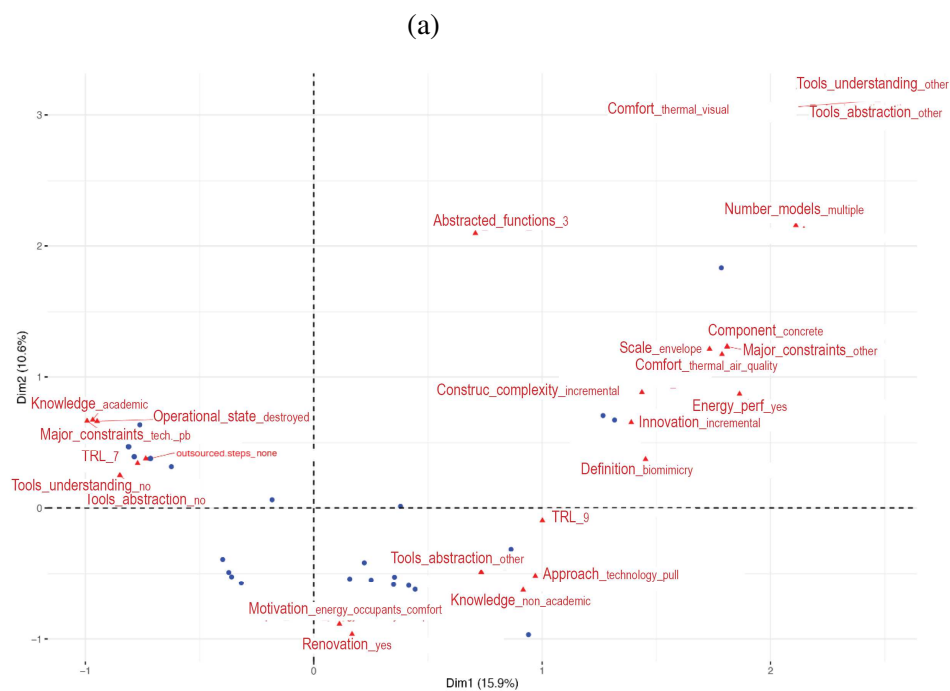
205 These preliminary results herald two main approaches for the design process of Bio-BS, with different
 206 constraints, context, stakeholders and resources. Data collected from the interviews was then analysed
 207 through univariate analysis for each of the 5 design process steps defined in **Section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

208

209

210

211



212 (b)

213

214 **Figure 3.** MCA maps of all Bio-BS (blue points) and the 30 parameters (red triangles) **(a)** with the name of the
 215 Bio-BS, **(b)** with the name of the variables. All studied Bio-BS can be summarized in multidimensional spaces:
 216 each dimension stands for different variables describing the individuals. The first two dimensions, with here a
 217 total eigenvalue of 26.4%, can be considered representative of the correlations between the variables of the
 218 dataset. See supplementary data B. MCA Analysis for structuring variables contributing to these dimensions.

219 **4.2. Univariate Analysis**

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

222

223 **4.2.1 Context**

224 **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

225

226 Half of the selected projects are located in Europe and others are equally distributed between
227 America, Asia and Africa. This distribution might be either due to a lack of financial resources in the
228 construction field of less wealthy countries, or to a quieter communication from them in the
229 biomimetic field; some regions might simply use other semantics than what is defined by the ISO
230 standard[4]

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

237 Even if some completions of projects are spread over the last fifty years – the West German Pavilion
238 being the first built of the selected Bio-BS, in 1967 – half of the Bio-BS were completed in the last
239 decade. Surprisingly, none of the latter was designed for the renovation of an existing building, while
240 building renovation is considered as the main challenge over the coming years regarding
241 environmental needs [108].

242

243 **4.3. Overview of the biomimetic design process**

244 **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

245

246 **Main motivation(s)** – This parameter was introduced in order to clarify the design teams' motivation
 247 to use biomimetics during their design process. More than half of the interviews confirmed that
 248 biomimetics was primarily used to improve the energy performance or occupants' comfort of the Bio-
 249 BS rather than to respond to environmental issues [107]. However, the ambivalence of this parameter
 250 was highlighted when design teams judged biomimetic skins being more sustainable solutions than
 251 traditional ones; improving the Bio-BS energy performances or the comfort of occupants indirectly
 252 contributes to environmental issues, by potentially reducing energy demands and use of building
 253 materials. Likewise, the ICD/ITKE teams clearly expressed structure performance as the main
 254 motivation for biomimetics, and building sustainability as a secondary objective. However, they
 255 pointed out that their work was part of a longer process beginning with using less negative impact
 256 material for lighter structures, and eventually finding a way to replace them by more sustainable
 257 materials. Further investigations must provide a qualitative evaluation of these parameters since
 258 biomimetic buildings usually impact energy efficiency, sustainability and occupants' comfort. These
 259 novel investigations must be aligned with previous works as carried out by [109], [110].

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

267 **Outsourced steps** was defined to evaluate the contribution of external assistance provided outside of
 268 the initial design teams. The interviews suggested that the design teams outsourced very little design

269 steps; for medium to large public buildings, most of them took part in steps 1 to 3, steps 4 and 5 being
270 partially or fully assigned to another entity. Note that the authors could not interview all actors
271 involved in the design process, hence some parts are not fully documented.

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

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

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

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

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

289

290 **4.4. Step 1 - Functional analysis**

291 **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

292

293 **Definition** – The Bio-BS are equally distributed between bio-inspiration, biomimicry and
294 biomimetics according to the definition provided by [4] Associating semantic to these projects helped
295 dissociate levels of abstractions; biomimetics requires a higher level of abstraction of biological
296 models than bioinspiration. As for biomimicry, it reflected considerations to sustainability when
297 designing a bio-inspired solution.

298 **Approach** – Most Bio-BS were designed following a biology-push approach, i.e. starting with the
 299 discovery of a biological property then its transfer to a technical solution [111]. These results are
 300 consistent with the main trends in bio-inspiration; the absence of systematic selective methodology to
 301 identify the relevant biological models results in a practice of biomimetics more driven by a biology-
 302 push approach [112]. However, interviews and literature analysis showed that the line between the
 303 technology-pull and biology-push approaches is difficult to draw. In fact, designers make permanent
 304 back and forth between the two approaches. Their research process is not linear, but rather consists in
 305 feedback loops and iterations, as discussed by [113].

306

307 **4.5. Step 2 - Understanding of biological concepts**

308 **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

309

310 **Knowledge and Inputs of biologists from the design team** – Biologists were not integrated in the
 311 design process of public projects: either the architects had a strong sensitivity to biology, or they
 312 intended to perform ecological architecture. Bio-BS Pho’liage and Bloom remain an exception, since
 313 the architects Steven Ware and Doris Kim Sung have a first-degree in biology (Ids. 2,5). 58% of all
 314 design teams (public building projects Ids. 6, 8, 9, 10, 15 and pavilions Ids. 2,4) based their
 315 understanding of the living systems on non-academic biological knowledge, i.e. documentary or
 316 popular scientific writing. Only Mick Pearce performed experiments himself on the endemic termite
 317 mounds *odontotermes transvaalensis* to understand the involved physical phenomenon and then
 318 replicate their performance into the Eastgate Centre (Id. 13) (5) [68], [114]. However, although the
 319 Eastgate is a beautiful example of what bioinspiration or biomimicry can promote, his analysis was
 320 eventually proved erroneous [69]. On the other hand, Bio-BS from ICD/ITKE/University of Stuttgart

321 based their transdisciplinary research on existing academic knowledge in biology developed by the
322 scientific community (40% of all cases); most of the inputs from biology were provided by
323 researchers of the University of Tübingen and the Plant Biomechanics Group of the University of
324 Freiburg. When launching new pavilion projects, collaborations starts in the early phases of the design
325 process [105], and according to the interviews, lead to co-discoveries .

326 **Tools for understanding biological model** is a variable entirely based on parameters described in
327 [115] depicting the current biomimetic types of tools in the literature existing to help understanding
328 and selecting relevant of biological models, abstraction, and transfer to a design. The results can
329 hardly be evaluated since the interviewees partially answered to that question. Interviewees from
330 ICD/ITKE, whose projects benefited from the involvement of biologists, explained that biologists are
331 usually much involved at the beginning of their design process, to help understand and select models
332 with designers, then slowly fade away in favour of designers.

333 **Model kingdom** (according to the six kingdoms classification of [116]) – As highlighted by Figures 6
334 and 7, the distribution of inspiring biological models is not proportionate to the distribution of
335 biomass of estimated and described species on Earth; the species *homo sapiens*, for instance, was used
336 as an inspiration for 15% of the Bio-BS with a 0.01% proportion in the biomass. Although these
337 results convey a propensity by designers to use visible daily life biological inspirations (plants,
338 animals), they could be explained by a problem of scale effect during the design process: the range of
339 sizes of man-made technical devices are different from living organisms, and so are their constraints.
340 This scale effect underpins technical problems mentioned in 3.3; abstracting biological functions and
341 implementing them into a functional design certainly is a challenge, even more with very small range
342 living systems such as Protista, Bacteria and Archaea.

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

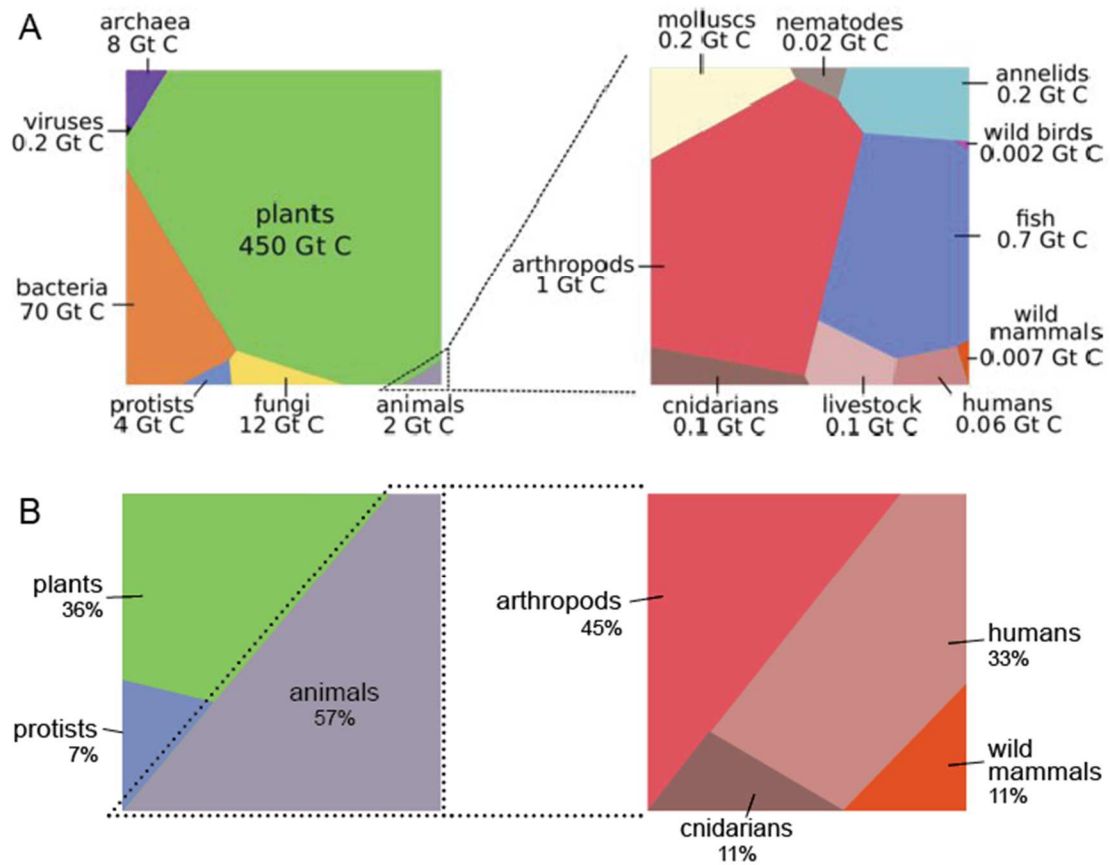
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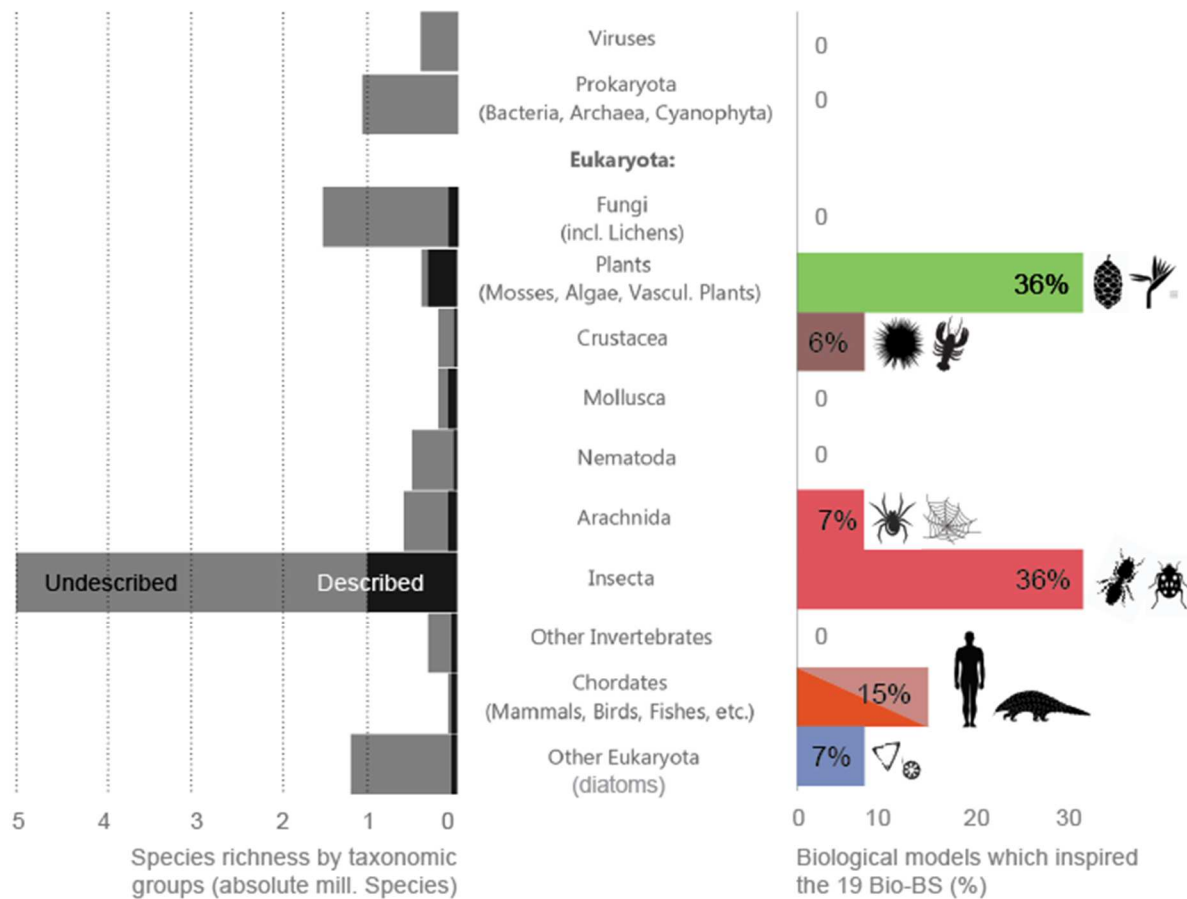
346

347 **Figure 5.** Temperature measurements of termite mounds carried out by Mick Pearce (left), CC0 Licence, Mick
 348 Pearce. **(b)** Heat exchange floor under construction, abstraction of the biological principles of termite mounds,
 349 CC0 Licence, Mick Pearce.

350



351
 352 **Figure 6.** **(A)** Distribution of the estimated biomass on earth in gigatons of carbon (GT C), reproduced with
 353 permission from [117]. **(B)** Distribution in percentage of the biological models which inspired the 19 Bio-BS.



354

355 **Figure 7.** Distribution of the major groups of biological models which inspired the 19 Bio-BS according to the
 356 distribution of estimated species on earth (absolute number of species on the left (grey = estimated number of
 357 yet to be described species, black = already described). This figure uses the same colour code as **Figure 5**.
 358 Reproduced and adapted with permission from [118].

359

360 Combining the results led the authors to the following statements:

- 361 (i) The chosen biological models for bioinspiration are often from plant or animal kingdoms.
 362 We assume it is either because they are visible in humankind daily life or because other
 363 kingdoms present scale effects harder to abstract into designs. Exceptions exist when
 364 biologists are involved in the design process.
- 365 (ii) The inspiring biological model usually is chosen by instinct or perception when designers
 366 have specifications in mind. The use of biomimetic tools to understand or choose
 367 biological models seems rare or devolved to biologists. It is hard to tell if that is because
 368 the design teams did not express the need to use existing ones, because they could not
 369 find suitable ones, or because the biologists actually use these tools and the authors would
 370 not be aware. The second explanation is valid when crossed with the lack of biomimetic
 371 tools expressed by some projects as a constraint.

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

378 **4.6. Step 3 - Abstraction**

379 **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

380 **Tool for abstraction** – The authors received few replies on this variable (n=5); the interviews did not
 381 provide detailed information on this step since most of the designers described the abstraction as a
 382 creative step which can hardly be qualified. The few results suggested that none of the design teams
 383 abstracted biological principles using biomimetic tools, apart from the Sierpinski Forest (Id. 7, Table
 384 2), which is the result of an opportunity during an abstraction phase [119], [120].

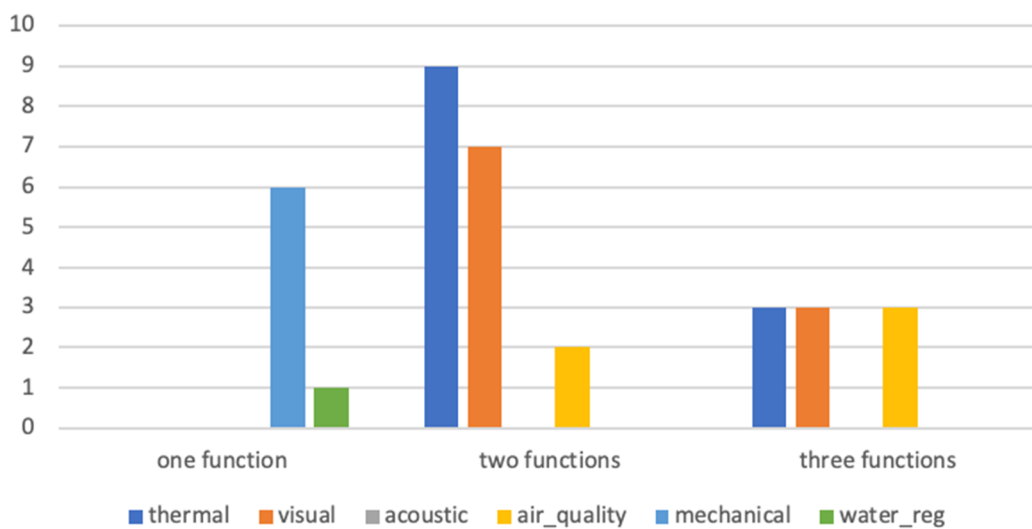
385 **Abstracted functions of regulation** – Bio-BS mostly abstracted one or two functions. **Figure 8**
 386 shows the distribution of regulated factors by number of abstracted functions. Almost half of them
 387 address mono-regulation, mostly mechanical stress (Ids. 1, 10-12, 18-27, Table 2). Then,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

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

- 394 (i) The abstraction phase highly rests on the design team expertise and own creativity
 395 process. These results are aligned with recent research that highlighted limited tools to
 396 support the abstraction phases [22], [121].
- 397 (ii) Since the characterization of the biological systems was found mainly mono model in
 398 step 2, the abstraction step followed the same trend. Design teams only abstracted one to
 399 two features of their inspiring model, often resulting in mono or bi-functional Bio-BS.

400 Also, we noted that both thermal and visual comfort are interdependent and usually
 401 simultaneously targeted . There is a need for the development of building envelopes with
 402 multi-regulation capacities to address contradictory requirements as highlighted by [20]
 403 [20], [122]. For this purpose, several methodologies have been developed such as BioGen
 404 by L. Badarnah [25] and Kuru et al. [123]. However, as outlined by the variable ‘use of
 405 design frameworks’ in Table 4, none of these frameworks were used to design the Bio-BS
 406 studied in this paper. The interviews confirm that only the ISO Standard 18458 was used
 407 for the 5% of Bio-BS that used a biomimetic framework.

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



410
 411 **Figure 8.** Distribution of the function of regulation of the 19 Bio-BS

412
 413 **4.7. Step 4 - Feasibility and prototyping**

414 **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

415

416 **Optimization tools** – This variable was defined to give insight about tools used for Bio-BS
417 modelling, prototyping, and design optimization. The answers suggested a frequent use of the
418 following:

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

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

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

436 **Level of innovation** – Radical and incremental describe two different types of technological process
437 innovations. Radical innovations refer to fundamental changes that represent new changes in
438 technology whereas incremental innovations are minor improvements or adjustments in current
439 technology according to [124]. The results show that the number of radical innovations is twice higher
440 for research pavilions than for public buildings.

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

- 442 (i) Public building Bio-BS projects tend to use conventional design methods. Likewise, the
443 induced design outcomes usually require common construction techniques only. The
444 analysed projects were mostly designed using classic CAD modelling, and the
445 technological transfer resulted in the design implementation through well-known
446 construction systems (Ids. 6, 8, 12-15, Table 2).
- 447 (ii) The teams of Bio-BS research pavilions undertook the technological transfer using highly
448 complex design and construction systems. Their research context led towards a high
449 design complexity requiring advanced modelling tools for parametric design, and high

450 construction complexity exploring new manufacturing methods using robotic assistance.
 451 More generally, the construction complexity naturally increases when the design
 452 materials are non-usual for building skins (e.g., fibreglass, carbon fibre, hygroscopic
 453 wood) and are not necessarily suited for real-world construction.

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

461

462 **4.8. Step 5 - Outcome: improved or new design**

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

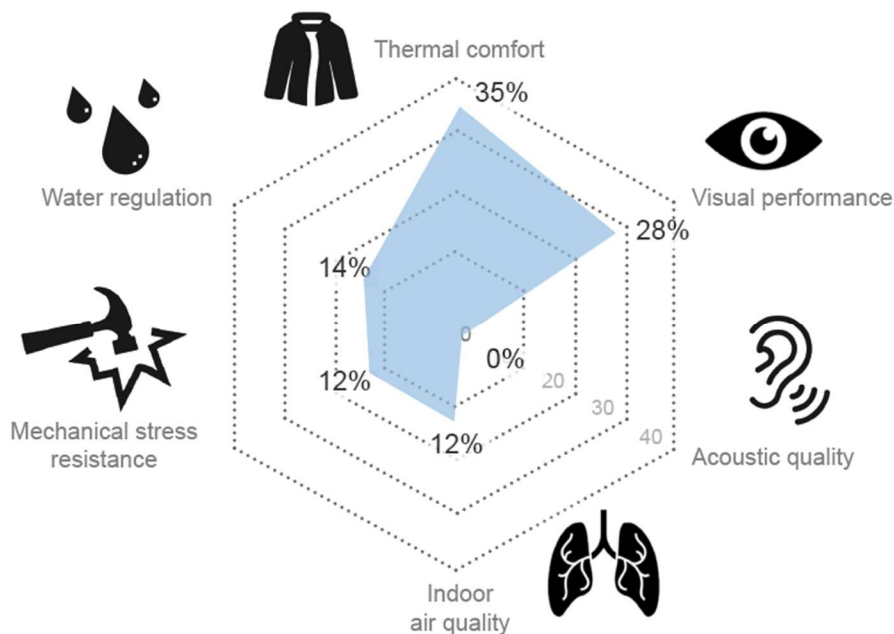
Variables	Parameters distribution in percentage
Integration scale of bioinspiration	31% Shading system 26% Façade element 11% Material 11% Roof 21% Envelope 0% Fenestration 0% Wall
Technology readiness level - TRL	30% TRL9 27% TRL8 23% TRL7 20% TRL6
Comfort	35% Thermal comfort 28% Visual performance 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

464 **Spatial scale** (classification according [125]) – Some Bio-BS were found hard to classify since the
465 biomimetic system is both embedded in the roof, wall and fenestration (Ids. 9-11, 18-30). These
466 projects were classified as “envelope”.

467 **TRL** – The concept of TRL was defined by the ISO standard 16290:2013 [33]. This concept is widely
468 used in all fields of engineering in order to measure the maturity level of a particular technology.

469 **Assessment of energy and structural performances** – This variable specifies if the performance of
470 the Bio-BS, from an energy and structural point of view, was assessed. Very few quantitative
471 assessments of the Bio-BS were found and they were all carried out for public building projects
472 (hygrothermal performance assessment for Ids. 10,13,14 and structural assessment for Id. 23, Table
473 2).

474 **Comfort** – The distribution of targeted performance is shown on **Figure 9**. Thermal and visual
475 comfort were simultaneously addressed since most of the Bio-BS were shading systems. This result is
476 consistent with previous studies [20].



477

478

Figure 9. Distribution of the Bio-BS according to the comfort.

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

484 **Adaptation to stimuli** – Almost half of the Bio-BS (47%) can adapt over time in response to external
 485 stimuli to improve the overall building performance. Referring to the definition of Loonen *et al.*, their
 486 adaptation was mostly extrinsic – *adaptation which implies first information retrieving and*
 487 *processing and then, actions to be taken* - rather than intrinsic – *self-adjusting automatically triggered*
 488 *by environmental stimuli* (Ids. 2, 5, 16-17) [125].

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

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

494 **Cost** – The cost of the solutions was specified for 7 Bio-BS, as shown in **Table 10**. Results show a
 495 wide disparity of costs among office building Bio-BS, i.e. from 900 €/sqm up to 11k €/sqm while
 496 building cost average in Europe varies from 960 €/sqm in Moscow, 2 400 €/sqm in Paris and over 3
 497 350 €/sqm in London [126]. These strong price variations can be explained by the innovative
 498 manufacturing process and use of new technologies for Bio-BS. In order to compare and quantify the
 499 cost of bioinspiration, further research will have to assess the details of the distribution of costs during
 500 the design process (staff time, resources, etc.), during the construction (materials, manufacturing
 501 technics) and afterwards (maintenance, renovation, cost of HVCA, etc.).

502 **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)	55k	30M	545
8	Esplanade theatre	Public (museum)	5.5k	5.5	1 000
15	Nianing church	Private (church)	457	1M	2340
9	Art Sciences Museum	Public (museum)	350k	75	4 655
10	Eden project	Public (green house)	23k	239	10 391
14	Davies Alpine House	Public (green house)	70	800	11 430

503

504

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

- 506 (i) There is a lack of qualitative data on the Bio-BS. It probably does not help the promotion
507 of biomimicry as a lever to environmental and energy performance challenges. Since
508 public authorities have no tangible data, they are not driven to advocate or encourage
509 (e.g., by grants) public procurement to apply biomimetic approaches. Hopefully, with the
510 current biomimetics emergence, more effort will be made in the future to provide
511 performance assessments (in terms of life cycle assessment, comfort, etc.) when
512 designing Bio-BS.
- 513 (ii) Thermal and visual comfort/performance are the most targeted performances, largely
514 implemented into shading systems, while other regulation parameters are not ensured by
515 the biomimetic design. There is a need for more multifunctional designs for the building
516 skin, covering functions that also have a strong impact on the comfort and the energy
517 efficiency of the building.
- 518 (iii) There was no case of renovation: it implies that possibilities of already existing designs
519 are not considered enough by renovation stakeholders. This may be linked to points (i)
520 and (ii); possibilities of multifunctionality are little-known, applied, and assessed.

521
522

523 **5. Discussion**

524

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

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

537 As seen in this study, the methodologies and tools used in their bioinspiration design process are
538 diverse, and yet, the number of projects in the literature reaching a TRL of 6 is low. Despite a high
539 potential for product development, the implementation of Bio-BS elements in practice is challenging.
540 During abstraction and technical feasibility steps, designers have to take into account market
541 specifications, but they should also retrieve feedbacks and experience from the users afterwards, to

542 allow scalable and repeatable models, and avoid successful but unique-application biomimetic
543 designs.

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

548

549 **6. Conclusions**

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

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

559 **(A) Academic projects** which present a strong correlation with the biology input in their design
560 process; architects, engineers and biologists collaborate closely at an interdisciplinary level.

561 The abstraction then the transfer of biomimetic principles into building constructions have
562 mostly resulted in some radical innovations.

563 **(B) Public building projects** are mainly characterised by a scarce involvement of biologists
564 during the design process and no thorough understanding of biological models. The projects
565 used conventional design and construction methods for incremental innovation by improving
566 existing building construction systems. The use of a biomimetic approach was motivated to
567 provide neutral to positive impact design towards environmental issues, but almost none of
568 them assessed the final impact of their implemented design.

569 The results demonstrated that the integration of biological knowledge has a strong influence on the
570 following design steps and the final result since academic projects resulted in radical innovation
571 whereas public buildings in incremental. These two main groups highlighted the gap between
572 academic research and building applications as discussed by [127] as “the valley of the death”.

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

574 (i) Being precisely described for the biomimetic design process.

- 575 (ii) Integrating scientific biological knowledge during the design process since inputs from
576 biology are mostly based on knowledge for general public (58%). 82% of biomimetic
577 projects are inspired by a single biological organism which belongs to the kingdoms of
578 animals (53%) and plants (37%) kingdoms which represent a small part of the diversity of
579 species on earth.
- 580 (iii) Addressing multi-regulation since 47% of the Bio-BS one function and 30% two
581 functions. When the Bio-BS addressed more than one function, it is mostly thermal
582 comfort and visual performance, which are correlated functions. Very few Bio-BS meet
583 contradictory requirements.
- 584 (iv) Being evaluated with numerical analysis to quantify energy performances (thermal,
585 visual, acoustic, mechanics). The authors founded quantitative data for only 16% of the
586 Bio-BS.
- 587
588
589
590
591

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604

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615

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

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626 **Credit author statement**

627 **Estelle Cruz:** conceptualization, investigation, formal analysis, visualization, writing – original draft,
628 **Tessa Hubert:** conceptualization, investigation, formal analysis, visualization, writing – original
629 draft, **Ginaud Chancoco:** investigation, **Omar Naim:** investigation, **Natasha Chayaamor-Heil:**
630 conceptualisation, investigation, writing- reviewing and editing, **Raphaël Cornette:** methodology,
631 formal analysis, writing- reviewing and editing; **Lidia Badarnah:** conceptualization, methodology,
632 writing- reviewing and editing, supervision; **Kalina Raskin:** conceptualization, methodology,
633 supervision, writing- reviewing and editing; **Fabienne Aujard:** conceptualization, methodology,
634 supervision, writing- reviewing and editing.
635

Supplementary data

A. Interviews

Table A1. Interviewees and associated types of interviews for the 30 Bio-VSBS

Id	Case study	Interviewees (name, contact, degree/title)	Type of interviews or visits (Name of the authors involved)
1	Shadow Pavilion	Karl Daubmann k Professor Architect and designer	Email exchanges with T. Hubert Review and comments on data sheet
2	Bloom	Doris Kim Sung Architect, master's in biology	Email exchange with E. Cruz Review and comments of datasheet
3	Homeostatic facade	Martina Decker Associate Professor	Email exchange with E. Cruz Review and comments of datasheet
4	Breathing Skin pavilion	Tobias Becker Engineer	Email exchange with E. Cruz Press release sent to the authors for additional information
5	Pho'liage Facade	Steven Ware Architect	Face-to-face interview with E. Cruz and review of datasheet
6	Umbrella Al Hussein Mosque	Mustafa Rasch Engineer	Email exchange with E. Cruz and T. Hubert. Review and comments of datasheet
7	Sierpinski Forest	Satoshi Sakai Professor	2-months participant observation in 2016 carried out by R. Cruz Review of datasheet
8	Esplanade Theatre Singapore Art Centre	Michael Wilford Architect	Face-to-face interviews in 2019 and visit of the building in 2017 by Natasha Heil
9	ArtScience Museum	None	Use of literature only
10	Eden project	Andy Watts Architect	Face-to-face interviews carried out by Natasha Heil
11	West German Pavilion	None since the architect Frei Otto died in 2015.	Use of literature only
12	International Terminal	Andy Watts Architect	Face-to-face interviews carried out by Natasha Heil
13	Eastgate Centre	Mick Pearce Architect	3-months participant observation in 2016 carried out by R. Cruz Review of data-sheet

14	Davies Alpine House	Patrick Bellew Engineer	Email exchange with E. Cruz Review and comments of data-sheet
15	Nianing Church	Nicolas Vernoux-Thélot Architect	Face-to-face interviews carried out by E. Cruz and T. Hubert
16-17	HygroScope HygroSkin	Dylan Wood	Face-to-face interviews carried out by E. Cruz and T. Hubert during à 2-weeks participant observation at ICD/ITKE
18-22	FB Lobster research pavilion FB Spider research Pavilion FB Elytra I research pavilion FB Elytra II research pavilion FB Moths research pavilion FB BUGA Fibre research pavilion	M.Sc. Axel Körner Engineer Niccolò Dambrosio Architect	Face-to-face interviews carried out by E. Cruz and T. Hubert during à 2-weeks participant observation at ICD/ITKE Video interview carried out by E. Cruz Face-to-face interviews carried out by E. Cruz and T. Hubert during à 2-weeks participant observation at ICD/ITKE Visit of the BUGA Fibre
24-26	SE Sand dollar I research pavilion (Stuttgart, 2011) SE Sand dollar II research pavilion (Stuttgart, 2015-16) SE LAGA research pavilion (Stuttgart, 2014) SE BUGA Wood research pavilion (Heilbronn, 2019)	Daniel-Alexander Sonntag Engineer Tobias Schwinn Architect	Face-to-face interviews carried out by E. Cruz and T. Hubert during à 2-weeks participant observation at ICD/ITKE
27	SE BUGA Wood research pavilion (Heilbronn, 2019)	Monika Göbel	Face-to-face interviews carried out by E. Cruz and T. Hubert during à

			2-weeks participant observation at ICD/ITKE Visit of the pavilion.
28-30	Flectofin Thematic Pavilion ITECH Pavilion	M.Sc. Axel Körner	Face-to-face interviews carried out by E. Cruz and T. Hubert during à 2-weeks participant observation at ICD/ITKE Visit of the pavilion.

B. MCA analysis

B.1. Principle

Multiple Correspondence Analysis – MCA is a **descriptive** technique of relationships between elements of a large qualitative dataset. It is used to both detect and explore relationships between various qualitative variables in a complex dataset.

MCA is based on simple correspondence analysis (CA) [128]. CA can be applied to a two-way contingency table, leading to a graph that visualizes the association between two categorical variables. In extension, MCA tackles the associations of a large set of variables. To do so, it either uses an indicator matrix, called a complete disjunctive table, or a Burt matrix (presentation of all contingency tables of the variables taken two by two and combined into a single matrix). [129].

The results are modelled as clouds of points in a two-dimensions (or more) Euclidian space and can be graphically interpreted observing the relative positions of all points as well as their distributions for each dimension. The closer to each other, the more similar are variables or individuals.

The principle of the MCA is that all individuals (i.e. the studied Bio-BS) can be summarized in multidimensional spaces: each dimension stands for different variables describing the individuals. More precisely, for each variable (i.e. each question of the data sheet), n-1 axes can be used to describe the correlations between the n modalities (i.e. the answers); as interpreting graphs with more than two to three axes is likely to be more difficult than interpreting a table of dataset, the MCA will project all individuals on a new system of dimensions, while combining the majority of the previous dimensions in the first ones of the new system.

In other words, the first new dimensions will be representative of the correlations between the variables of the dataset, and the other dimensions only represent a small additional amount of information; hence, the results can be summarized in a two-dimensional graphical form.

Hence, MCA is a powerful tool that offers insights on a dataset without the need to make beforehand assumptions on variables correlations. In this study, to reveal unclear patterns and avoid potential biased analyses from the authors, MCA appeared as an alternative to the meta-univariate analysis.

The analysis was performed on the software R [130] using the MCA tool from R package “FactoMineR” [131].

B2. Results of the MCA

As a reminder, clusters of ICD/ITKE/University of Stuttgart were balanced as four projects during the univariate analysis (section **4. Results** of the article), which reduced the sample of Bio-BS to nineteen rather than thirty ($n_{\text{cases}} = 19$). For the MCA, all thirty Bio-BS were considered ($n_{\text{cases}} = 30$).

As mentioned, MCA is a descriptive tool. Obtaining robust results preferably requires large data samples (more observations than variables or modalities). However, it does provide information even with a rather small sample. Unlike univariate analysis, missing information was removed from the dataset to avoid potential inaccuracy in the structuration of the dimensions. The following variables were used:

- Active variables – All variables from **Table 1** except “Outsourced steps”, “Initial biological inspiration obtained through”, “Tools for understanding and selection of relevant biological models”, Optimization tools”.
- Supplementary variables – Bio-BS General data (Name, Climate (Köppen), Continent, City, Country, Year of construction, Surface (m²), Cost (€/m²), Project use, Renovation).

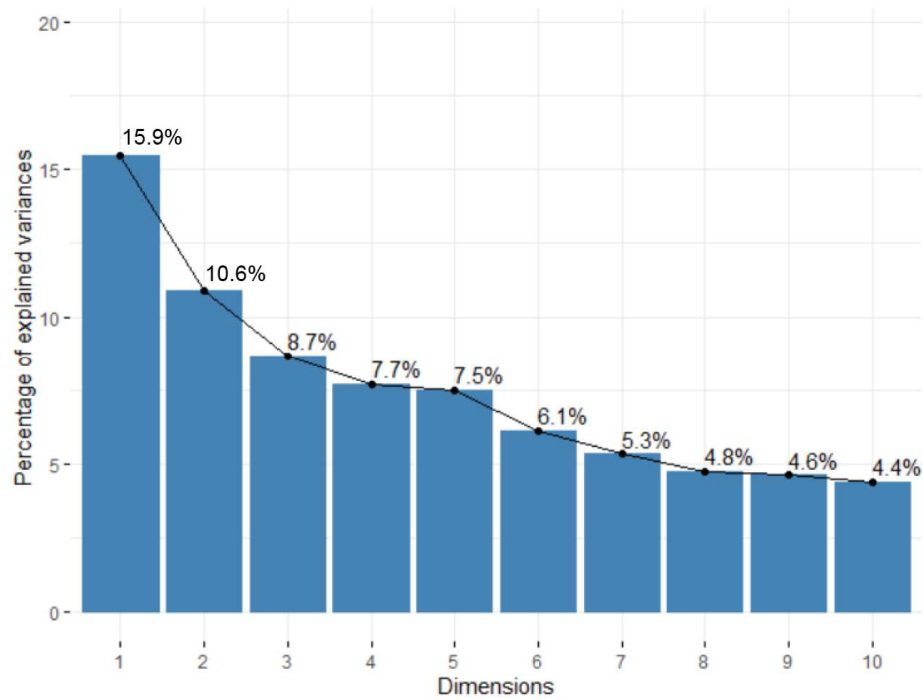
Active variables are used during the MCA while supplementary variables are predicted after the MCA is done. Supplementary data helps understand some behaviours or characterizing variables while only illustrating descriptive data.

The percentage of inertia explained by each MCA dimensions is displayed on **Figure B1 (a)**. Correlations between the variables and MCA principal dimensions, dimensions 1 and 2, are plotted in **Figure B1 (b)**. The inertia of dimensions 1 and 2 respectively are, eigenvalue, 15.5% and 10.9%, for a total of 26.4%.

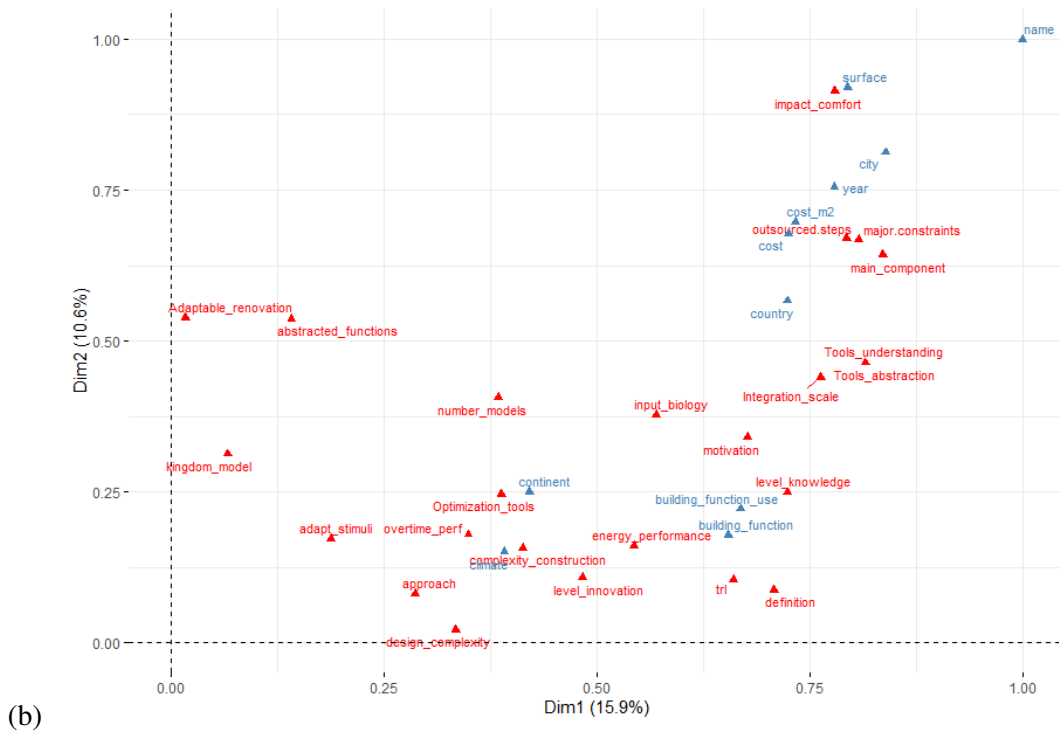
Figure B1 (b-c) show the most structuring variables and modalities contributing to both principal dimensions; **Figure B1 (b)** plots the contributions of variables for both dimensions (the closer to 1, the

most contributing), **Figure B1 (c)** plots the modalities (structuring answers) for dimension 1 then dimension 2 (the red dashed line indicates the expected average value if the contributions were uniform).

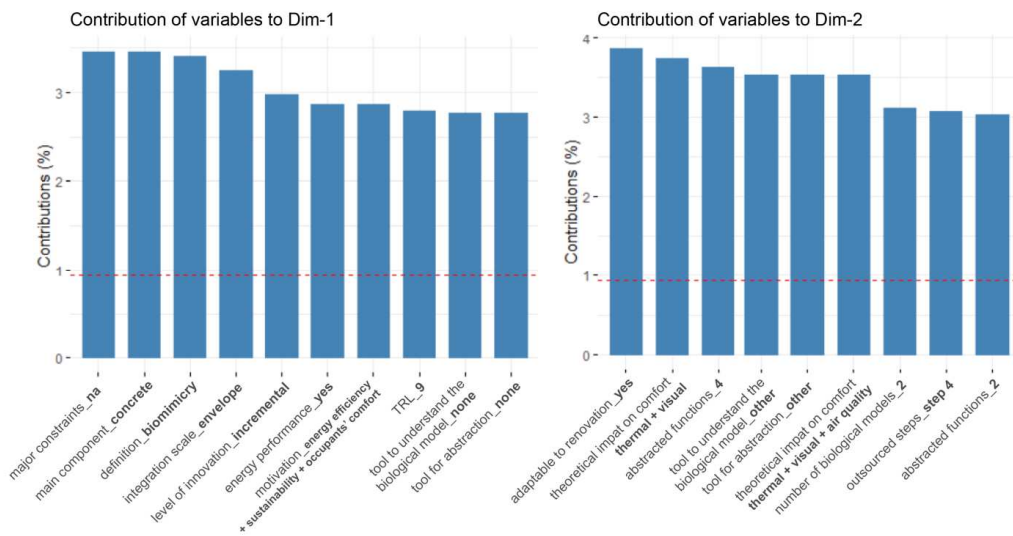
Here, the most structuring variables for both dimensions are for instance the motivation of the biomimetic approach (step 1), the type of knowledge (step 2), the major constraints (step 4), the main component (step 5). Note that variables, such as mentioned above from steps 1 and 5 are structuring for both dimensions 1 and 2, while other are structuring for one only, e.g., “variable type of knowledge” for dimension 1. On the contrary, variables (such as the use of a design framework, the biomimetic approach or the model kingdom which inspired the design) had a very small impact on both dimensions (values close to 0). It means they do not structure clusters, either because all answers are equally distributed in a random way correlated to other parameters, or because of common modalities between all variables.



(a)



(b)

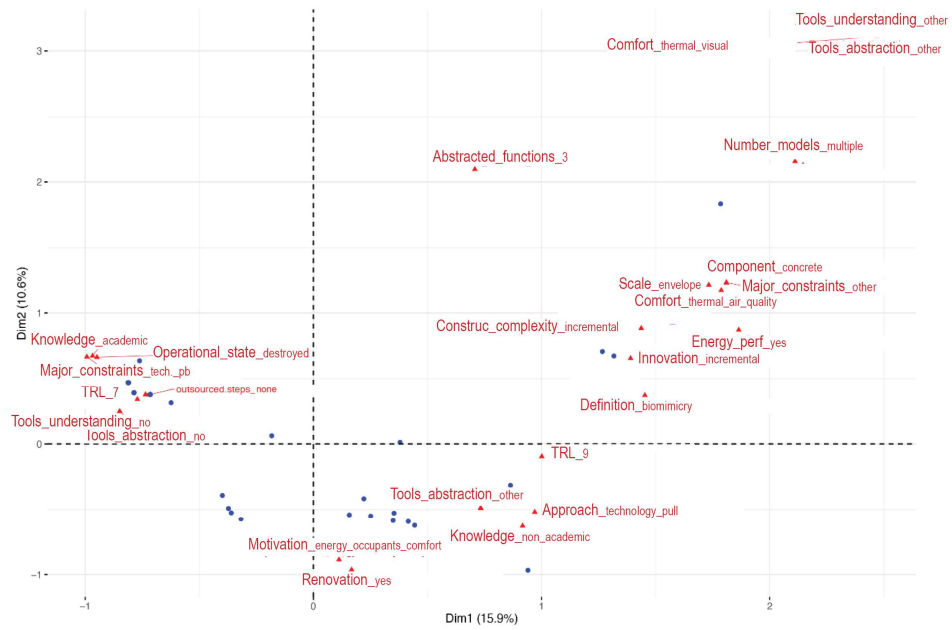


(c)

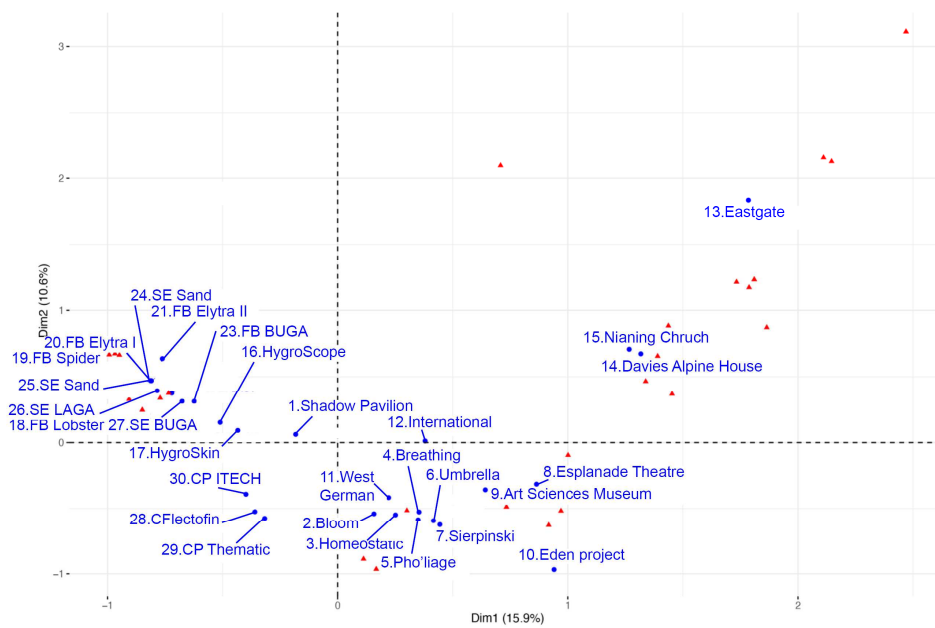
Figure B1. (a) Percentages of inertia explained by each MCA dimension (variables in red, supplementary data in steel blue) (b) Correlation between the variables and MCA principal dimensions (Euclidian space, axes from 0 to 1) (c) Total contribution (percentage) to dimension 1 and 2 of modalities.

All thirty Bio-BS projects and the 25 most structuring modalities are plotted on **Figure B2**:

- Two individuals (here Bio-BS studies by the authors under design process criteria) are similar if they have the same modalities,
- The contributions (displayed on **Figure B1**) explain the intensity of the presence of a modality on axes.



(a)



(b)

Figure B2. MCA factor maps of all Bio-BS (points) and the 30 most structuring parameters (triangles) **(a)** with the name of the variables, **(b)** with the name of the Bio-BS.

B.3. Analysis

Two main clusters of similar individuals can be observed on **Figure B2**:

1. **Academic research projects group:** On the left of the vertical axis, all Bio-BS developed by ICD/ITKE/University of Stuttgart are clustered together. This group is structured by modalities (displayed on **Figure B2 (a)**) such as: Technical constraints (from variable *major constraints*), Biologists integrated in the design (variable *Inputs in biology*),

Knowledge for specialists + Created by specialists or by experimentation during the design process (variable *Level of scientific knowledge*).

2. **Public building projects group:** On the right of the vertical axis are the other Bio-BS, mostly non-academic office building from public procurement, generally structured by: Incremental (variable *Level of innovation*), Low (variable *Construction complexity*), Feasibility (variable *Outsourced steps*).

These individuals are on the other side of the vertical axis; they are different from the ICD/ITKE/University of Stuttgart projects but they also have their own dissimilarities since they are quite spread out on the positive part of Dimension 1. They are differentiated as follows:

- The bottom part (Bloom, Pho'liage, Breathing Skin, etc.) is structured by: N/a (variable *Tools for understanding and selection of relevant biological models*), Thermal + Visual (variable *Comfort*);
- The top part (Eden, Eastgate Building, Alpine House) is structured by: Others (*Tools for understanding and selection of relevant biological models*), Thermal + Visual + Air quality + Other (variable *Comfort*).

Both groups are more described in the following two sections.

B.3.1. Academic research projects description

Individuals: This groups includes Bio-BS from Ids. 16 to 30. Project Shadow Pavilion (Id. 3) can also be included in the following observations since it is also located on the negative side of Dimension 1. These individuals are highly correlated to various modalities, which can help characterize the typology of this cluster.

Correlations with:

Biologists' inputs: *biologists integrated in the design process*

Level of scientific knowledge: *knowledge for specialists + created by specialists or by experimentation during the design process*

Tools for understanding and selection of relevant biological models: *none*

Tools for abstraction: *none*

The projects are based on existing specialized knowledge in biology developed by the scientific community. The teams have interdisciplinary collaborations (as a fact, with various biologists for ICD/ITKE/University of Stuttgart, and a botanist for the Bloom pavilion), allowing them to co-discover new properties of living organisms creating mutual benefits between academic research in

biology and architecture. In ICD/ITKE, most of the inputs in biology are provided by biologists or groups of biologists strongly collaborating in the early phases of the design process and continually integrated as well thereafter. The group is also characterized by no use at all of tools referenced in the literature for helping step 2 (Understanding of biological principles) and step 3 (Abstraction).

Correlations with:

Design construction: *high*

Construction complexity: *high*

Level of innovation: *radical*

Major constraint: *technical*

Operational state: *destroyed*

The group is mainly characterized by a high construction complexity. In fact, for Ids. 16 to 30, the technological transfer between biology and architecture required advanced modelling tools for parametric design (from the authors interviews, tools such as Grasshopper from Rhinoceros among others). This seems directly correlated with a high construction complexity; the architecture research teams at ICD and ITKE explore new manufacturing methods using robotic assistance, e.g., RP 2015-16 manufacture which combined sewing machines and a robotic arm. The complexity also naturally increases when the construction materials are non-usual for building envelopes (e.g., fibreglass, carbon fibre, hygroscopic wood); quite logically, the underlying main constraint happens to be technical, with a will to transfer deep-abstracted biological models to technologies. In contrast to the other group, this cluster tend to have projects eventually destroyed; it recalls the demonstrative and experimental nature of these projects. In opposition, all the other projects still exist and are operating, whatever the typology of projects, pavilion or tertiary public.

B.3.2. Public building projects description

Individuals: This groups includes Bio-BS from Ids. 1 to 15. The distribution of individuals on the MCA shows a group of projects which are all from public procurement and for most of them implemented (TRL > 9).

Correlations with:

Main component: *concrete*

Level of innovation: *incremental*

Design complexity: *low*

Construction complexity: *low*

Major constraints: *other*

Outsourced step: *feasibility*

As opposed to the majority of the projects in the first cluster, projects are characterized by a predominant use of concrete as main material, with low design and construction complexities. The major constraints were mainly qualified as 'other' for this group, mostly because the answers were very diverse; types of projects are more eclectic in terms of limitations (time, costs, human resources and objectives).

The feasibility step defined by the authors as Step 4, was more outsourced than for academic research projects. This can be expected for large-scale and implemented projects, since there are regulations in the public construction world.

Correlations with:

Tools for understanding and selection of relevant biological models: *other*

Comfort: *visual + thermal + air quality + other*

Assessment of energy performance: *yes*

Level of innovation: *incremental*

Level of scientific knowledge: *existing for general public*

Three projects are offset from both axes on the MCA factor map and correlated with the variables mentioned above: the Eastgate Centre, Davies Alpine and Nianing Church. All of them were inspired from the same systems (termite mounds) but were built years apart, respectively in 1996, 2006 and 2019. The biological transfer is similar for all three cases; thermal draft, passive ventilation and high thermal inertia materials, such as bricks or concrete. Even though thermal draft is a well-known technique for passive ventilation (e.g., windcatchers in West Asia), it was reinterpreted again and implemented differently through to the study of termite mounds, with either intrinsic thermal regulation or separated system. These are not breakthrough innovation, but projects improving already existing systems or building construction with classical material.

The correlation to *Other* (from variable Tools for understanding and selection of relevant biological models) is only due to the Eastgate Centre: indeed, the architect Mick Pearce performed experiments himself on termite mounds to try understanding the involved physical phenomenon. Overall, the cluster is correlated to the modality Existing for general knowledge (variable Level of scientific knowledge), since no biologists were integrated in the designs: either the architects had a strong sensitivity to biology, or they intended to perform ecological architecture. The project Pho'liage remains an exception, since the architect Steven Ware, which led the project, happens to have a biology degree from previous studies.

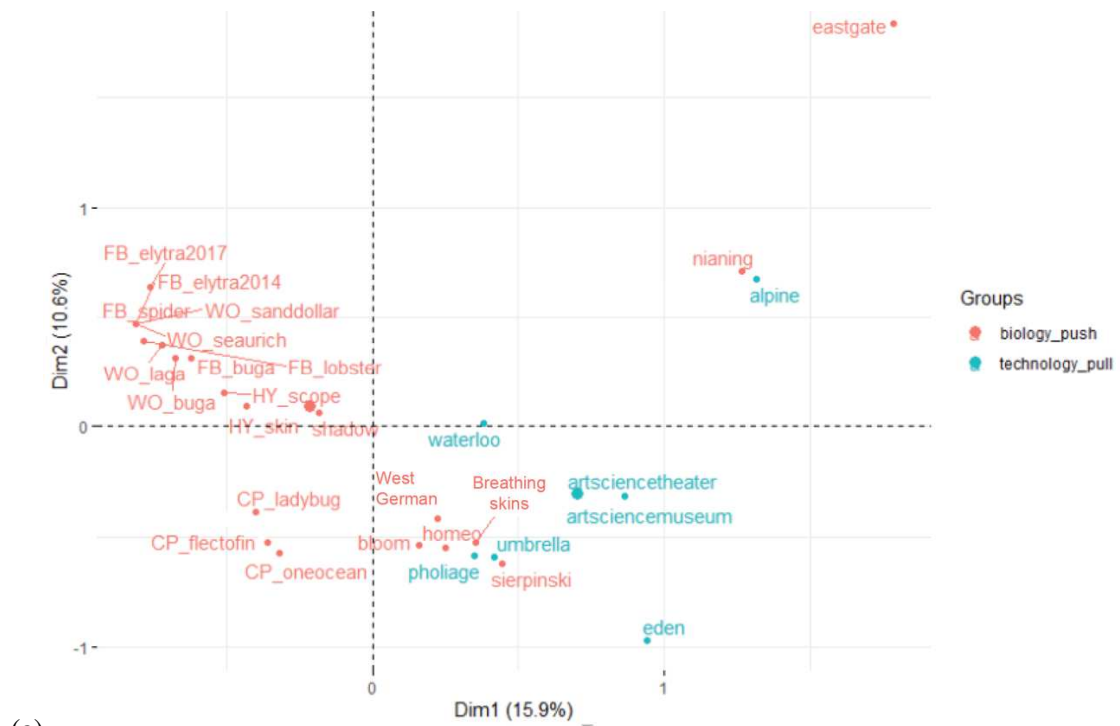
The observed sprawl on the MCA factor map is also correlated the comfort: unlike the majority of the other projects, which “only” improve thermal and/or visual aspects through bio-inspiration, Nianing Church, Eastgate Centre, the Eden project, and Davis Alpine include other parameters such as water regulation (relative humidity). Out of 14 projects included in this cluster, only the latter three assessed the final performance of their design: the Eastgate Centre, the Eden project, and Davis Alpine.

Conclusion

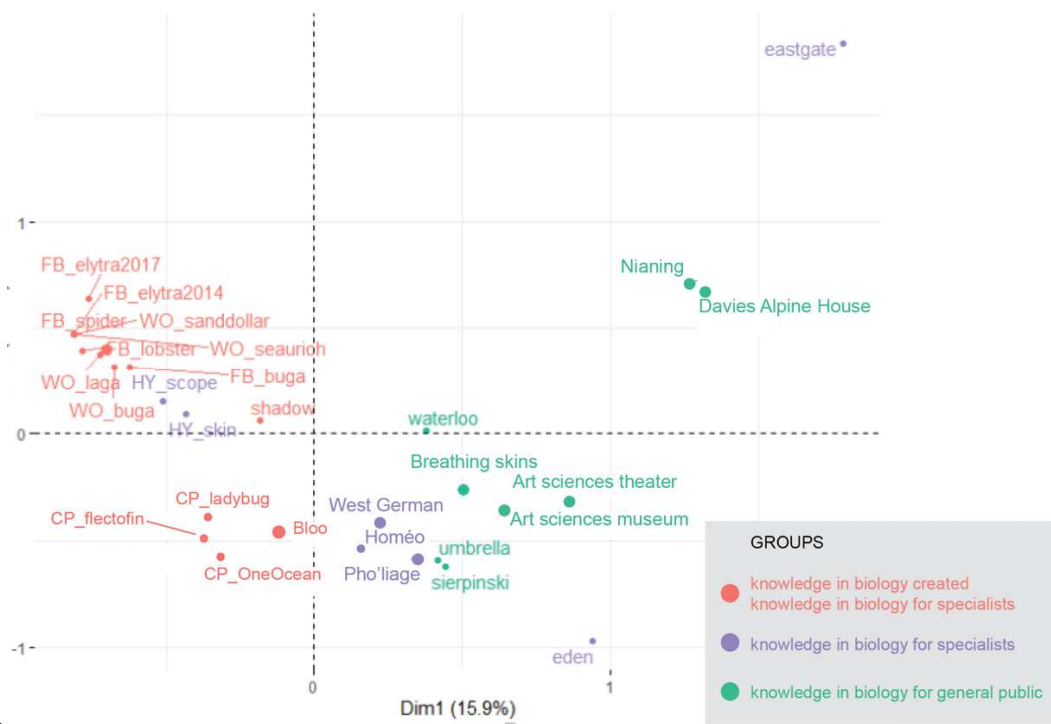
The MCA put forward two main typologies of projects, opposed by different modalities. Since these modalities are based on variables defined following the standard ISO design process (section **2.2. Design process** in the article), they give clues on differences and similarities between projects and the design output, as well as the involved key steps of the design process.

MCA have shown relevant information for each step, such as:

- Step 1 (Functional analysis) – As shown on **Figure B.3 (a)**, the majority of projects have a technology pull approach, apart from some public projects.
- Step 2 (Understanding of biological principles) – Research projects necessarily include biologists in the process. They do not use specific tools for this step since they rely on scientific knowledge and interdisciplinary collaborations. The public projects do not use tools either: they seem to be divided between punctually seeking advice from biologists and no interaction at all (see **Figure B.3 (b)**).
- Step 3 (Abstraction) – Incremental innovation is very common for the second group.
- Step 4 (Feasibility) – Design and construction complexities are clearly opposed between both groups.
- Step 5 (Outcome) – The main components are standard in public/private building projects while uncommon materials, such as carbon fibre, seems more appropriate to academic/research projects. Likewise, research projects are more correlated to radical innovation than commissioned projects, which tend to rely more on incremental development.



(a)



(b)

Figure B.3. Factor maps of individuals distinguished by modalities for the variable (a) Approach and (b) Biologists' inputs.

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