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

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 tools and methods are limited for the development of biomimetic systems and they highly influence the final design performances. 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 for the development of Bio-BS using proper tools to improve multi-regulation 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 [1], [2]. Their performances highly influence the building total energy consumption, since they filter the environmental constraints [3, Ch. 1]. In order to improve building skins efficiency, academics and industrial have explored nature-inspired solutions that are referred to Bio-BS (Bio-Inspired Building Skins).

Biomimetics is a contemporary approach based on the interdisciplinary cooperation of biology and technology, by transferring nature's principles into a technological solution [4], [5]. This approach has inspired innovation in diverse fields and had a significant impact in architecture for the design of sustainable built-environments [6]–[8]. International research has focused on the development of adaptive energy efficiency of building skins inspired by living systems [9], [10]. The latter two have to filter simultaneously several changing environmental factors to maintain their physical integrity [11].

Literature reviews have counted more than seventy proof-of-concepts of bio-inspired building skins designed over the last two decades, and this number is increasing across industry and academia [12]–[17]. However, few of these cases address multi-criterion challenges. Kuru *et Al.* [16] has outlined that only 13.4% of fifty-two published biomimetic adaptive skins (Bio-ABS) control more than one parameter. Multifunctionality is not yet embedded in biomimetic envelopes and needs further development to address multiple contradictory functional requirements [16]. In addition, Svendsen *et Al.* [18] reviewed that only 8 methodologies and 12 stage-specific tools addressed multi-functionality in biological inspired design. Multi-functionality has been treated in only a limited set of papers which suggests a need for the development of design supports to handle multi-functional challenge [19]. More generally, these suggestions converge with recent studies, showing limited tools and methods to increase the development of bioinspired applications [20]–[22].

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. Definitions

The Bio-BS can meet different definitions according to ISO 2015:18458 [23] :

- *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.

2.2. Design process

The Bio-BS can result from two design processes: technology pull and biology push. The ISO standard 2015:18458 [23] 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 pattern follows a progression of five steps from the technical problem to the improved biomimetic product (**Figure 1.a**.). **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*". This pattern also follows a sequence of five stages, but the starting point is a particular biological solution (**Figure 1.b**.).

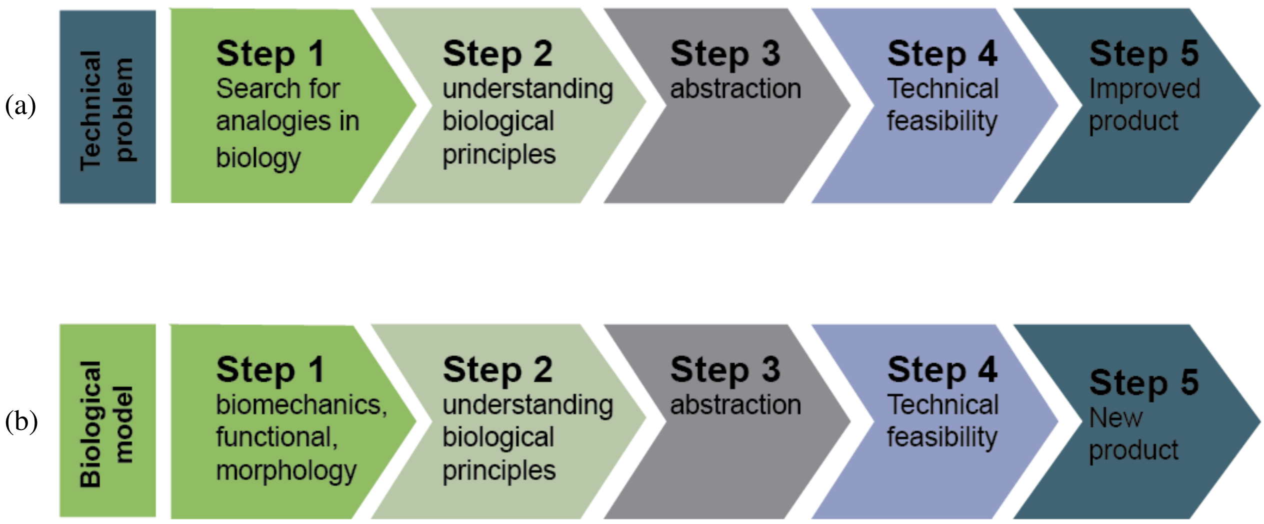


Figure 1. Biomimetic design process. (**a**) technology pull, (**b**) biology push. Adapted with permission from ISO standard 2015:18458 [23].

2.3. Overview of the 30 Bio-BS

Table 2 lists the thirty selected Bio-BS. Thirty cases of Bio-BS were chosen 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"* [24]. It excluded student or research projects which had not resulted in a prototype so far. A TRL of 6 insured 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, biomimicry or biomimetics according to [25]. 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.
- Biomimetics 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 [26].

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) [27]. 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.

Figure 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) CC0 Creative Commons Licence, (11) © Frei Otto, (12) CC0 Creative Commons Licence, (13) © ARUP, (14) © Oast House Archive, (15) Regis L'Hostis, (16-30) © ICD/ITKE University of Stuttgart.

3. Method

Thirty applications of Bio-BS have been selected according to 3 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 5 biomimetic design steps according to ISO standard 2015:18458 [23]. **Table 1** provided an overview of the variables and parameters.

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:

- 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)

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 (m²)	-
	Cost (€/m²)	-
	Building function	Public building (museum, hospital, university, office...) | Housing (collective, individual) | Pavilion
	Renovation	Yes | No
Design process overview	Motivation	Energy efficiency | Occupant's comfort | Structure performance | Sustainability | Promote research
	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. Functional analysis	Approach	Biology push | Technology pull
	Definition	Biomimetics | Bio-inspiration | Biomimicry

Step 2. Understanding 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
	Level of scientific knowledge	Existing for general public | for specialists | created by specialists and/or by experimentation during the design process
	Biologists' inputs	Biologists consulted ǀ Biologists integrated in the design process ǀ 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 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 performance	Yes | No
	Overtime performance	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. **Building function**: Public Building (Pub.), Housing (H), Pavilion (Pav.) – **Motivation**: Energy efficiency (EE), Occupant's comfort (Oc), Structure performance (S), Sustainability (Su), Promote research (P) – **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**: Existing for general public (G) | for specialists (S), Created by specialists and/or by experimentation during the design process (C) – **Abstracted functions**: 1 to more than 3 - **Level of innovation**: Radical (Ra), Incremental (In) – **Construction complexity**: High (H), Low (L) – **Integration scale:** Material (M), Façade element (FE), Shading system (SS), Roof (R), Wall (W), Fenestration (F), Envelope (E) – **Assessment of energy performance:** yes, no, na - **Comfort**: Thermal comfort (T), Visual performance (V), Indoor air quality (I), Mechanical stress resistance (Me), Acoustic quality (A), Other (O).

Id	**Building envelopes** (City, Country, Date) Description of the bioinspired system	Building function	Motivation	Approach	Models' kingdom	Level of 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 [28]–[30]	Pav.	Oc, S, Su	Bio	Pl	G,S	3	rad	H	FE	no	O
2	**Bloom** (Los Angeles, USA, 2011) – Adaptive material inspired by adaptation mechanisms in nature [31]–[33]	Pav.	EE, Oc	Bio	An	G	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 [34]–[36]	Pub.	EE, Oc	Bio	An	G	2	rad	H	SS	no	T,V
4	**Breathing Skin pavilion** (Mandelbachtal, Germany, 2015) – Pneumatic façade component inspired by human skin for light, air and thermal regulation [37]	Pav.	EE, Oc	Bio	An	Gen	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 [38], [39]	Pub.	EE, Oc, Su	Tech	Pl	G,S	2	rad	H	SS	na	T,V
6	**Umbrella Al Hussein Mosque** (Cairo, Egypt, 2000) – Deployable shading system inspired by opening and closing of flower petals [40] [41]	Pub.	S	Tech	An	G	2	in	H	SS	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 [42]–[45]	Pub.	EE, Oc, Su	Bio	Pl	S	2	rad	L	SS	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 [46], [47]	Pub.	EE	Tech	Pl	G	1	in	H	SS	na	T,V
9	**ArtScience Museum** (Singapore, 2011) – Building's shape inspired by the shape of the lotus flower to collect and harvest water [48], [49]	Pub.	EE, Oc, Su	Tech	Pl	G	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 [50]–[53]	Pub.	S,Su	Tech	Pro	G	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) [54] [55] [56]	Pub.	S	Bio	Pro	G,S,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 [57], [58]	Pub.	S	Tech	An	G,S	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 [59]–[61]	Pub.	EE, Oc, Su	Bio	An	G,S,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 [62], [63]	Pub.	EE, Oc, Su	Tech	An	G,S	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 [64], [65]	Pub.	EE, Oc Su	Bio	An	G	3	in	L	E	no	T,I
	ICD/ITKE 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) [66], [67]	Pav.	EE, Oc	Bio	Pl	S	2	rad	H	M	no	T,V
17	**HygroSkin** (Paris, France, 2013) – HygroScope adaptation into a meteorosensitive pavilion in real conditions [68]–[70]	Pav.	EE, Oc	Bio	Pl	S	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 [71]–[73],	Pav.	S	Bio	An	S,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 [74], [75]	Pav.	S	Bio	An	S,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 [76], [77]	Pav.	S	Bio	An	S,C	3	rad	H	FE	no	T,V,Me
21	**FB Elytra II research pavilion** (London, 2015-16) – Pavilion inspired by the Elytra [78], [79]	Pav.	S	Bio	An	S,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 [80], [81]	Pav.	S	Bio	An	S,C	3	rad	H	FE	no	T, Me
23	**FB BUGA Fibre research pavilion** (Heilbronn, 2019) – Load-bearing structure inspired by beetle wings [82]	Pav.	S	Bio	An	S,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 [83], [84]	Pav.	S	Bio	An	S,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 [85], [86]	Pav.	S	Bio	An	S,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 [87], [88]	Pav.	S	Bio	An	S,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 [89], [90]	Pav.	S	Bio	An	S,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 [91], [92]	Pav.	EE, Oc, Su, P	Bio	Pl	S,C	2	rad	H	SS	yes	T,V
29	**Thematic Pavilion** (South Korea, 2012) – Shading system for the façade of an exhibition hall which adapt the CP Flectofin system [93]–[95]	Pub.	EE, Oc, Su, P	Bio	Pl	S,C	2	rad	H	SS	yes	T,V
30	**ITECH Pavilion** (Stuttgart, 2019) – Adaptive compliant structure inspired by the folding mechanisms of the Coleoptera coccinellidae wings. ITECH 2019 [96], [97]	Pav.	EE, Oc, Su, P	Bio	An	S	2	rad	H	SS	yes	T,V

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 [98].

Data analysis was conducted through:

- **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.

- **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**).

4. Results

First, the results of the MCA are given in order to characterize the main types of Bio-BS. Then the results of the univariate analysis are presented step by step in the following sections. The results are expressed in percentage and discussed in each section.

4.1. 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. **Figure 3** outlines the distribution of the variables **(a)** and projects **(b)**.

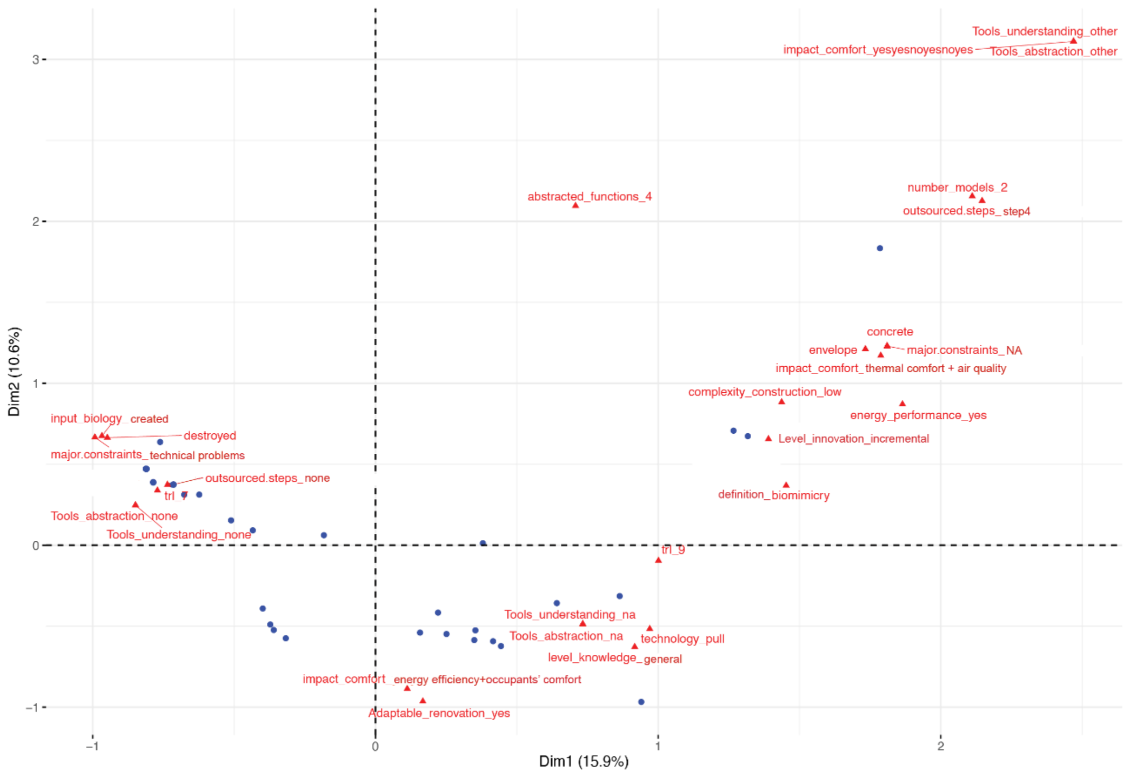
Academic projects (on the left of **Figure 3** (**a**) and **(b)** (Ids. 3, 16-30)) all presented a strong correlation with biology inputs in their design process; architects, engineers and biologists collaborate closely at an interdisciplinary level. For all these projects, the abstraction then the 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 **Figure 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 to positive impact design towards environmental issues, but only a few of them assessed the final impact of their implemented design.

These preliminary results herald two main approaches in terms of biomimetic building skin design processes. Constraints, players and means, are different from one typology to another; both are worth digging to extract their specific limitations and edges.

Data collected from interviews was then analysed with univariate through the 5 defined process steps detailed in section **1. Introduction** and highlighted in **Figure 1.**

(a)


Tools_understanding_other
impact_comfort_yesyesnoyesnoyes
Tools_abstraction_other
abstracted_functions_4
number_models_2
outsourced.steps_step4
concrete
envelope
major.constraints_NA
impact_comfort_thermal comfort + air quality
complexity_construction_low
energy_performance_yes
Level_innovation_incremental
definition_biomimicry
input_biology_created
destroyed
major.constraints_technical problems
outsourced.steps_none
trl_7
Tools_abstraction_none
Tools_understanding_none
trl_9
Tools_understanding_na
Tools_abstraction_na
technology_pull
level_knowledge_general
impact_comfort_energy efficiency+occupants' comfort
Adaptable_renovation_yes
Dim2 (10.6%)
Dim1 (15.9%)
3
2
1
0
−1
−1
0
1
2

(b)


13.Eastgate Centre
15.Nianing Chruch
14.Davies Alpine House
20.FB Elytra I
21.FB Elytra II
19.FB Spider
24.SE Sand dollar I
25.SE Sand dollar II
26.SE LAGA
18.FB Lobster
23.FB BUGA
27.SE BUGA
16.HygroScope
17.HygroSkin
1.Shadow Pavilion
12.International Terminal
30.CP ITECH
28.CFlectofin
29.CP Thematic
11.West German Pavilion
4.Breathing Skin
6.Umbrella
2.Bloom
5.Pho'liage
7.Sierpinski Forest
3.Homeostatic
8.Esplanade Theatre
9.Art Sciences Museum
10.Eden project
Dim2 (10.6%)
Dim1 (15.9%)
3
2
1
0
−1
−1
0
1
2

Figure 3. MCA maps of all Bio-BS (blue points) and the 30 parameters (red triangles) (**a**) with the name of the variable and the parameter in bracket, (**b**) with the name of the Bio-BS. 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.

4.2. Context

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

Variable	Parameter distribution in percentage
Climate	**68% C (temperate)** I 16% B (dry) I 11% A (tropical) I 5% D (continental)
Continent	**52% Europe** I 16% America I 16% Asia I 16% Africa
Building function	**63% Public building** (museum, hospital, university, office...) | **37% Pavilion** | 0% Housing (collective, individual)
Renovation	**100% No** I 0% Yes

Half of the selected projects are located in Europe and others are equally distributed between America, Asia and Africa. Their locations correspond to developed and temperate climates according to the Köppen-Geiger classification [99]. The results suggest that this distribution could 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 [23].

Public buildings are the most represented (63%) compared to pavilions (37%) which are mostly temporary constructions. **Figure 4** outlines the different building functions of the studies Bio-BS; exhibition halls count for half of the public buildings which might be explained by public building project briefs usually allowing more stimulation of creativity than in housing projects.

Last but not least: 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. 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 [100].

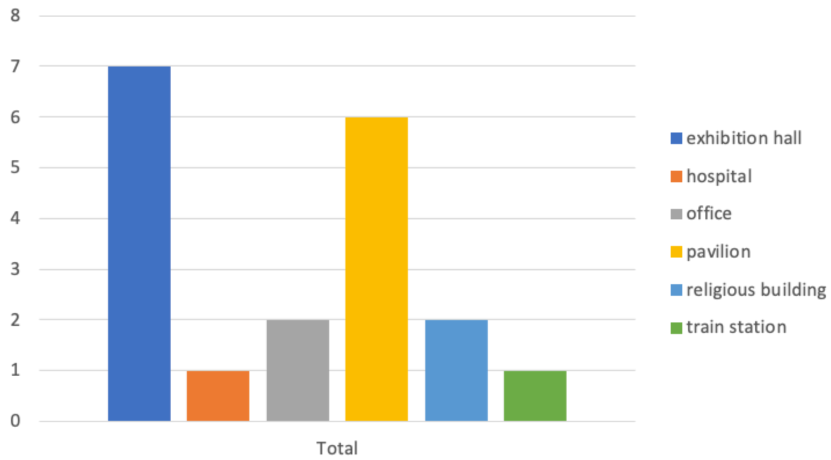


Figure 4. Bio-BS distribution according to their building function (n=19)

4.3. Overview of the biomimetic design process

Table 4. Variables distribution of category *Design process overview* for the 19 Bio-BS

Variables	Parameters distribution in percentage
Motivation	**27% Energy efficiency | 27% Occupant's comfort** | 18% Structure performance | 18% Building sustainability | 9% Promote research
Use of design framework	**95% No** | 5% Yes
Major 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

Motivation – This parameter was introduced in order to clarify the design teams' motivation to use biomimetics during their design process. 18% of the 19 analysed Bio-BS were developed with the objective of addressing environmental issues, 27% were targeting energy efficiency and comfort for the occupants. 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 [98]. However, the ambivalence of this parameter was highlighted when design teams judged biomimetic skins more sustainable solutions than traditional ones; improving the Bio-BS energy performances or occupants' comfort 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.

Use of design framework – The designation framework covers the contributions describing the hole development process such as process, method, tools. Very few Bio-BS consciously followed a biomimetic design framework (5%). The only followed framework 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. When asked, most of them admitted they had not felt the need to use one. Hence, the only demonstration of a pre-established design process happened in the frame of research projects and academia. In addition, it confirms the popular belief that designers usually have their very own ways and habits in their creative processes, even when it comes to biomimetics.

The parameters **Outsourced steps** and **Major constraints** were defined to evaluate the faced difficulties and external assistance provided outside of the initial design teams. These parameters were scarcely documented: for some interviewees the boundaries were not precisely defined of their own team in the frame of design process defined by the authors. The results have however 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. On the contrary, Steps 4 and 5 were fully undertaken for pavilion. Note that the authors could not interview all actors involved in the design process: some parts are not fully documented.

Likewise, the answers to constraints faced by the interviewees were not comprehensive, and this, because the suggested answers to the question were chosen to be broad. If it allowed an open discussion and maybe the highlighting of not obvious constraints to authors, it also might have confused interviewees to take a position. The identified constraints were however distributed between the followings: lack of adapted biomimetic tools known by the team, 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, projects researchers from ICD/ITKE/University of Stuttgart openly admitted they had little limitation in terms of time.

Hence, before a deeper analysis of all steps in the design process, the authors made the following observations:

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

(ii) These limitations appear quite different between academia/research projects and public projects, that is to say the two typologies of projects observed using MCA (see section 3.1. Main trends).

It emphasizes the initial questions of this study: how does their design process differ to lead to such different design / 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. Variables distribution of category *Step 1 – Functional analysis* for the 19 Bio-BS

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

Definition – The Bio-BS are equally distributed between bio-inspiration, biomimicry and biomimetics according to the definition provided by [23]. 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 - In most cases, the 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 [101]. 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 which is more driven by a biology-push approach [102]. In addition, interviews and literature analysis showed that the border between the technology-pull and biology-push approaches is difficult to establish. 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 [103].

4.5. Step 2 - Understanding of biological concepts

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

Variables	Parameters distribution in percentage
Type of knowledge	**58% Existing for general public** ǀ 40% for specialists ǀ 12% created by specialists and/or by experimentation during the design process
Inputs of biologists from the design team	**47% No interaction with any biologists** ǀ 31% Biologists integrated in the design process ǀ 21% Biologists consulted
Tools for understanding biological models	**80% NA** | **20% none** | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm | Other
Model kingdom	**57% Animalia ǀ 36% Plantae** ǀ 7% Protista ǀ 0% Archaea ǀ 0% Fungi ǀ 0% Bacteria
Number of models	**84% Single** ǀ 16% Multiple

Type of knowledge and **Inputs of biologists from the design team –** Biologists were not integrated in the design process of the selected Bio-BS public projects: either the architects had a strong sensitivity to biology, or they intended to perform ecological architecture. The Bio-BS Pho'liage and Bloom remains an exception, since the architects Steven Ware and Doris Kim Sung has a first-degree in biology (Ids. 2,5). Given the absence of biologists, 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 biological knowledge for general public, 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, then replicate their performance into the Eastgate Centre (Id. 13) (**Figure 7**) [59], [104]. However, although the Eastgate is a beautiful example of what bioinspiration or biomimicry can promote, his analysis was eventually proved erroneous [60]. On the other hand, Bio-BS from ICD/ITKE/University of Stuttgart based their transdisciplinary research on existing specialized knowledge in biology developed by the scientific community (40% of all cases); most of the inputs from biology are 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 [96], and according to the interviews, lead to co-discoveries .

Tools for understanding biological model is a variable based on [105] 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 but showed that no specific tools were used (Ids. 18-30). Projects that benefited from the involvement of biologists clearly compensated this lack: for instance, ICD/ITKE 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.

Model kingdom - According to the six kingdoms classification of [106], living systems which inspired the Bio-BS mostly belong to the kingdoms of animals (57%) and plants (36%). As highlighted by **Figure 5** and **Figure 6**, the distribution of inspiring biological models is not proportionate to the distribution of biomass, estimated and described species on Earth. For instance, the species *homo sapiens* is over-represented in Bio-BS (33%) related to its proportion in the biomass (0,01%). Even though these results convey a propensity by designers to use 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.

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).

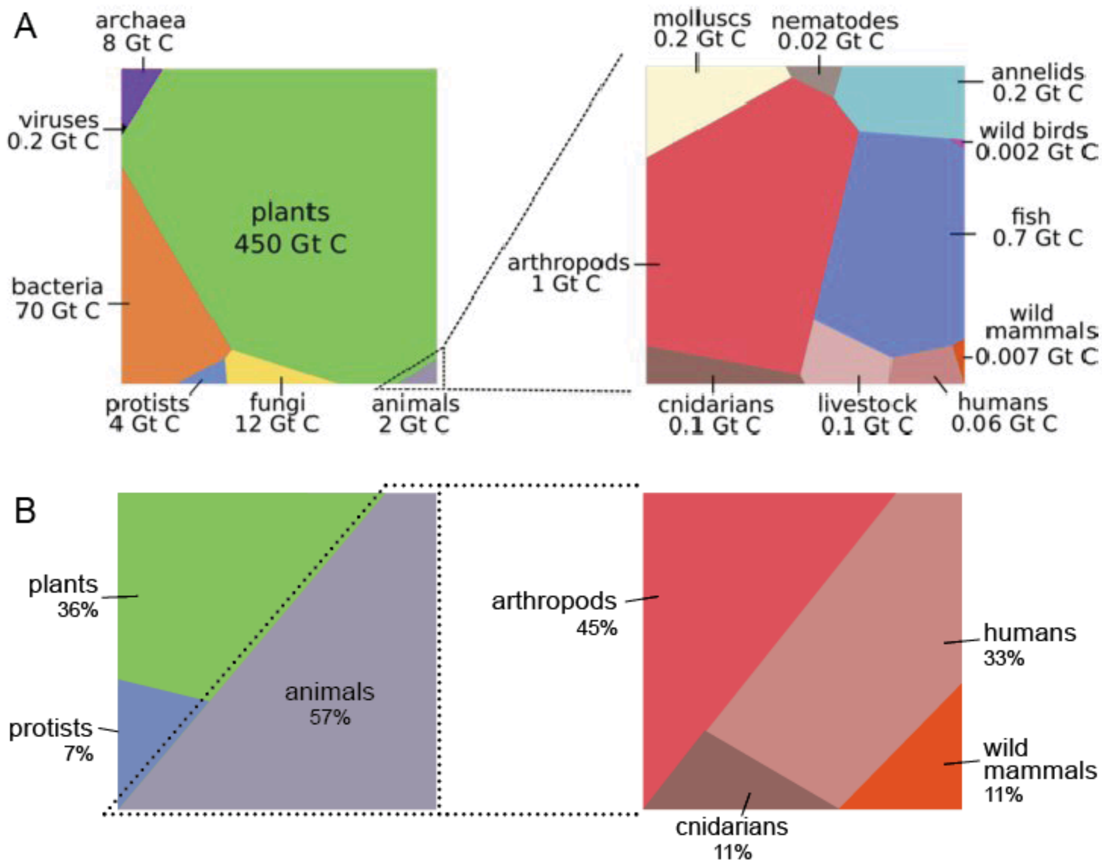


Figure 5. (**A**) Distribution of the estimated biomass on earth in gigatons of carbon (GT C), reproduced with permission from [107]. (**B**) Distribution in percentage of the biological models which inspired the 19 Bio-BS.

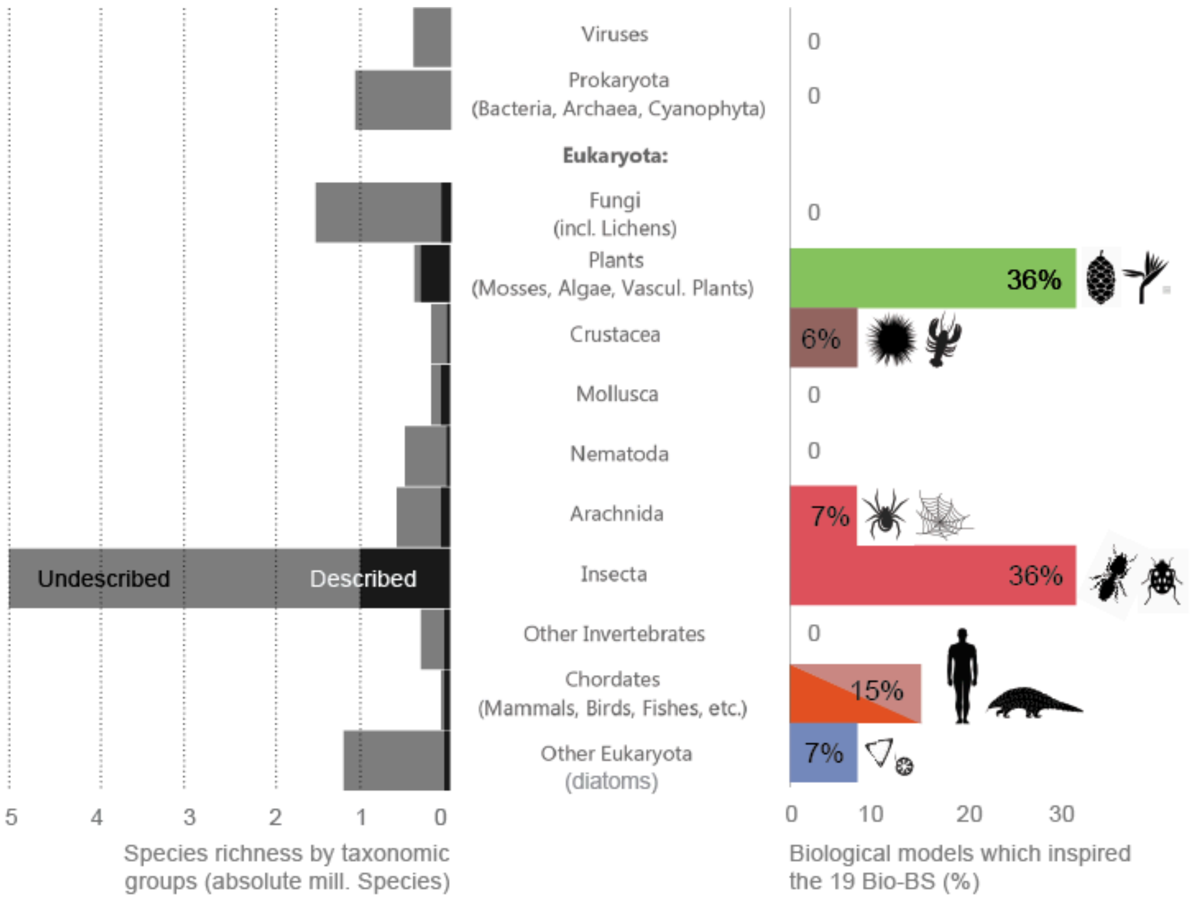


Figure 6. Distribution of the major groups of biological models which inspired the 19 Bio-BS according to the distribution of estimated species on earth (absolute number of species on the left (grey = estimated number of yet to be described species, black = already described). This figure uses the same colour code as **Figure 5**. Reproduced and adapted with permission from [108].

Figure 7. Temperature measurements of termite mounds carried out by Mick Pearce (left), CC0 Licence, Mick Pearce. **(b)** Heat exchange floor under construction, abstraction of the biological principles of termite mounds, CC0 Licence, Mick Pearce.

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.

(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. 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

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 [109], [110].

Abstracted functions of regulation – Bio-BS mostly abstracted one (47%) or two (30%) functions. **Figure 8** shows 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 bioinspired 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.

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 [19], [20].

(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 [111]. There is a need for the development of building envelopes with multi-regulation capacities to address contradictory requirements as highlighted by [16] [112], [113].

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.

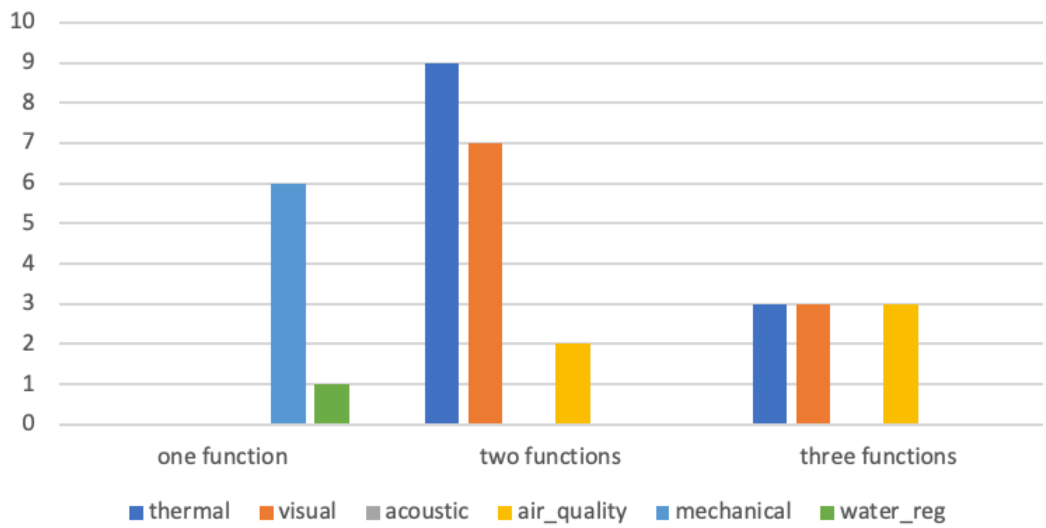


Figure 8. Distribution of the function of regulation of the 19 Bio-BS

4.7. Step 4 - Feasibility and prototyping

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 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

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:

- **CAD 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, Table 2), CATIA (Ids. 2, 10, Table 2), Revit (Id. 10), FEM (Id. 10), AutoCAD (Id. 2), Ecotec (Id. 2), Structural Analysis (Id. 2), Heliodon (Id. 15).
- **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). The percentages were equally distributed between public buildings and research projects.

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 resulted in high construction complexity, which are mostly research pavilions. For instance, the ICD/ITKE fibrous morphology research pavilions (Ids. 18-22, Table 2) have explored 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 [114]. 74% of the Bio-BS resulted in radical innovative systems rather than incremental (26%). This result shows 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) Bioinspired projects can benefit from internal *and* external collaborations, whatever level of innovation (incremental or radical) is expected. 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** - Understanding of biological concepts), hence scientific grounding or technological opportunities would be a worthwhile consideration to push forward further development in bioinspired architecture.

4.8. Step 5 - Outcome: improved or new design

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 performance	**63% No** | 16% Yes | 21% NA
Overtime performance	**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

Spatial scale – Referring to Loonen *et al.,* Bio-BS were sorted accordingly to a façade classification [26]. Most of the Bio-BS were referred as façade element (26%) or shading systems (31%). 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 [24]. This concept is widely used in all fields of engineering in order to measure the maturity level of a particular technology. Their definitions go as follow:

- TRL 6 – System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL 7 – System prototype demonstration in a space environment
- TRL 8 – Actual system completed and "flight qualified" through test and demonstration (ground or space)
- TRL 9 – Actual system "flight proven" through successful mission operations

Bio-BS were equally distributed from TRL 6 to 9 where research pavilions mostly meet a TRL between 6 and 8, and public buildings a TRL of 9 (30% of all cases).

Assessment of energy performance – This variable specifies if the energy performance of the Bio-BS was assessed. Very few quantitative assessments of the Bio-BS were found and all of them were carried out for public building projects (Ids. 10,13,14, Table 2).

Comfort – Thermal and visual comfort (74%) were the most targeted performances (**Figure 9**). They were simultaneously addressed since most of the Bio-BS were shading systems. This result is consistent with previous studies [16].

Overtime performance – This parameter provided a qualitative evaluation of the biomimetic systems' performance after the building completion. 74% of the Bio-BS still ensure the same performance as for delivering. Most of the research pavilions have been destroyed after completion excepted the BUGA Wood and Fibre exhibited in Germany in Heilbronn, and the Laga pavilion (Ids. 23, 26-27). 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) [26].

Main component – Half of the Bio-BS were made of polymer material (26%) and metal alloy (26%) rather than wood (11%) or textile (5%). Polymer and metal alloys which can more easily adapt their shape to respond to stimuli, were mostly used for adaptive Bio-BS.

Adaptable to renovation – None of the Bio-BS were applied to new buildings. However, 58% 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 11k €/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 [115]. 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.).

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

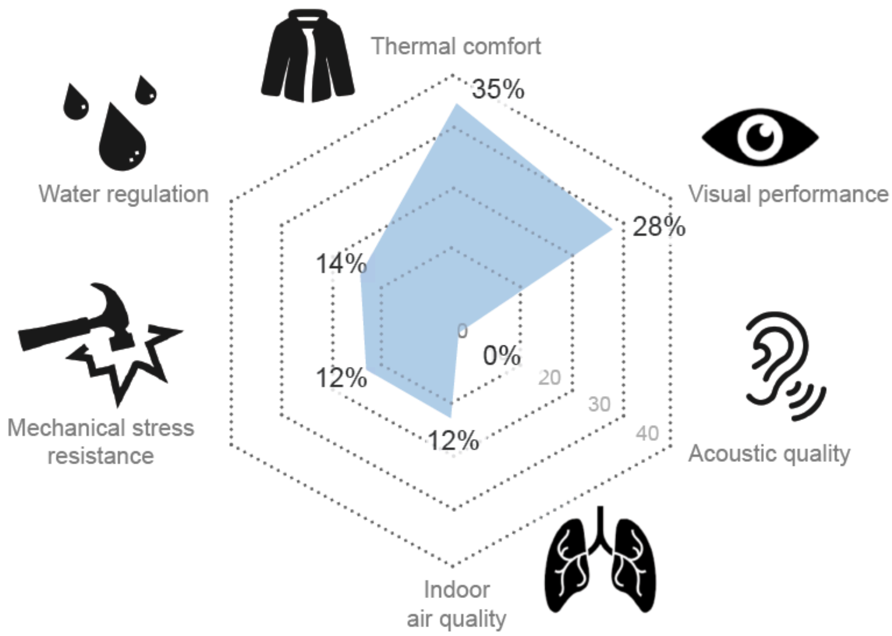


Figure 9. Distribution of the Bio-BS according to the comfort.

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 bioinspired 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 bioinspired 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.

(iii) There was no case of renovation: it implies that existing 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

It is consistent with observation from previous sections. 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 bioinspired design process.

Selecting and abstracting the accurate biological model for a bioinspired solution is intricate. Even trained biomimetic practitioners, such as researchers of ICD, ITKE or Stuttgart, need a preselection of groups of organisms with the involvement of biologists to help focus the research project. However, if approach stimulates co-discoveries, it is unfortunate these projects are quasi-systematically restrained to one taxonomic group only.

As seen in this study, the methodologies in bioinspiration are diverse and quite specific to the designers, but in the literature the number of projects reaching TRL6 is low; in the vain of helping design process steps, as biological data comprehension, selection, abstraction then transfer to technology, means such as data exploration and structuring tools need to be further developed. Further research from the authors will focus on the development of tools to access to biological data during the design process.

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 bioinspired 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 [116] 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 bioinspired 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.

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Authors declaration of interest

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Credit author statement

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

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 Professor **Jan Knippers** 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) [117]. 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). [118]

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 [119] using the MCA tool from R package "FactoMineR" [120].

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 ($n_{cases} = 19$). For the MCA, all thirty Bio-BS were considered ($n_{cases} = 30$).

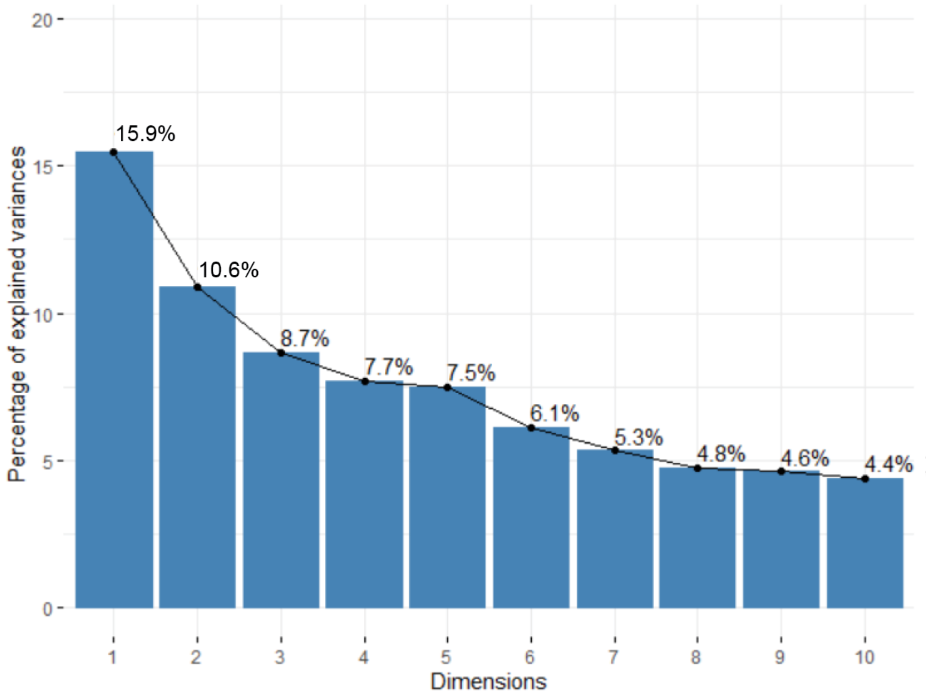
As mentioned, MCA is a descriptive tool. Obtaining robust results preferably requires large data samples (more observations than variables or modalities). However, it does provide information even with a rather small sample. Unlike univariate analysis, missing information was removed from the dataset 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 (m^2), Cost (€/m^2), 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.

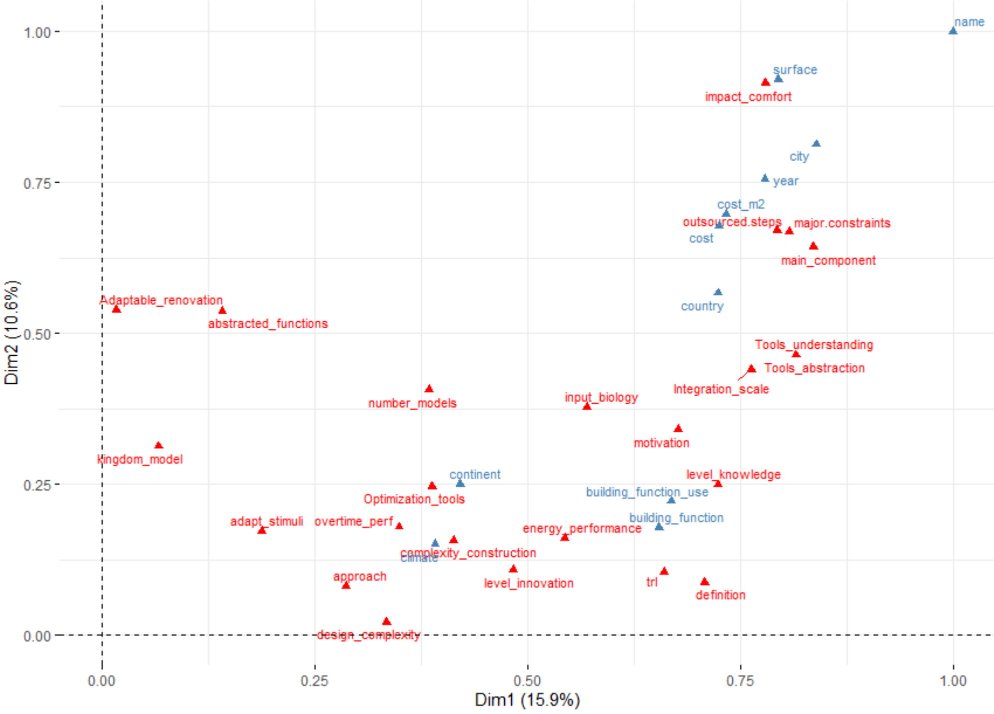
The percentage of inertia explained by each MCA dimensions is displayed on **Figure B1 (a)**. Correlations between the variables and MCA principal dimensions, dimensions 1 and 2, are plotted in **Figure B1 (b)**. The inertia of dimensions 1 and 2 respectively are, eigenvalue, 15.5% and 10.9%, for a total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



Percentage of explained variances
Dimensions
15.9%
10.6%
8.7%
7.7%
7.5%
6.1%
5.3%
4.8%
4.6%
4.4%
0
5
10
15
20
1
2
3
4
5
6
7
8
9
10

(a)



Dim1 (15.9%)
Dim2 (10.6%)
0.00
0.25
0.50
0.75
1.00
name
surface
impact_comfort
city
year
cost_m2
outsourced.steps
major.constraints
cost
main_component
country
Adaptable_renovation
abstracted_functions
Tools_understanding
Tools_abstraction
Integration_scale
input_biology
number_models
motivation
kingdom_model
continent
level_knowledge
Optimization_tools
building_function_use
building_function
adapt_stimuli
overtime_perf
energy_performance
complexity_construction
climate
approach
level_innovation
trl
definition
design_complexity

(b)

(c)

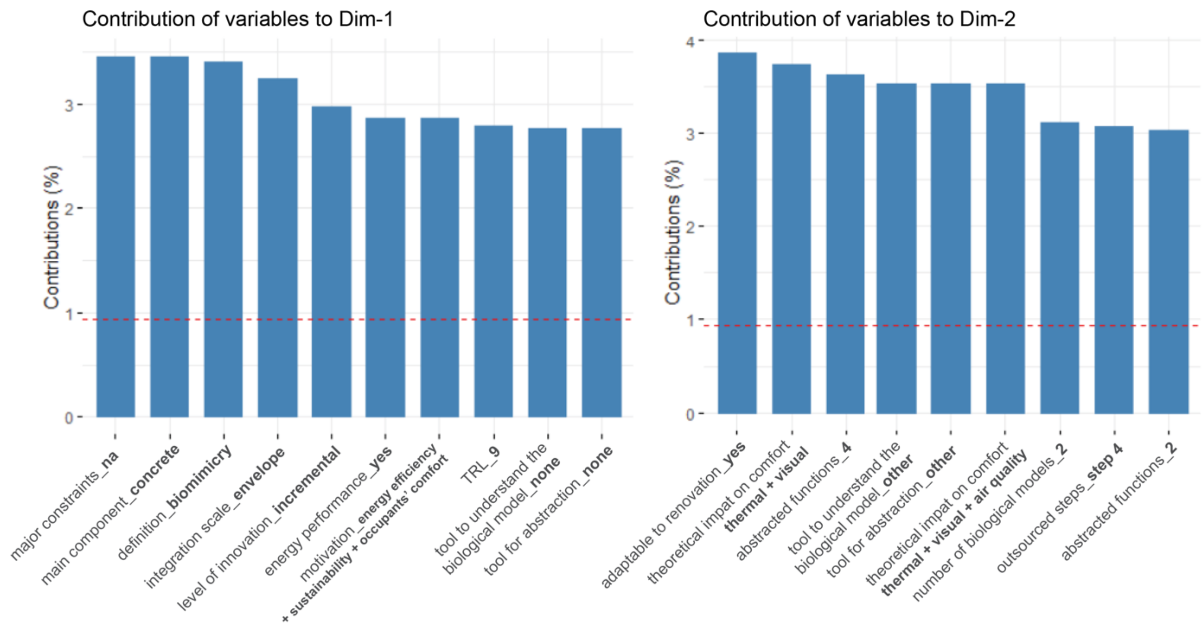
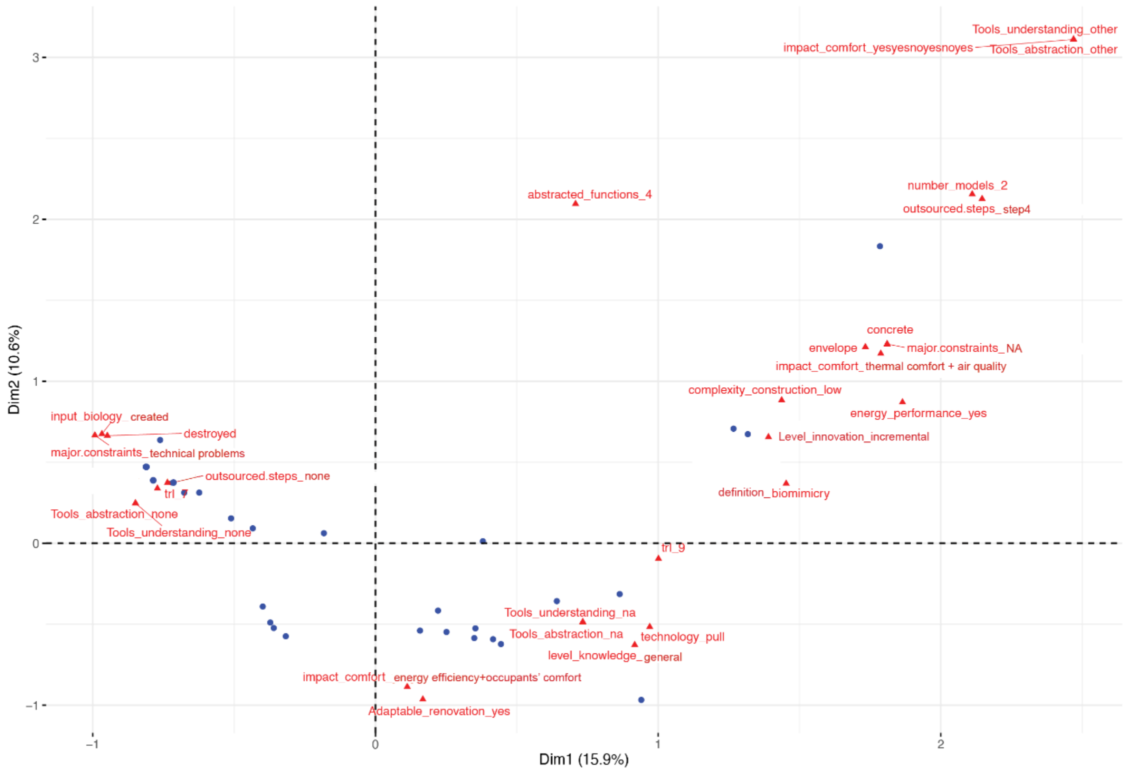


Figure B1. (a) Percentages of inertia explained by each MCA dimension (variables in red, supplementary data in steel blue) **(b)** Correlation between the variables and MCA principal dimensions (Euclidian space, axes from 0 to 1) **(c)** Total contribution (percentage) to dimension 1 and 2 of modalities.

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 variable and the parameter in bracket, **(b)** with the name of the Bio-BS.

B.3. Analysis

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

1. **<u>Academic research projects</u>** <u>group:</u> 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. **<u>Public building projects</u>** <u>group:</u> 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

<u>Individuals</u>: 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.

<u>Correlations with:</u>

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*
Overtime performance: *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).

<u>Correlations with:</u>

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.

<u>Correlations with:</u>

Tools for understanding and selection of relevant biological models: *other*
Comfort: v*isual + 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.

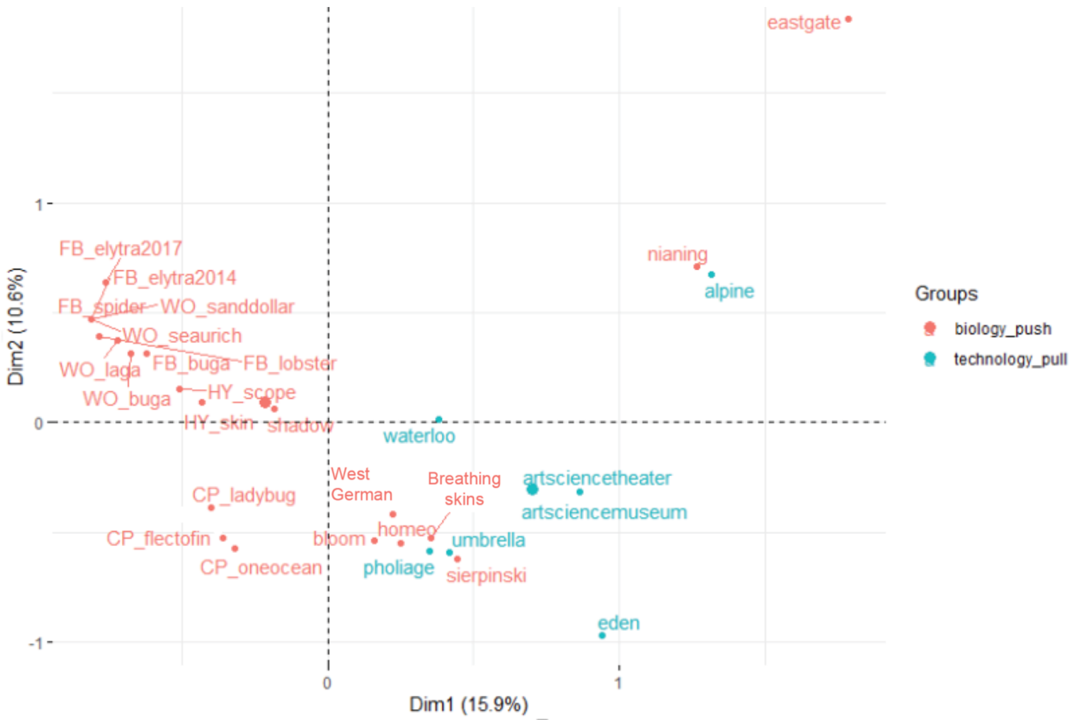
The observed sprawl on the MCA factor map is also correlated the comfort: unlike the majority of the other projects, which "only" improve thermal and/or visual aspects through bio-inspiration, Nianing Church, Eastgate Centre, the Eden project, and Davis Alpine include other parameters such as water regulation (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

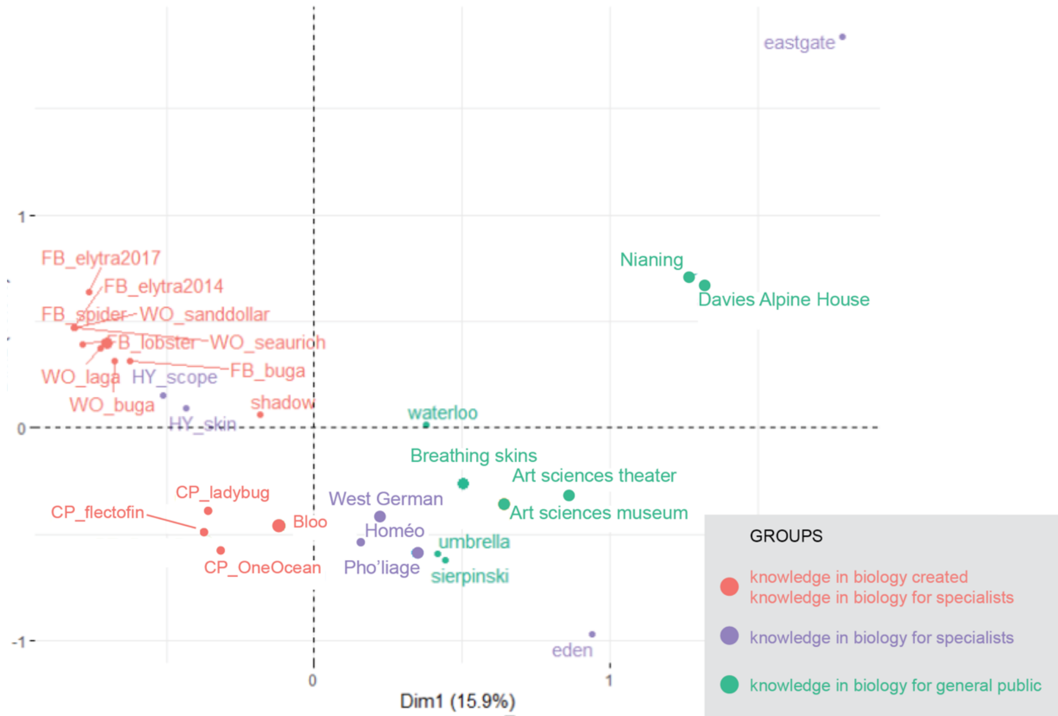
The MCA put forward two main typologies of projects, opposed by different modalities. Since these modalities are based on variables defined following the standard ISO design process (section **2.2. Design process** in the article), they give clues on differences and similarities between projects and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