Multi-criteria characterization of biological interfaces: Towards multi-functional biomimetic building envelopes

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Caractérisation multi-critères des enveloppes biologiques : vers la conception de façades multi-fonctionelles

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To living species

To their beauty and complexity

Au vivant,

A sa beauté et complexité

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Multi-criteria characterization of biological interfaces: towards multi-functional biomimetic building envelopes

The envelope is a concept that defines an interface between an internal and external environment. They can be 'living' (skin, hair, feather, bark, membrane of a cell) or 'non-living' (egg, animal architecture, shell) or man-made design (packaging, building facade, car body, etc). Nowadays, industry, architecture and product design are particularly interested in replicating the properties of biological envelopes in order to improve the performance of man-made envelopes (mechanical resistance, acoustic and thermal insulation, water and air permeability, etc.). However, these bio-inspired researches are often inspired by the same panel of biological organisms characterized according to a single-criterion approach.

This research first presents a comparative analysis of bio-inspired building skins built over the last fifty years in chapter 1. The second chapter provides a multi-criteria analysis of a selection of ten types of biological envelopes of eukaryotes in terrestrial environment and on a macroscopic scale (skin, hair, feathers, bark, etc.). By classifying these organisms using several criteria of analysis (functions of regulation, time scale, size scale), this research enhances connexions between life and design sciences. The third chapter proposes a multi-criteria analysis tool for biological organisms allowing a systemic understanding of living beings in a perspective of biological properties transfer for a multi-criteria design. Last section of this research discusses the ethical aspects of biomimetics and the relevance of the acquisition of new biological data, the taxonomic bias and the methodological aspects of the approach in architecture.

Foreword

Reconciling architecture and sustainability through biomimicry

2009, I am 19 years old, Gauthier Chapelle[1] is here, in front of us, in the Lyon School of Architecture amphitheatre, to introduce us to biomimicry in architecture. At last, a systemic and multi-criteria approach that allows us to combine aesthetics, creativity, technical performance and regenerative[2] design. We are a long way from the tedious energy performance calculation tables used in our undergraduate courses. The approach of biomimetics revitalises our vision of energy transition by stimulating the creativity of designers through the abundance and diversity of shapes, colours, patterns and performances suggested by living species. At the crossroads between several disciplines, biomimetics creates strong connections between life sciences, architecture and civil engineering.

From a practical point of view, how is this approach implemented in architectural design? Some architects choose termite mounds, other shellfish or pinecones as study models. But why these models? Why not others? Among the 1.9 million species described today, how do they choose the ‘right’ model? Besides, is there one or more ‘good’ models to design a building or to solve a technical building challenge?

From architectural theory to practice

At that time, the frameworks made accessible to the widest public by Biomimicry 3.8 remained generic for design problems and not adapted to architecture. They are therefore unfortunately unsuitable for our project workshops in architecture schools where the design process is above all ruled by artistic practice and exploration in three dimensions with our Kusch, models, tubes of glue and Rotring pens. Fortunately, in 2012 the first academic works dealing specifically with these methodological aspects in architecture were published[3].

[1] Dr. Gauthier Chapelle is the co-founder of the association Biomimicry Europa - https://biomimicry.eu/ and author of several books including 'Le vivant comme modèle' (2015) 'Humanité Bio-inspirée - Une autre approche' (2020) with Kalina Raskin.

[2] Regenerative design is the design of objects, buildings and other artefacts that allow the regeneration of ecosystems degraded by human activities. See Chapter 2 and 5.

[3] See Chapter 2, Figure 1.6. Hype Cycle of Biomimicry in Architecture

In 2015, after graduating as a Architect and a year out of engineering school, I spent a year to learn from those who design biomimetic buildings and develop the associated methods and tools. This one-year of research is organized around 4 successive research internships[4],[5]. It was sponsored by several building manufacturers, including the international Vicat cement group, the Nobatek/INEF4 institute for energy transition, Saint-Gobain Isover, and with the educational supervision of Olivier Scheffer[6] and Romain Rieger[7].

In Harare, I worked for several months on architectural competitions and the rehabilitation of the emblematic top floor of the Eastgate Building. Working with the designer, Mick Pearce, I discovered that biomimetics goes far beyond imitating the 'technical prowess' of living organisms to develop more efficient technical systems. With a deeper understanding of Life, for example through the key concepts of ecosystem services, trophic networks or emerging properties, biomimetic approach proposes a reintegration of buildings into ecosystems. I then spent 3 months modelling fractal envelopes, inspired by the geometry of trees at Kyoto University with the Professor Satoshi Sakai. These solar envelopes, called 'Sierpinski Forest' limit the building's heating. After these two design internships, I became familiar with academic research and the notions of regenerative architecture, deep-ecology and ecosystem services with the Dr. Maibritt Pedersen Zari at Victoria University. This was followed by several months of research with the Dr Lidia Badarnah in Boston at the MIT Building Technology lab. She introduced me the design methodologies to draw a bio-inspired building envelopes from a problem-based perspective.

Back in France in 2017, I joined the CEEBIOS - French Centre for Studies and Expertise in Biomimetics- within the architecture section. Our missions consist in facilitating the biomimicry approach in urban projects, with the project management actors (architecture agency, design office) within the framework of competitions, as well as with the project management for the constitution of calls for tenders[8]. As observed in the scientific literature and during the world tour, the phases of selecting biological models, abstraction and then transfer remain the most difficult for designers. In architecture, this limitation leads to an almost systematic selection of termite mound models for passive ventilation and pinecone models for adaptive facades. However, the diversity of living species is rich with 8.7 million of estimated species, and bio-inspired architectures cannot be reduced to a few ‘termite mound buildings’ and ‘lotus facades’. These limits too often encountered during CEEBIOS’s project accompaniments were the motivation for this thesis research.

[4] TEDx Cannes, 'L'architecte à l'école du vivant'. https://www.youtube.com/watch?v=6CcYusdQ2Jo

[5] Biomimicry World Tour 2015-2016, research paper. https://www.researchgate.net/project/World-Tour-of-Biomimicry

[6] At the time an active member of Biomimicry Europa and recently Development Director of Ceebios since the end of 2020.

[7] Lecturer at the Ecole Centrale de Lyon since 2012 and researcher in the LTDS laboratory.

[8] Ceebios expertise within the architecture department. Assistance with projects mainly led by Eduardo Blanco and Chloé Lequette.

Towards multifunctional bio-inspired envelopes

Studying building envelopes and multi-regulation in this PhD resulted from observed needs of the building sections at CEEBIOS. This research topic was also motivated by intellectual interest by the author following its collaboration with the Dr. Lidia Badarnah in 2016. This work started from the conclusion and discussion of her PhD published in 2012.Likewise, the subject of this PhD is strongly connected to the international researches of Dr. Petra Gruber, Dr. Marlen Lopez Fernandez, Dr. Suzanne Gotovski, Illaria Mazzoleni, Dr. Aysu Kuru and Tessa Hubert on methodologies and tools for biomimetic architecture.

Building interdisciplinary dialogue

This PhD started in 2017 within the Ceebios and Mecadev laboratory - Adaptive and Evolutionary Mechanisms - Joint Research Unit of the CNRS 7179 at the National Museum of Natural History (MNHN). The Mecadev has a history of research and industrial partnerships in biomimicry and has the particularity of being interested in a large diversity of biological models within eukaryotes[9]. This collaboration was set up with a vision to explore the tree of life as widely as possible and thus overcome the current taxonomic bias in biomimicry, which was already anticipated at the time.

This thesis manuscript establishes a dialogue between three disciplines: architecture, civil engineering and life sciences, and also geometric optics, thermodynamics, acoustics, solid mechanics and fluid mechanics. The approach is intended to be as rigorous as possible, however being on the interface between several disciplines requires simplifications. As far as possible, these will be mentioned throughout the manuscript.

All of the graphic productions resulting from this research were produced by hand. Drawing - schematic diagrams, schematic sections, axonometry and sketches - is a language common to all three disciplines: architecture, civil engineering and life sciences. It has two main functions in this work. On the architectural level, it gives a more sensitive and aesthetic dimension to this work, which is essentially focused on quantifiable physical and biological phenomena. From research and learning point of view, drawing promotes observation and therefore understanding. It was used throughout this work as a learning and communication tool.

Explore, participate, teach, interview

In the same way as the biomimicry world tour in 2015, this work has benefited from numerous interactions with researchers and practitioners through the Museum of Natural History of Paris, and Ceebios partners. Beyond scientific publications, face-to-face exchanges and collaborations have played a key role in the development of the PhD. In particular, the author conducted 3 weeks of interviews and observations thanks to the grant 'Transhumance' of the doctoral school of the Museum

[9] . The Eukaryote domain includes the following 5 kingdoms: animal, plant, fungus, protists, bacteria. See chapter 2

of Natural History in 2019, within the ITKE laboratory of the University of Stuttgart. In collaboration with ICD - Institute for Computational Design - this laboratory has so far built almost twenty biomimetic pavilions leading to the creation of start-ups such as FibR. Their vision, research and teaching methods have shed important light on this research. The results of these exchanges have mainly enriched the chapter 2 and the discussion presented in chapter 5.

Likewise, the author spent 4 weeks of volunteering in the national park of la Réunion at the end of the 1st year of his thesis. It was essential to experiment with the different stages of research, i.e. from data collection in the field to data processing and analysis in the laboratory[10].

As part of her missions at Ceebios, the author was also able to create and teach the first French 35-hour module on bio-inspired envelopes as part of a Master's seminar on bio-inspired envelopes at the ENSA Paris Val de Seine School of Architecture in partnership with real estate developer ICADE. In collaboration with the professors, the author guided the students from the concept stage to the numerical modelling. These teaching periods made it possible to test the tools being developed as part of the thesis and their completed version is presented in chapter 3.

Facilitating the selection of biological models in practice

This research proposes tools to facilitate the selection and then combination of several biological models during the architectural sketching phases. By developing a way of exploring existing biological knowledge in relation to a multi-criteria problem, it allows designers to develop a systemic understanding of biological organisms, beyond the 'exceptional' performance that makes some organisms so 'well-known' to the general public and to designers.

Drawing on the feedback from Ceebios' project support to integrate biomimicry, this thesis highlights the main difficulties encountered during the design process and proposes tools and recommendations for architectural practice.

[10] Identification of a pest impact - the psyllid (Acizzia uncatoides) - on tamarinds (Acacia heterophylla) of the island of Réunion at CIRAD. The mission consisted in collecting insect samples in the field and analyzing them in the laboratory - https://umr-pvbmt.cirad.fr/principaux-projets/creme

Acknowledgements

This thesis results of three years of passionate study in collaboration with a wide range of practitioners of the building sector - architecture studio, design offices, material manufacturers, building contractors - and from fundamental and applied research in biology, civil engineering, architecture and biomimetics.

I see this research as the result of collective work, offering a viewpoint on the current progress of research in bio-inspired building envelopes in 2022. Being at the interface between different fields is a complex and collaborative process that requires a lot of time to understand disciplinary fields that are not our initial background, and then to build convergences between disciplines. One person cannot hold in depth all the knowledge mobilised in this research.

I would like to express my gratitude to the researchers, architects, engineers and friends who have taken the time to exchange, proofread, support and share their knowledge over the last three years. In these periods of *Great acceleration*[11], giving time is a precious gift. *acceleration*. As a result, each person who has contributed to this thesis by proofreading, advising in the writing and bringing significant knowledge is accredited at the beginning of each chapter. I hope I have remembered everyone!

More personally, this PhD went through many emotional stages; the euphoria due to a statistical model works and (finally!)reveals correlations, the fascination of imagining the diversity of 1.7 million species recorded on Earth and the infinite possibilities of architectural combinations that could result, but also stages of deep frustration at not being able to explore all the paths. I am deeply grateful for this deep and collective investigation.

[11] The trajectory of the Anthropocene : the great acceleration (2015), W. Steffen.

Jury. I would like to thank Jan Knippers and Olga Speck as the rapporteurs of this thesis. Many thanks for your feedback and evaluation of this work as biologists and engineers. I would also like to thank Guillaume Lecointre and Christophe Goupil as examiners and our rich exchanges during this thesis and during the defence. A special thank you to Stéphane Blanc and Marc Desmulliez for having accepted to be part of the jury as examiners of this thesis work, your crossed views during the defence will allow to enrich the continuation of this work.

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I would like to thank Laury Barnes-Davin, Eric Bourdon and Pierrick Serres from the cement group VICAT for their support and confidence since our first meeting in 2015. Your invitations to speak to your research teams to discuss the progress of my thesis reflections have helped to refine the research directions.

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This thesis has also benefited from the contributions and recommendations of Lidia Badarnah of the University of West England. I would like to thank her sincerely for her time and expertise on bio-inspired built envelopes and for her hospitality in Boston and Cardiff.

As a CIFRE thesis - Conventions Industrielles de Formation par la Recherche - I was part of two teams belonging to two different institutions: the Mecadev laboratory of the MNHN – National Museum of Natural History of Paris - and the Ceebios - Centre d'Études et de Recherche en Biomimétisme (Centre for Studies and Research in Biomimicry).

Ceebios. All this work is greatly due to the CEEBIOS team, of which I have now been a member for more than 4 years in the housing division. At the beginning of this thesis, we were 5 members and under an associative status, we are now 21 in full mutation towards a status of cooperative society of collective interest (SCIC)!

I would also like to thank the whole team, namely Laura, Anneline, Dounia, Adrien, Eliot, Hugo, Luce-Marie, Chloé, Eduardo, Juliette (with whom I worked during these years of thesis), as well as Olivier, Yann, Félix, Cécile, Bertrand, Thomas, Ludivine and Hadhoum, who have more recently joined the team. I am happy and somehow very proud to be part of this team which works with strength and conviction for the development of biomimicry in France. Our collective debates and questions have considerably enriched this thesis research. It is a real pleasure to move forward and contribute to the development of biomimicry in France today with you.

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A particularly thank Eduardo and Chloé for their unrivalled enthusiasm and, above all, for having taken charge of all the missions of the habitat unit during the last two years of this PhD. Eduardo I am looking forward to collaborations at the crossroad between multi-function and regenerative urbanism!

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Special thanks to Tessa Hubert for our collaboration on our first thesis paper. It was a real pleasure to build this research together around the methodologies, to visit the ITKE laboratory in Stuttgart and to carry out together these dozens of interviews. Your efficiency and organisation always impress me.

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Résumé

Caractérisation multicritère des enveloppes biologiques :
Vers des enveloppes multi-régulantes et bio-inspirées

L'enveloppe est un concept qui définit une interface entre un milieu intérieur et extérieur. Elles peuvent être ‘vivantes’ (peaux, poils, plumes, écorces, membranes d'une cellule …) ou ‘non vivantes’ (œuf, architectures animales, coquilles …) ou encore conçues par l'homme (packaging, façade de bâtiment, carrosserie de voiture, etc.). A ce jour, l'industrie, l'architecture ou encore la conception de produits s'intéressent particulièrement à la réplication des propriétés des enveloppes biologiques afin d'améliorer les performances des enveloppes construites par l'homme (résistance mécanique, isolation acoustique et thermique, imperméabilité à l'eau et à l'air, etc.). Or ces études en bio-inspiration s'inspirent souvent du même panel d'organismes biologiques caractérisés suivant une approche uni-critère.

Cette recherche propose dans un premier temps une analyse comparative des façades bio-inspirées construites au cours des cinquante dernières années. Le second chapitre est consacré à une analyse multicritères d'une sélection d'enveloppes biologiques au sein du domaine des eucaryotes et spécifiquement les espèces vivants en milieu terrestre. En classant ces organismes via différentes critères d'analyses (fonction de régulation, échelle temporelle, échelle de taille), cette recherche explore les points de convergence et possibilités de transfert entre les sciences de la vie et de la conception architecturale. Le troisième chapitre présente un outil d'analyse multicritères des organismes biologiques permettant une compréhension systémique des êtres vivant dans une optique de transfert des propriétés biologiques à une conception multicritères. La dernière section de cette recherche discute les aspects éthiques liés au biomimétisme et acquisition de nouvelles données biologiques, le biais taxonomique ainsi que les aspects méthodologiques de la démarche.

Avant-propos

Réconcilier architecture et durabilité par le biomimétisme

2009, j'ai 19 ans, Gauthier Chapelle[12] est là, devant nous, dans l'amphithéâtre de l'Ecole d'Architecture de Lyon. Il vient de nous initier à la démarche du biomimétisme appliqué à l'architecture grâce à la présentation d'une multitude d'espèces aux performances structurelles, de thermorégulation ou encore environnementales bien plus ingénieuses que nos systèmes constructifs actuels. Enfin une approche systémique et multicritères qui permet de combiner esthétisme, créativité, performance technique et design régénératif[13]. Nous sommes bien loin de nos fastidieux tableaux de calcul de performance énergétique des cours de licence. Le biomimétisme donne du panache à la transition énergétique en stimulant le génie créatif des concepteurs par l'abondance et la diversité de formes, couleurs, motifs et performances techniques observées au sein du vivant. Mieux encore, à la croisée entre plusieurs disciplines, le biomimétisme réouvre un ancien dialogue entre sciences du vivant, architecture et génie civil.

D'un point de vue pratique, comment met-on en œuvre cette approche lors de la conception architecturale ? Certains architectes choisissent la termitière, d'autres les carapaces de crustacés ou encore des pommes de pin comme modèles d'études. Pourquoi ces modèles-là ? Pourquoi pas d'autres ? Parmi les 1,9 millions d'espèces aujourd'hui décrites comment choisir le *bon* modèle ? D'ailleurs, y a-t-il un ou plusieurs *bons* modèles pour concevoir un même bâtiment ou résoudre une même problématique technique ?

De la théorie à la pratique architecturale

A cette époque, les canevas rendus accessibles au plus large public par Biomimicry 3.8 restent génériques pour des problèmes de conception non spécifiques à l'architecture. Ils sont malheureusement inadaptés à nos ateliers de projet en école d'architecture où le processus de conception passe avant tout régit par la pratique artistique et l'exploration en trois dimension grâce à nos Kusch, maquettes, tubes

[12] Dr. Gauthier Chapelle est co-fondateur de l'association Biomimicry Europa - https://biomimicry.eu/ et auteur de plusieurs ouvrages dont 'Le vivant comme modèle' (2015) et 'Humanité Bio-inspirée – Une autre approche' (2020) avec Kalina Raskin.

[13] Le design régénératif consiste à concevoir des objets, bâtiments et tous autres artefacts permettant la régénération des écosystèmes dégradés par les activités humaines. Voir Chapitre 2 et 5.

de colle et stylos Rotrings. Il faudra attendre 2012 pour que soient publiés les premiers travaux académiques[14] traitant spécifiquement ces aspects méthodologiques et facilitant l'intégration du biomimétisme en architecture.

En 2015, diplômée Architecte d'Etat et en année de césure d'école d'ingénieur, je planifie une année[15,16] pour apprendre auprès de ceux qui conçoivent des bâtiments biomimétiques et développent les méthodes et outils associés. Cette année de recherche s'articule autour de 4 stages de recherche successifs. Elle est sponsorisée par plusieurs industriels du bâtiment dont le groupe cimentier Vicat, l'institut Nobatek/INEF4 pour la transition énergétique, le groupe Saint-Gobain Isover, et avec l'encadrement pédagogique et bénévole d'Olivier Scheffer[17] et Romain Rieger[18].

A Harare, je travaille plusieurs mois sur des concours d'architecture et à la réhabilitation du dernier étage de l'emblématique bâtiment de bureaux Eastgate Building. Auprès de son concepteur, Mick Pearce, je découvre rapidement que le biomimétisme va bien au-delà d'imiter des 'prouesses techniques' du vivant pour développer des systèmes techniques plus performants. Une compréhension plus large du vivant, en particulier via les notions de services écosystémiques, réseaux trophiques ou encore de propriétés émergentes, la démarche du biomimétisme propose une réintégration des bâtiments dans les écosystèmes existants. Je modélise ensuite pendant 3 mois des enveloppes fractales, inspirées de la géométrie des arbres à l'Université de Kyoto auprès du professeur Satoshi Sakai. Ces enveloppes solaires baptisées 'Sierpinski Forest' permettent la limitation de l'échauffement du bâtiment. Après ces deux stages de conception, je me familiarise avec la recherche académique et les notions d'architecture régénérative, de *deep-ecology* et services écosystémiques auprès du Dr. Maibritt Pedersen Zari à l'Université Victoria. S'en suivent plusieurs mois de recherche, auprès de Lidia Badarnah à Boston au Building Technology lab du MIT qui m'introduit aux enveloppes bâties bio-inspirées et méthodologies de conception d'un problème technologique vers la biologie.

De retour en France, j'intègre rapidement la SCIC[19] Ceebios – Centre français d'études et d'expertise en biomimétisme – au sein de l'équipe habitat. Nos missions consistent à faciliter la démarche du biomimétisme dans les projets urbains, auprès des acteurs de la maitrise d'œuvre (agence d'architecture, bureau d'études) dans le cadre de concours, ainsi qu'auprès de la maitrise d'ouvrage pour la constitution d'appels d'offres. Comme observé dans la littérature scientifique[20] et lors du tour du monde, les phases de sélection des modèles biologiques, d'abstraction puis de transfert restent les plus difficiles pour les concepteurs. En architecture, cette limitation conduit à une sélection quasi-systématique des modèles

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[14] Voir chapitre 2, Figure 1.6. Cycle de Hype du biomimétisme en architecture

[15] TEDxCannes, 'L'architecte à l'école du vivant'. https://www.youtube.com/watch?v=6CcYusdQ2Jo

[16] Tour du monde du biomimétisme 2015-2016, mémoire de recherche. https://www.researchgate.net/project/World-Tour-of-Biomimicry

[17] A l'époque membre actif de Biomimicry Europa et Directeur Développement du Ceebios depuis fin 2020.

[18] Maitre de conférence à l'Ecole Centrale de Lyon depuis 2012 et chercheur au sein du laboratoire LTDS.

[19] SCIC : Société Coopérative d'Intérêt Collectif

[20] Voir chapitre 2, état de l'art.

termitières pour la ventilation passive et pomme de pin pour les façades adaptatives. Mais la diversité du vivant est riche de 8,7 millions d'espèces estimées, l'architecture bio-inspirée ne peut se résumer à quelques 'bâtiments termitières' et 'façades lotus'. Ces limites trop souvent rencontrées lors de ces accompagnements de projets[21] sont à l'origine de cette recherche de thèse.

Vers des enveloppes bio-inspirées multifonctionnelles

Le choix du sujet des enveloppes et de la multi régulation résulte de l'analyse des besoins du secteur de la construction identifiés lors des accompagnements de projet. Il fut aussi choisi par intérêt intellectuel par l'auteur.e suite à la collaboration avec le Dr. Lidia Badarnah. Ce travail s'inscrit donc dans le prolongement de ses recherches et conclusion autour de la multi-régulation publiées dans le cadre de sa thèse en 2012. Dans la même lignée les recherches internationales des chercheuses Petra Gruber, Marlen Lopez Fernandez, Suzanne Gotovski, Illaria Mazzoleni et plus récemment du Dr. Aysu Kuru et de Tessa Hubert, cette recherche approfondit le développement de méthodes et outils pour la conception de façade multi-régulantes. Cette thèse s'articule donc avec ces recherches en plein développement.

Construire un dialogue interdisciplinaire

Cette thèse débute en 2017 au sein du Ceebios et laboratoire Mecadev – Mécanismes d'Adaptatifs et Évolution – Unité Mixte de Recherche du CNRS 7179 et au Muséum National d'Histoire Naturelle de Paris (MNHN). Le Mecadev a un historique de recherches et partenariats industriels en biomimétisme, et présente la particularité de s'intéresser à une grande diversité de modèles biologiques au sein des eucaryotes[22]. Cette collaboration fut mise en place dans l'optique, d'explorer le plus largement possible l'arbre du vivant et ainsi dépasser l'actuel biais taxonomique en biomimétisme, à l'époque déjà pressenti.

Ce manuscrit de thèse instaure dès le début un dialogue entre trois disciplines majeures : architecture, génie civil et sciences de la vie et d'optique géométrique, thermodynamique, acoustique, mécanique du solide et mécanique des fluides. L'approche se veut la plus rigoureuse possible, cependant être à l'interface entre plusieurs disciplines nécessite des simplifications. Dans la mesure du possible celles-ci seront mentionnées tout au long du manuscrit.

L'ensemble des productions graphiques issues de ces recherches ont été réalisées à la main. Le dessin – schémas de principes, coupes schématiques, axonométrie et croquis – est un langage commun aux trois disciplines : architecture, génie civil et sciences de la vie. Dans le cadre de ce travail, il a deux fonctions principales. Sur le plan architectural, il donne une dimension plus sensible et esthétique à ce

[21] Constat observé par les équipes habitat Ceebios lors des accompagnement de projets menés en phase concours

[22] Le domaine des eukaryotes inclus les 5 règnes suivants : animal, végétal, champignon, protistes, bactéries. Voir chapitre 2.

travail essentiellement focalisé sur des phénomènes physiques et biologiques quantifiables. D'un point de vue recherche et apprentissage, le dessin favorise l'observation et donc la compréhension. Il a été utilisé tout au long de ce travail comme outil d'apprentissage et communication.

Explorer, participer, enseigner, interviewer

Dans la même démarche que le tour du monde du biomimétisme en architecture en 2015, ce travail se base sur de nombreuses interactions avec des chercheurs et praticiens via les écosystèmes de partenaires du MNHN et Ceebios. Au-delà des publications, les échanges en face-à-face et collaborations en présentiel ont joué un rôle clé dans le développement de doctorat. J'ai en particulier mené 3 semaines d'interviews et d'observations grâce à la bourse de recherche Transhumance du MNHN et de l'Ecole Doctorale ED 227, au sein du laboratoire ITKE de l'Université de Stuttgart. En collaboration avec ICD - Institute for Computational Design - ce laboratoire a jusque-là construit près d'une vingtaine de pavillons biomimétiques débouchant sur la création de start-up telles que FibR. Leur vision, méthode de recherche et d'enseignements ont apporté un éclairage important à cette recherche. Les résultats de ces échanges ont majoritairement alimenté le chapitre 2 et la discussion.

Dans la même lignée, j'ai effectué 4 semaines de bénévolat[23] sur le terrain en fin de 1ère année de thèse au sein du CIRAD de l'île de la Réunion. Pour développer une compréhension plus profonde de la recherche fondamentale en biologie en complément de l'environnement de la thèse, il était essentiel d'expérimenter les différents temps d'une recherche, soit de la collecte de données sur le terrain et leur traitement puis analyse en laboratoire.

Dans le cadre de mes missions au Ceebios, j'ai a également pu créer et enseigner le premier module français de 35 heures de cours sur les enveloppes bio-inspirées dans le cadre d'un séminaire de Master sur les enveloppes bio-inspirées à l'Ecole d'architecture ENSA Paris Val de Seine en partenariat avec le promoteur Immobilier ICADE. En collaboration avec les enseignants, j'ai accompagné les étudiants à la conception d'enveloppes bio-inspiré du stade du concept jusqu'à la modélisation numérique. Les résultats sont présentés et discuté au chapitre 5. Ces temps d'enseignement ont permis de tester les outils en cours de développement dans le cadre de la thèse et leur version aboutie est présentée au chapitre 3 BioMatrix.

Faciliter la sélection des modèles biologiques dans la pratique

Cette recherche propose des outils pour faciliter la sélection puis combinaison de plusieurs modèles biologiques lors des phases d'esquisse architecturale. En développant une manière d'explorer les connaissances existantes en biologie par rapport à un problème multicritères, elle permet aux concepteurs de développer une compréhension systémique des organismes biologiques, au-delà de leurs

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[23] Identification de l'impact d'un ravageur – le psylle (*Acizzia uncatoides*) – sur les tamarins des Hauts (*Acacia heterophylla*) de l'île de la réunion au CIRAD. La mission consistait à collecter des échantillons d'insectes sur le terrain et les analyser en laboratoire - https://umr-pvbmt.cirad.fr/principaux-projets/creme

performances ‘exceptionnelles’ qui rendent certains organismes si ‘célèbres’ auprès du grand public et des concepteurs. En s’appuyant sur le retour d’expérience de l’accompagnement de projets du Ceebios pour intégrer le biomimétisme, cette thèse met en lumière les principales difficultés rencontrées lors de la conception et propose des outils et recommandation pour la pratique architecturale.

Remerciements

Cette thèse est le résultat de trois années d'études passionnées en collaboration avec une grande diversité de praticiens issus du secteur de la construction - agences d'architecture, bureau d'études, fabricants de matériaux, promoteurs, construction - et de la recherche fondamentale et appliquée en biologie, génie civil, architecture et bien sûr en biomimétisme.

Je la considère avant tout comme le résultat d'un travail collectif, proposant un point de vue sur l'avancement actuel de la recherche en enveloppes bâties bio-inspirées en 2022. Être à l'interface entre différents champs d'études est une démarche complexe et collaborative qui requière un temps considérable afin de comprendre des champs disciplinaires qui ne sont initialement pas les nôtres, pour ensuite bâtir des convergences entre les disciplines. Une seule personne ne peut détenir de manière approfondie l'ensemble des connaissances mobilisées dans le cadre de cette recherche.

Je souhaite donc exprimer ici toute ma gratitude aux chercheur.ses, particien.nes et ami.es qui ont participé à ces temps d'échanges, de relecture, d'accompagnement et partage. En cette période de *Great acceleration*[24], donner de son temps est un précieux cadeau ! Chaque personne ayant directement contribué est accréditée en début de chaque chapitre. J'espère avoir pensé à tout le monde !

Sur un plan plus personnel, ce doctorat est passé par tous les stades émotionnels ; l'euphorie parce qu'un modèle statistique fonctionne et fait (enfin !) apparaitre des corrélations, la fascination parce qu'il est vertigineux d'imaginer 1,9 millions d'espèces recensées sur Terre et les infinités de possibilités de combinaisons architecturales et régénérative pour la construction qu'il pourrait en résulter, mais également des phases de frustration profonde de ne pas pouvoir explorer toutes les pistes envisagées. Aujourd'hui demeure une profonde gratitude pour toutes ces étapes et rencontres !

Jury. Je souhaite remercier Jan Knippers et Olga Speck qui ont accepté d'être rapporteur.trices de cette thèse et poser leur regard de chercheurs biologistes et ingénieurs sur ce travail Je remercie particulièrement Guillaume LeCointre et Christophe Goupil en tant qu'examinateurs et nos échanges ponctuels mais riches durant cette thèse et lors de la soutenance. Un grand merci à Stéphane Blanc et Marc Desmulliez en tant qu'examinateurs de ce travail de thèse, vos regards croisés lors de la soutenance permettront d'enrichir la suite de ce travail.

[24] The trajectory of the Anthropocene : the great acceleration (2015), W. Steffen

Encadrement pédagogique. Toute ma reconnaissance va à mes deux exceptionnelles directrices de thèse - Kalina Raskin et Fabienne Aujard – qui m'ont accordée toute leur confiance par une grande autonomie dans mes directions de recherche, mais aussi écoute et soutien à tous les stades du doctorat. Votre confiance, encadrement bienveillant et encouragements m'ont aidée à franchir de nombreux caps durant ces trois années. J'ai beaucoup aimé votre encadrement pédagogique car il était complémentaire tout comme vos apports techniques et scientifiques. 1.000 mercis pour cette belle étape de vie franchie !

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English scientific writing
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Nicolas Raulin (EHESS)

Key concepts

bioinspiration
biomimetics, biomimicry
multi-regulation
multi-criteria
biological envelopes
building skins
interview, drawing
research collaboration

Introduction

Chapter 1

Summary

Chapter 1 first presents the motivations of this PhD thesis in the light of current biomimetic developments across architecture and design methods. To assess the research context, the first part introduces key concepts in bioinspiration, provides an overview of nature-based architecture with a focus in the industrial age, and then presents the concept of 'envelope' in both biology and architecture. The two following sections introduce the main research objectives based on current limitations and challenges for the design of multi-functional building envelopes. The fourth section describes the methodology by presenting the research environment, the groups of taxa studied within the 1.7 million described living organisms, and the drawing and interviews' place throughout this dissertation. The last section outlines the research question and outlines.

1.

Table of contents

1.1. Motivation

1.1.1. Bioinspiration in 2020

Definition. 'Biomimetics', 'biomimicry' or 'bioinspiration', defined as the transfer of strategies from biology to technology, is an growing research area between Life Sciences and Design Sciences [1], [2]. 'Biomimicry' refers to a "*philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development*", while biomimetics refers to an "*interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution*" according to ISO 2015:18458 [2]. The only significant difference between 'biomimetics' and 'biomimicry' is that approach referring to the latter intend it to be specifically focused on developing sustainable solutions, the former does not have to fit that requirement. This chapter mostly uses the term 'bioinspiration' - *creative approach based on the observation of biological systems* – since its both includes 'biomimetics' and 'biomimicry'.

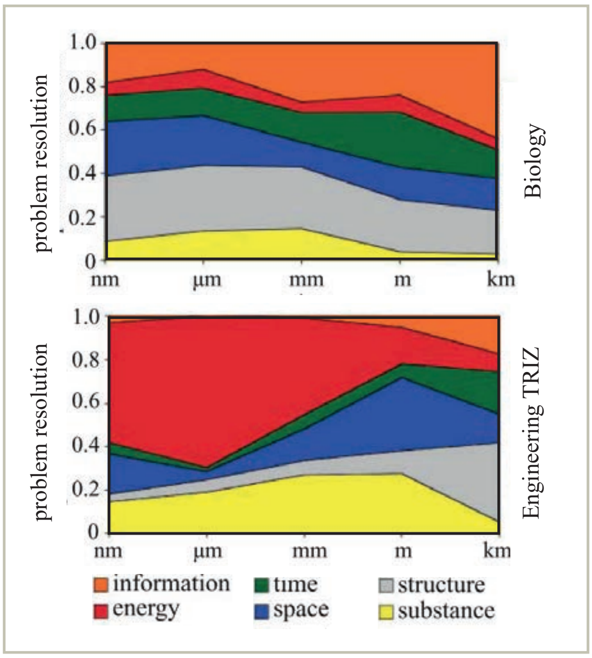
Why bioinspiration now? Studies of natural systems have long been sources of inspiration in design, from Leonardo da Vinci's sketchbooks to Antoni Gaudi's Sagrada Familia [1], [3, p. 5]. Today, interest in natural systems beyond aesthetic inspiration has been strengthened by the combination of environmental awareness and advances in technologies that have allowed us to understand life from the cellular to ecosystemic levels [4], [5]. IPCC[25] and IPBES[26] have demonstrated *Homo sapiens'* dramatic impact on climate change and biodiversity, unlike any other species. This dichotomy is glaring since our activities emit high rate of carbon dioxide, consume large amounts of energy, use natural resources to transform them into waste with long time of degradation. Biologists have outlined that living systems perform the same with little amount of energy for the benefit of degradable and local materials, matter structuration and considerable exchange of information (see **Fig. 1.1**) [6]. Human societies must design restorative[27] artefacts by achieving 'radical increases in resource efficiency, shifting from a fossil-fuel economy to a solar economy and reach completely closed-loop model in which all resources are stewarded in cycles' as supported by M. Pawlyn [3], [7].

In addition to environmental impact, this cross-cutting approach is poised to play a major part in efforts to solve systemic problems related to health, energy efficiency, transports, food security, and creating economic and social value [8], [9]. Indeed, bioinspiration has spread over all research fields, from chemistry, molecular biology, materials [10]–[13] to architecture [3], [14]–[17] over the past decades (see **Fig. 1.2**). From an economic perspective, the global bioinspired technology market is expected to reach \$18.50 billion by 2028 according to [9]. The development of bioinspired innovation may also create more than 2 million new jobs by 2030, where the building sector will provide a quarter of them (See **Fig. 1.3**) [18]. Mimicking living systems' strategies that has benefitted from a '3.8-billion-year research and development period' will help reveal many of the solutions that humans need.

[25] https://www.ipcc.ch/

[26] https://www.ipbes.net/

[27] Beyond the concepts of 'sustainability', 'carbon reduction' or 'circular economy', 'restorative' design restore social, and ecological systems to maintain a healthy state [109, p. 8].



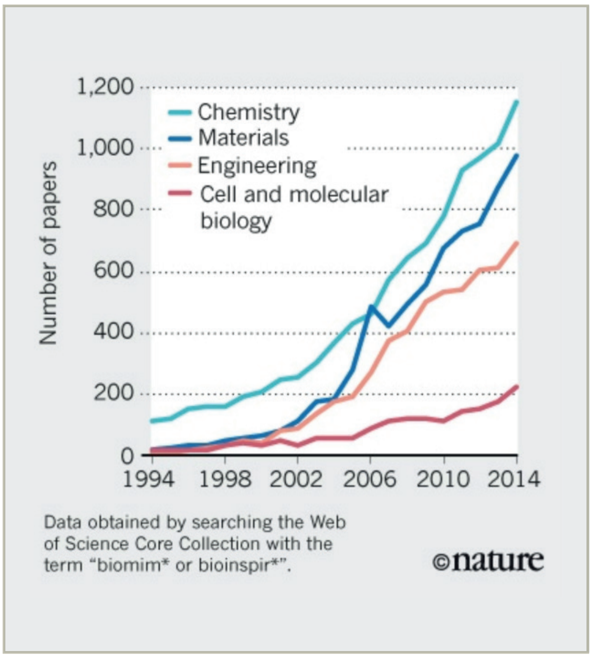


Figure 1.1. **Main differences between living systems and engineer problem solving**

This figure illustrates Engineering TRIZ* solutions and biological effects arranged according to size/hierarchy. Engineering problem solving mostly remain on 'energy' and 'substance', while living systems are mostly based on 'information and 'structure'. Credit: © J. Vincent [6].

Figure 1.2. **Trends in biomimetics: chemistry, material, engineering, cell, molecular biology**

Studies are mainly restricted to physical and Life Sciences. Design Sciences are not represented yet. Credit: © Nature [13].

* TRIZ - Theory of Inventive Problem Solving developed 50 years ago in Russia.

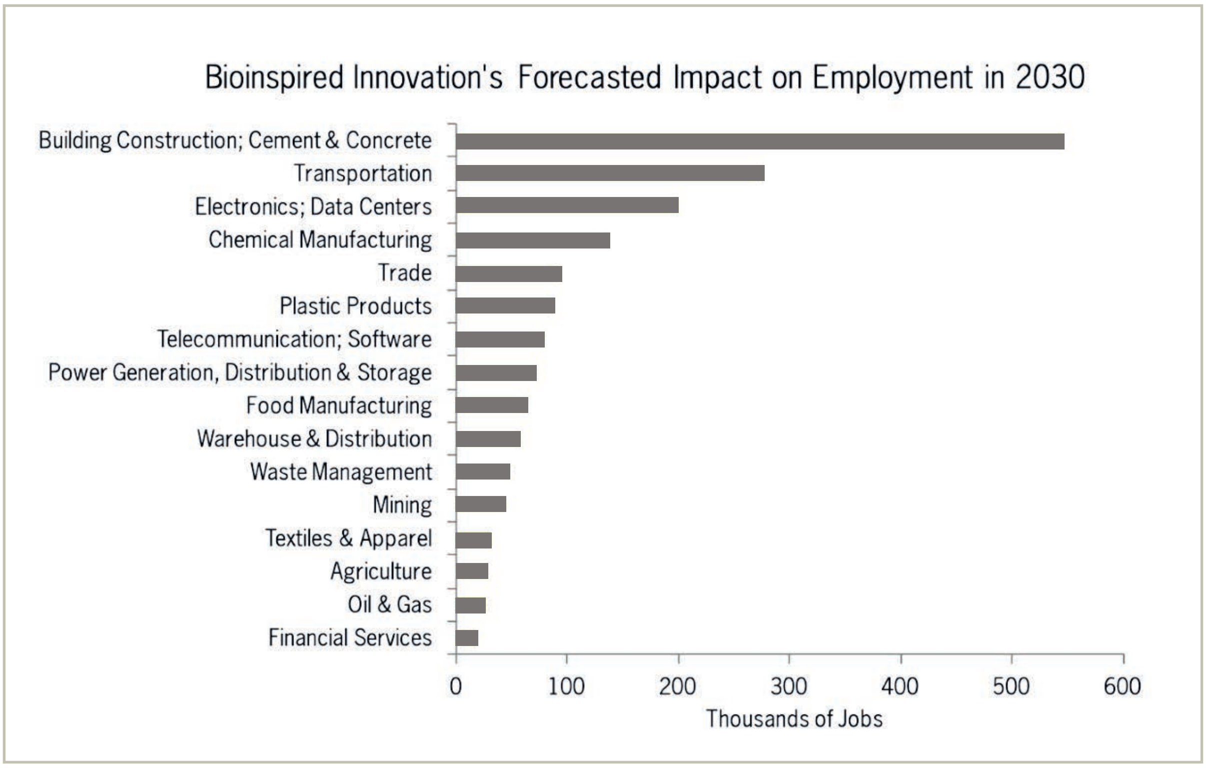


Figure 1.3. **Bioinspired Innovation's Forecasted Impact on Employment in 2030.** The development of bioinspired innovation is expected to create more than 2 million new jobs by 2030. A quarter of them belong to the building sector. Credit: Copyrights FBEI - Fermanian Business & Economic Institute [18].

1.1.2. A brief history of bioinspired architecture

Nature-based architecture before the XX century. Throughout history, architects have looked to nature for inspiration from building forms to decoration. On one hand, Nature has been used as an aesthetic sourcebook as outlined by various architectural styles such as ‘biomorphism’ and ‘Art Nouveau’ that mimic organic shapes, textures or patterns. On the other hand, architectural styles such as ‘vernacular’, ‘bioclimatic’, ‘ecological’ and ‘solar design’, have also been nature-based design since the building is adapted to environmental conditions and locally available resources. These styles can be grouped under the terms ‘organic architecture’ or ‘biophilic architecture’ which promotes harmony between human habitation and the natural world [19]. Regardless to the period, architects have thus ensured a strong link between Nature and architecture [3], [20] (see **Fig. 1.4**).

From fossil-fuel based architecture to regenerative design. Access to cheap energy since the Industrial Revolution has changed our relationship to the natural environment. The whole building lifecycle was impacted due to the development of new materials and technical systems. For instance, the development of highly resistant materials such as concrete or steel, has resulted in the increase of buildings’ height and reduction wall thickness. Likewise, heating and cooling systems based on cheap fossil-fuel energy has allowed buildings to achieve high thermal comfort.

However, since the seventies, scientists have promoted to shift from the industrial age to the ecological age of humankind [21]–[23]. The whole building lifecycle - from material extraction to the building maintenance - has a large negative effect on the Earth system [24]. Focusing on energy consumption, the building sector is one of the largest energy end-use sectors in many developed countries. For instance, buildings - both residential and commercial - account for about 40% and 37% of the global energy consumption in USA and the European Union [25]. A large proportion of this energy is used for thermal comfort in buildings. As a result, the building sector contributes over 30% of the CO_2 emissions, which for instance contributes to the exceeding of planetary limits [26] (see **Fig. 1.5.A**).

In the XXI century, more than half of all humans reside in urban areas, a figure predicted to rise to 60% by 2030 [27]. Consequently, new buildings must be developed to reverse the effects of climate change, increase the strength of natural systems and create a circular - carbon positive built environment that supports inhabitant’s wellbeing [28]. But most of the current buildings have been built in the Industrial Age when energy optimization was not the main concern. For instance, the majority of the current European residential building stock was built during the 1940s-1970s, and is of a low standard, especially with regard to energy performance [29]. The potential for retrofitting existing housing stock in terms of energy saving, reducing CO_2 emissions, human and ecosystems well-being is high. Both building facades and internal regulation systems – e.g. heating, cooling and ventilation – play a key role in the energy consumption of the building. The improvement of the envelope (additional roof insulation, additional facade insulation, and new sealing to reduce ventilation) yielded a significant potential for environmental improvement [30] (see **Fig. 1.5.B**).

Several research focus on the development of efficient building facades such as the COST Action Adaptive Façade Network [31]. Similarly, efforts to design restorative buildings stimulated by the European research projects such as the COST Action Restore, certification such as the Living Building Challenge are now being undertaken to reduce humans’ pressure on ecosystems [28], [32] (see **Fig. 1.5.C**).

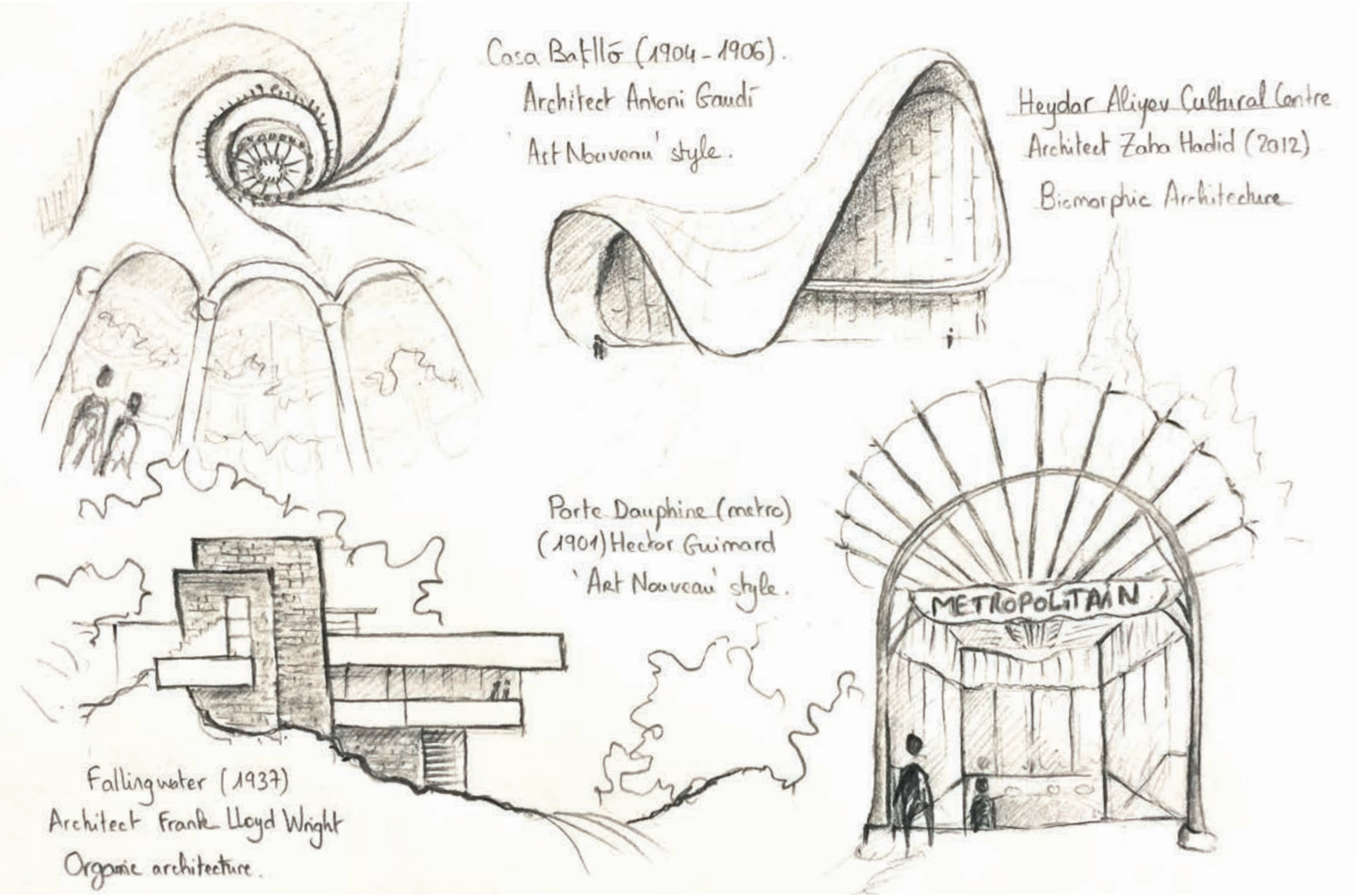


Figure 1.4. Nature-based architecture before the XX century. 'Biomorphism' and 'Art Nouveau' architectural styles mimic organic shapes, textures or patterns. Hand-drawn sketches. Credit: CC BY-SA-NC 4.0 Estelle Cruz

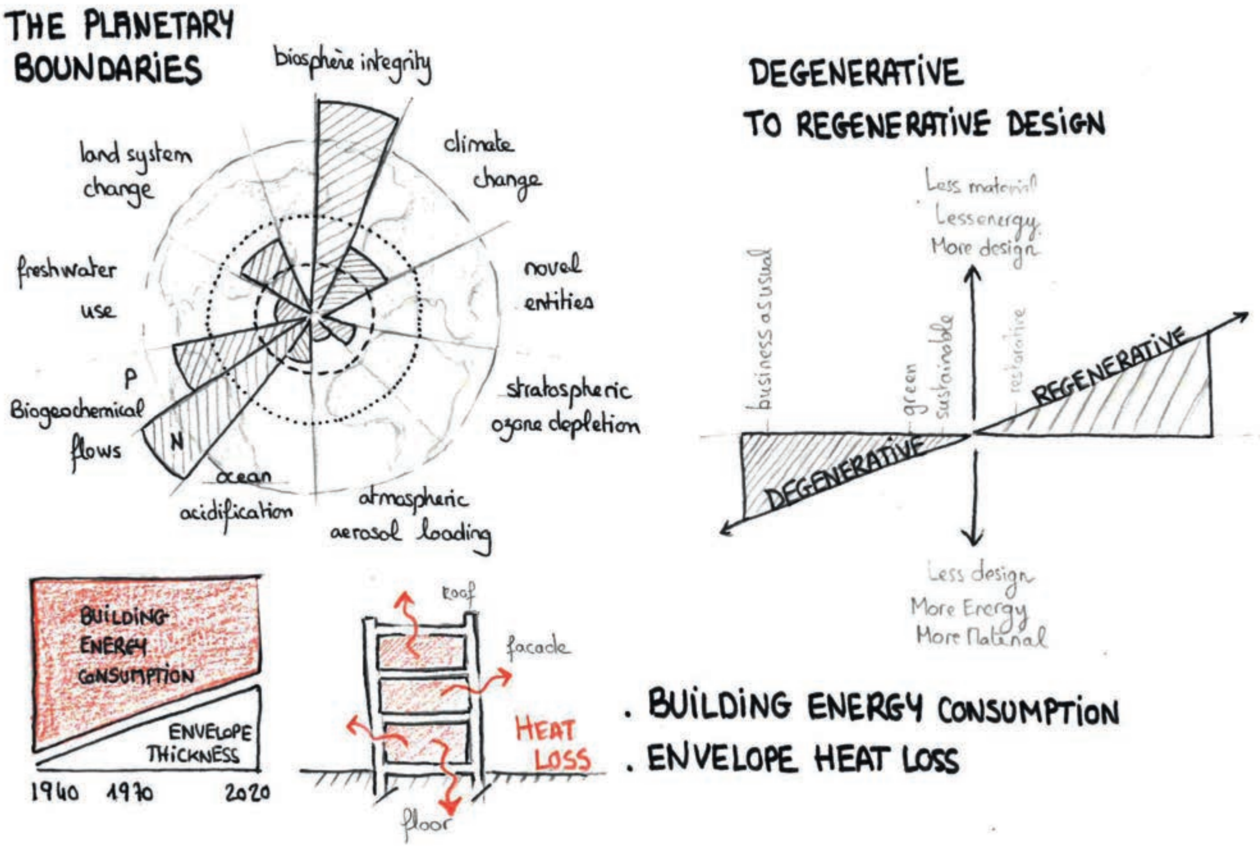


Figure 1.5. From fossil-fuel based architecture to regenerative design.

A. The planetary boundaries. Set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come. Credit: reproduced from [26]. **B. Envelope heat loss and building energy consumption,** sketches. Credit: CC BY-SA 4.0 Estelle Cruz. **C. Degenerative to regenerative design.** Credit: adapted from [28] [107].

The Hype Cycle of bioinspired architecture. Interest in biomimetic architecture increased throughout the nineties within a global context of energy transition and the development of iconic buildings such as the West German Pavilion designed by Frei Otto in 1967. Its development can be understood through the Hype Cycle as follows (see **Fig. 1.6.** adapted from [33] and information from various sources: [34]–[40]).

In the nineties, some iconic biomimetics success stories like the Eastgate building (1996) and self-cleaning hydrophobic surfaces relying on the 'Lotus effect' (1976) were developed. All emerged from a 'biology push'[28] approach in which a biological property is observed then transferred to solve a technical problem [2]. Nowadays, most of the biomimetic innovations result from this approach [41], [42]. In fact, methodological obstacles are primarily related to biological data where the access, understanding and selection remain the main challenges [43]–[46]. Despite the growing interest of the public, the media as well as academic and industrial actors, these barriers resulted in a 'peak of inflated expectations' followed by a 'phase of disillusionment' since today products' or buildings' development follow the biomimetic 'technology pull'[29] design process. At that time, methods and tools were not mature yet to facilitate this process, and biomimetic designs emerge from designers', architects', or researchers' own initiative. This awareness of the issues related to biomimetic application in architecture corresponds to the 'disillusion phase'.

Twenty years later, the ISO TC 266 and especially the ISO 2015:18458 Standard allowed an international formalization of the semantics associated to biological knowledge transfer, main steps, and defined criteria to classify biobased approaches. Furthermore, over 18 'technology pull' processes and 43 methods and tools have been developed for this purpose such and a 'unified technology pull biomimetic process' has been proposed by Fayemi et al, 2017 (2012) [2], [47]–[49]. Some tools were specifically proposed to support designers in applying biomimetic in architecture, such as BioGen developed by Lidia Badarnah (2012) [50].

In parallel, the development of incubators, research centres and funding programs dedicated to the development of biomimetics including architectural designs – e.g. the Collaborative Research Centre SFB-TRR 141 in Germany (Stuttgart – Tübingen – Freiburg Universities) [51], and the FIT - Freiburg Center for Interactive Materials and Bioinspired Technologies (University of Freiburg) [52], the Bio-inspired Material National Centre of Competence in Research in Switzerland (Fribourg University) [53] - have highly contributed to overcome the 'disillusion phases' then reach the current 'slope of enlightenment'. Indeed, the discipline of biomimetic in architecture has grown substantially. There has been an enormous surge of interest during the past twenty years due to the simultaneous development of biomimetic architecture in research, education and architectural practice [3], [7].

[28] 'Biology push' biomimetic design process – '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', according to ISO standard 2015:18458 [2], see chapter 2.

[29] 'Technology pull' biomimetic design process – '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', [2], see chapter 2.

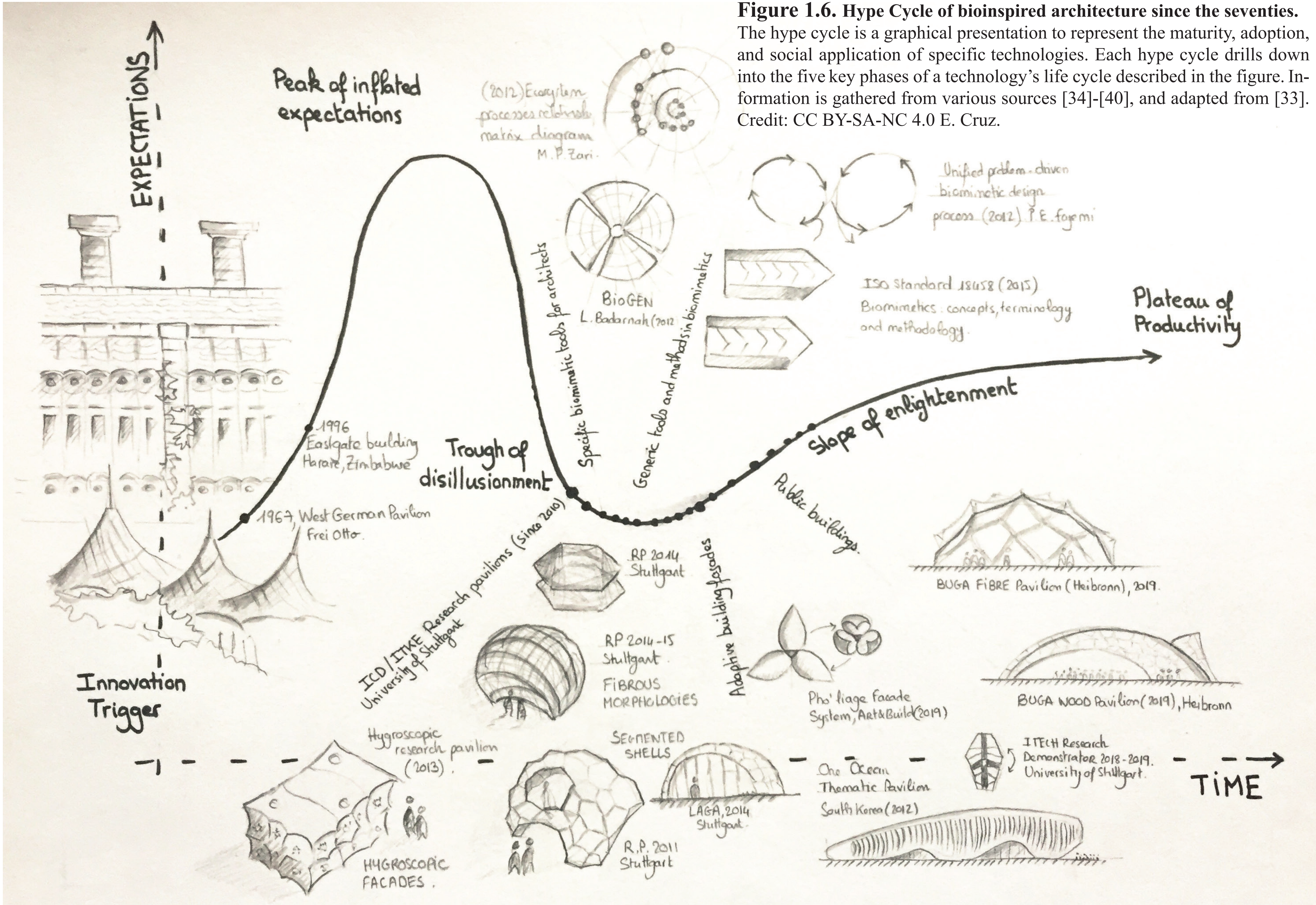


Figure 1.6. **Hype Cycle of bioinspired architecture since the seventies.** The hype cycle is a graphical presentation to represent the maturity, adoption, and social application of specific technologies. Each hype cycle drills down into the five key phases of a technology's life cycle described in the figure. Information is gathered from various sources [34]-[40], and adapted from [33]. Credit: CC BY-SA-NC 4.0 E. Cruz.

1.1.3. Multi-functional envelopes

Man-made building envelopes. 'Envelope' is a widely used concept in architecture to qualify the roof and the façades considered as the 'humans' third skin' or the 'extended organism' [54], [55]. In fashion, the 'second skin' refers to clothing. Recently, the design of building envelopes has caught the attention of academics and researchers given the importance of external membranes and packaging in all man-made objects from buildings to cars to mobile phones [56].

The building facade is a good example of an envelope. They have counted a wide diversity of colours, thickness, shape and building material across architectural styles (see **Fig. 1.6).** They have adapted over the building requirements - from curtain walls to bearing façade – and comfort – acoustic and thermal insulation, light regulation, etc. Their design must combine environmental, human well-being, technical, aesthetic and financial requirements [57, Ch. 2].

Limiting the scope to technical requirements, building skins are multi-functional systems that requires the control of many aspects such as heat, light, humidity and ventilation, among others [58], [59]. Today, the development of energy efficient building skins represents a major challenge since the facade highly influences the building energy consumption and maintains internal comfort [57, Ch. 1].

Literature reviews have counted more than seventy proof-of-concepts of Bioinspired Building Skins (Bio-BS) designed in the last two decades. The number of case studies across industry and academia is increasing [60]–[65]. However, few of these cases address multi-criteria challenge. Kuru et al. (2019) outlined that only 13,4% of 52 adaptive biomimetic building skins are multi-functional while others only control a single environmental parameter [63]. In addition, Cruz, Hubert et al. (2020) highlighted that 47% of 30 existing biomimetic building skins address one function and 30% address two functions (see chapter 2). When these biomimetic envelopes address more than one function, it is mostly thermal comfort and visual performance, which are linked functions. Very few of them meet contradictory requirements [66]. These designs do not fully explore the potential of life sciences.

Biological envelopes. The concept of the 'envelope', also referred to as the 'membrane', 'skin' or 'interface', can be applied to every living or non-living systems. Acting as a barrier, it filters the flux of matter, information and energy exchanged between the inside and the outside [67]. Shaped by environmental pressures, natural selection and the evolutionary heritage, the bodys of biological organisms adapt to their environment [68], [69]. They can self-adapt their phenotype[30] – e.g. morphology, behaviour, physiology - from days to seasons to maintain their internal environment in a stable state[31] [70, Ch. 20]. This research focuses on self-adaptation, which is a phenomenon at the level of individuals, rather than studying adaptation which refers to a phenomenon at the level of populations.

Limiting the scope to the outmost layers between the body and the surroundings of the living organisms and considering the diversity of species and biomes on Earth, the diversity of biological envelopes is

[30] Phenotype: the realized expression of the genotype; the observable manifestation of a trait (affecting an individual's structure, physiology, or behaviour) that results from the biological activity of the DNA molecules.

[31] This research little integrates the third component of Seilacher's triangle and mainly focus on phenotype adaptation [68]. This point is discussed in the last chapter of this work.

extensive. An insect's exoskeleton, the cuticle of a fungal fruit body or a tree bark all meet the definition of an envelope (See **Fig. 1.7**). These body's' outmost layers exhibit a high level of diversity: skin, exoskeleton, shells, cuticle, fur, feathers, scales [71]. Biological envelopes also provide a wide diversity of functions such as mechanical protection, light and thermal regulation to regulate the environmental stress in which they are exposed. They play a key role in keeping living systems alive [50, Ch. 8].

Animals' skin and associated tissues display multiple functions, principally providing a barrier to water diffusion and physical protection of underlying tissues. Mammals have inherited of thermal adaptations provided by layers of lipid filled cells with low thermal conductivity – e.g. fat and blubber - or by a keratin matrix that traps air - e.g. feathers and hair. The thermal characteristics of these enveloped are derived by a combination of physical structure, where some are dynamic controlled [72]. In addition, mammals' envelopes showed relevant adaptation for water and light regulation. Leaves have also displayed multi-functional properties since they can simultaneously regulate light and heat. Their composition, structure and adaptation behaviour allow them to overcome contradictory requirements by being exposed to strong solar radiation for photosynthesis while maintaining their leave' temperature between a narrow range. In biology, trade-offs - balance achieved between two desirable but incompatible features – are core components of many evolutionary models, particularly those dealing with the evolution of life histories [46], [73].

Towards the development of multi-functional building envelopes. Regulation of environmental aspects such as solar radiation, unwanted substances and other organisms is one of the most important functional aspects linking biological skins and building facades [54]. By analogy with building envelope, several biomimetic buildings [63], [66], and research in architecture [61], [64], [74], [75], have explored biological envelopes. Envelopes of living systems are tissues made of several layers and covers some organs or organ systems of an organism. Similarly, building skins are made of several layers e.g. bearing wall, insulation material, glazing – which covers internal building spaces (see **Fig. 1.8**).

According to [50, p. 3], "the implementation of successful adaptation strategies inspired from nature can result in adaptive building envelopes that *behave* as living organisms that accommodate the dynamic environmental changes". Indeed, if human-made designs are to behave as living systems they will be exposed to multiple environmental factors whilst maintaining the physical properties of their envelopes and stabilizing the internal environment. Both have to meet multi-dimensional challenges[32].

[32] The use of the terms 'challenge', 'strategy' to express biological adaptations is scientifically inaccurate regarding to Darwin's Theory. There is no 'designer' or 'creator' who design living systems to overcome the environmental See section '1.4.3. Linking Life Sciences and Design Sciences – the right level of information' of this chapter.

Figure 1.6. Examples of building envelopes. (a) Glass curtain walls, (b) ETFE envelope, (c) Bearing façade made of concrete and glass (c, d), (e) brick facade, (f) wood clading facade. Credit: Pixabay Licence

Figure 1.7. Examples of biological envelopes. (a) butterfly's wing, (b) scales of fish, (c) bark of tree, (d) plant leaf, (e) lichen, (f) fungi Credit: Pixabay Licence

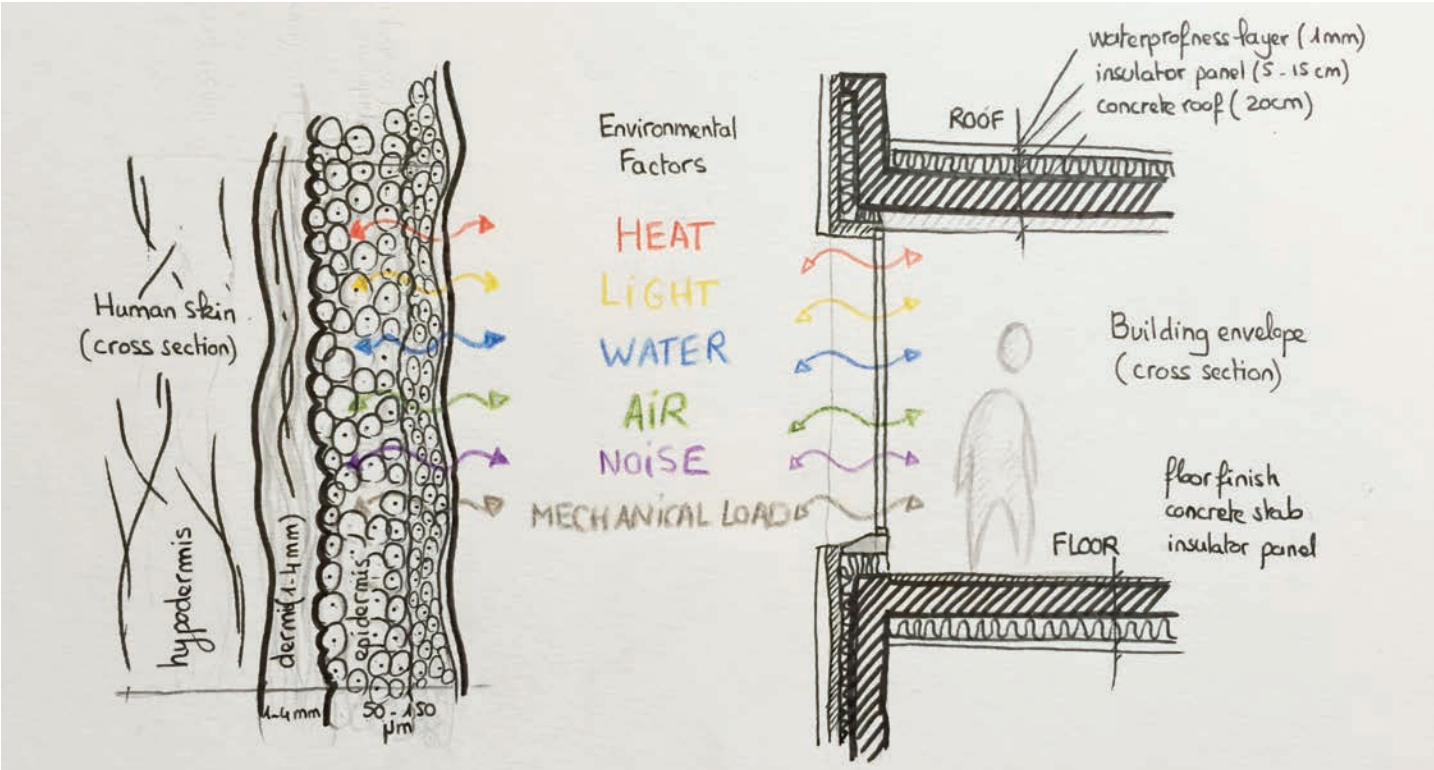


Figure 1.8. Analogy between biological interfaces and buildings envelopes.
Credit: Hand sketches, CC BY-SA-NC 4.0 E. Cruz.

1.2. Current limitation and challenges

Intensifying bioinspiration within architectural practice. Despite bioinspiration in architecture seems to reach the 'slope of enlightenment' of the Hype cycle, the approach is not widespread yet. Indeed, less than a hundred bioinspired buildings have been built over the past decade as reviewed by [3], [63], [66], [76], [77], while more than 400.000 housing units are for instance built per year in France [78]. Similarly, none of the worldwide under-graduated architecture programmes have placed bioinspiration as a central topic within the architectural practice; the approach has mostly been integrated within short-term theoretical courses [54], [79]–[83]. Basic and applied research have followed the same vein and bioinspiration is mostly integrated as a small part of research programs excepted for the Collaborative Research Centre SFB-TRR 141 in Germany (Stuttgart – Tübingen – Freiburg Universities), where biomimetics was embedded in all research areas [51].

Facilitating access to biological knowledge and the knowledge of theory of biology to design multi-functional envelopes. Although the research is progressing, the development of biomimetics 'technology push' methods and tools remains the main challenge [84]. Recent research assumed that the lack of a clear design method in architecture has limited the development of biomimetic within practice. Indeed, while generic biomimetic methods and tools have been developed, few of them are specific to architecture [48], [85].

In addition, current research and case studies have underlined certain limitations especially for the design phases related to biology [41], [42]. Recent studies have suggested that biomimetics systems are often inspired by one property of a biological system rather than a combination of biological principles [66], [86]. However, the selection of the biological models then abstraction are the key phases in order to develop successful biomimetic systems [42]. Wanieck et al. (2016) reviewed that most of the analysed biomimetic tools - 33% (25 out of 75) - were focusing on the design step 4 'identification of potential biological models' of a technology pull biomimetic approach, while other tools are distributed over the other eight steps [48]. Likewise, Chirazi et al (2019), outlined that the main challenges of biomimetic development remain phases of knowledge transfer from biology to technology [42].

Beyond mono-regulation, towards multi-regulation. Literature reviews have counted more than seventy proof-of-concepts of bioinspired building skins designed in the last two decades [63], [66]. The number of case studies across industry and academia is increasing [60]–[64], [87]. However, few of these cases address multi-criteria challenge, and most are inspired by a single function of one biological system according to [66]. These designs do not fully explore the potential of life sciences since biological data is not organized using the same criteria as those of the design sciences. If human-made designs are to behave as living systems, they will be exposed to multiple environmental factors whilst maintaining the physical properties of their envelopes and stabilizing the internal environment. Both have to meet multi-dimensional challenges[33].

1.3. Main objectives

The main objectives of this PhD are:

(a) To enhance the integration of biomimetics in the building design phases towards the **development of multi-functional building envelopes**.

(b) To introduce **a set of tools** to provide guidance for the selection and then the combination of biological systems strategies when designing a multi-functional biomimetic building envelope.

(c) To **strengthen the link** between basic research within the field of biology and architectural applications.

These developments aim to help architects, engineers, and biologists to intensify multi-criteria analysis of biological systems, and then co-design multi-functional building envelopes. Since architecture is both a creative and technical domain, these developments aim to provide a structured approach whilst allowing creativity.

The technological transfer, numerical modelling, and performances assessment are beyond the scope of this work since this is currently being investigated within the framework of another PhD thesis across research and practice, and in collaboration with the author[34].

This research is part of a wider French and European campaign to increase the development of biomimetics as carried out by Biomimicry Europa early 2000, then by the Ceebios – French Network in Biomimetics – since its creation in 2015 in partnership with the Museum of Natural History of Paris since 2019 [88], and other interested parties [89].

1.4. Approach and methodology

The research context has played a key role to achieve the main objectives of this PhD thesis. Interdisciplinarity, field survey, research collaborations and researching by drawing were at the heart of the research.

1.4.1. Research environment

This dissertation results from an ongoing discussion between the fields of Life Sciences and Design Sciences. Researches were thus undertaken simultaneously in two respective institutions: Ceebios and the lab Mecadev of the National Museum of Natural History of Paris.

[33] Scientifically inaccurate regarding the theory of evolution. Living systems are selected according to random variations and environmental pressure. There is no "designer" or “creator” in this selection process. Evolution is the result of random variations or adaptations of the environment [106], [110].

[34] In 1.4. Approach and methodology see section ‘Collaboration’.

Ceebios. Firstly, Ceebios is the French network and centre of expertise bringing together biomimetic practitioners and theoreticians with the aim of implementing biomimetics in R&D strategies and increasing innovation whilst supporting ecological transition [90]. This PhD thesis across research and practice was fuelled by the missions carried out by the author in Ceebios' architecture department. Working alongside practitioners such as architects, engineering consultants and territorial collectivity, Ceebios aims to enhance biomimetics within architectural and urban practices. This research has for instance benefited from the collaboration between Ceebios and the marine biomimetic centre of Biarritz in France [91], the involvement in the architectural design competition IMGP2 - Inventing the Greater Paris Metropolis [92] – that will result in the construction of Ecotone a 82.000 sqm real estate bioinspired project [93], [94], and the development of students' architectural competitions for the development of biomimetic envelopes in partnership with the building constructor ICADE and the architectural school ENSA Paris Val de Seine [79], [80].

Mecadev, MNHN. Secondly, Mecadev UMR 7179 - Adaptive Mechanisms & Evolution - specializes in the biology of integrated systems, the evolution of biodiversity, and the biology of conservation. This research covers a wide range of topics supported by a high diversity of multi-cellular biological systems within the domain of Eucaryotes, e.g. worms, elephants, primates, plants, insects [95]. While some labs are highly specialized in some living systems - e.g. unicellular, multicellular – or biomes – e.g. marine, terrestrial, polar, etc. - the Mecadev is one of the labs of the National Museum of Natural History of Paris which covers a wide diversity of living systems across kingdoms and biomes.

Since this PhD thesis aims to provide guidance for the selection, abstraction, and then combination of living systems' strategies across kingdoms, the Mecadev was identified as the most adapted lab to carry out this research.

Bioinspire-Museum program. In 2019, with funding from the French Ministry of Environment, the French Natural History Museum (MNHN) launched Bioinspire-Museum to coordinate and promote Bioinspiration across the full breadth of its activities [96]. In this context, this research has also been enriched by events and r1esources produced within that program.

Collaborations. In addition to the two formal institutions, this PhD thesis was carried out in collaboration with three main other institutions researching in multi-functional biomimetic envelopes – University of West England, NOBATEK/INEF4 and I2M - and in systemic biomimetic design methods – IFS, Institute of Desirable Futures.

Applied to architecture, several works aim to overcome these current design method limitations for the development of biomimetic and multi-functional building envelopes as reviewed by [76], [97]. For this purpose, these four following PhD-researches have been conducted since 2008:

- 2008-2012: 'Biomimetics for the building envelopes: towards the living envelopes', University of TU Delft, by Lidia Badarnah [59]
- 2014-2017: 'Living architectural envelopes that interact with their surroundings. Naturally designing', by Marlen Lopez Fernandez [98]
- 2016-2020: 'Biomimetic adaptive building skins for thermal comfort: an approach towards multifunctionality', University of Sydney, by Aysu Kuru [99]

- 2017-2021, ‘Multi-criteria characterization of biological interfaces: towards the development of biomimetic building envelopes’, by Estelle Cruz
- 2019-2022, ‘Designing of bioinspired building envelopes', by Tessa Hubert (ongoing) [100].

Such work continues in a manner complementary to the work of Lidia Badarnah. Indeed, multi-regulation across biomimetic and architectural practice is a wide and un-fully explored research field. In order to align this research with current industrial and research developments, this PhD thesis has benefited from collaborations with Lidia Badarnah and Tessa Hubert.

Similarly, the author has benefited from Tarik Chekchak’ knowledge – head of the biomimetic department of IFS – which has developed 4 –day - professional training in biomimetics based on the ‘unified problem driven biomimetic design process’ in partnership with the MNHN and Ceebios [47]. The development of the BioMatrix in chapter 3 and patterns in chapter 4 resulted of discussions over the last three years.

1.4.2. Data collection

Aligned with the research method of the World Tour of Biomimetics[35] [101], this PhD thesis is based on both literature review and interviews. They are mostly face-to-face formal and informal interviews with researchers and practitioners from both life sciences and design sciences.

Formal interviews. They were carried out to assess the biomimetic design process of thirty existing biomimetic building envelopes (Bio-BS). Data was gathered throughout interviews of the designers, architects and engineers involved in the design of the Bio-BS and has resulted in the publication of thirty datasheets[36]. Half of the interviews were conducted during a 3-weeks research period with Tessa Hubert at the lab ITKE – Institute of Building Structures and Structural Design - at the University of Stuttgart in 2019. Interviews’ outcomes are presented in chapter 2.

Unformal interviews. The research has also been enriched by many informal face-to-face interviews carried out throughout the last three years. They had different purpose: helping the author to understand biological key concepts and exchanging research ideas. Novel and unpublished research ideas resulting from these discussions are credited with the mention ‘personal conversion with name, institution, date’, and the author's agreement.

Since the research strongly relies on both formal and information interviews, the author has exchanged with more than 130 researchers and practitioners. Their specific contributions are both credited at the beginning of each chapter in the ‘Credits’ and in the ‘Acknowledgements’ sections at the beginning of the PhD.

[35] See section Foreword.

[36] Under review process. See section Publication.

1.4.3. Linking the life sciences and design sciences

Language. Being at the interface of two disciplines requires to adapt languages, methods, and level of information. Since there is not yet scientific consensus on the language to use in biomimetics [102], [103], this research avoid field-specific vocabulary. The concepts and vocabulary of physics provide quantitative and qualitative data to link the life sciences and design sciences. The vernacular and scientific Latin names are used to describe the taxa, e.g. human (vernacular) *Homo Sapiens* (Latin).

Towards the 'right' level of information. Likewise, providing the right level of information without altering required scientific precision, is one of the main challenges of this research. Footnotes throughout the thesis provide definitions and additional information while some concept specifically belong to the fields of biology or design. They are presented in a simplified form to allow both biologists and designers – e.g. architects, engineers – to appreciate each concept. Similarly, footnotes mention simplified concepts used to make the reading easier. For instance, the statement 'strategies found in living organisms' is not accurate in the light of the theory of Darwin's original theory[37]. Indeed, the term 'strategy' refers to 'a detailed plan for achieving success in situations such as war, politics, business, industry, or sport, or the skill of planning for such situations' [104]. There is no intention or intervention of a transcendent entity in Natural Selection as supported by the religious belief of creationism [105], [106]. However, this term has been widely used in biomimetics literature. As far as possible, footnotes will thus mention simplifications.

Researching by drawing. Both architects and biologists are familiar with drawing techniques. This media has played a key role in the history of architecture and biology. Drawings perform different functions from communication to learning. In architecture, various graphic conventions such as axonometries, perspectives, elevations, sections, and sketches allow the architect to illustrate a future building. These techniques allow design teams to represent buildings that do not yet physically exist. In biology, drawings represent existing and observable living systems. Graphical representations aim to inform through the description of living systems. To strengthen the link between these two domains, this research displays results and analysis using hand-drawn sketches and diagrams.

[37] 'The two components of Darwin's original theory, namely, the hypothesis of "descent with modification" (the idea of a genealogical nexus of all living beings, in all the immensity of time and space in which they are transformed) and the hypotheses of variation and natural selection (the processes that ultimately explain and largely control evolutionary change for Darwin)' according to [111, p. vii].

1.4.4. Scope of exploration and the Tree of Life

Six environmental aspects. The regulation of these six environmental factors – heat, light, water, air, noise and mechanical loads – frame the research since building envelopes at least requires the control of these six factors [58], [59] (see chapter 2, section 2.3). The 'BioGen' methodology developed by L. Badarnah's only addresses four of these environmental aspects: heat, light, water and air. This methodology provided independent investigations of these aspects rather than an integrative approach. In order to provide a framework for the development of multi-functional building envelopes aligned with previous research development, this research uses the same colours coding for each environmental aspect as developed by L. Badarnah's [50, p. 14] (see **Fig. 1.9** from [37]).

Biological interfaces. By analogy with building façades, this research focuses on the outmost layers of the body of the biological organisms. Indeed, this research does not analyse mucous membranes within bodies such as the lining of the intestine (see **Fig. 1.10** [107]).

Terrestrial eukaryotes. This research focuses on terrestrial multicellular organisms found within the plants (Plantae), animals (Animalia) and fungi (Fungi) kingdoms within the domain of eukaryotes. Indeed, as building envelopes, they are exposed to the same environmental conditions (see chapter 2, section 2.4). It should be noted that the investigation process and the underlying questions that this work establishes do not aim at maximizing knowledge about individual species or living envelope *per se*.

Biological organisms presented throughout this dissertation are outlined in **Figure 1.11**. The figure - The Evogeneao Tree of Life diagram – is a graphical adaptation and simplification of phylogenetic trees in order to explain evolution principles and the concept of mass extinction [108]. Phylogenetic trees show relationships between biological entities. In **Figure 1.11** the representation of archaea and bacteria is not proportional to the number of estimated and described species. This figure over-represents the domain of eukaryotes compared to the two other domains. However, this diagram is used throughout this dissertation in order to provide visual context for the species that illustrate that PhD. This research uses the same colour coding as **Figure 1.11.**

Functions	Heat				Air		Water				Light			
Processes	Gain	Retain	Dissipate	Prevent	Exchange	Move	Gain	Conserve	Transport	Lose	Filter	Illuminate	Harness	
Pinnacles														**Source**
Termite mounds	–	+	+	–	+	+	–	–	–	–	–	–	+	Korb and Linsenmair [68,111]
Prairie-dog burrow	–	–	+	–	+	+	–	–	–	–	–	–	–	Vogel et al. [73], Sheets et al. [112]
Veins/blood vessels	+	+	+	+	+	+	–	–	+	–	–	–	–	Arens and Zhang [113]
Human skin	–	+	+	–	–	–	–	–	–	+	–	–	–	Randall [114,115]
Skink scales	–	–	–	+	–	–	–	+	–	–	+	–	–	Vrcibradic and Rocha [116]
Elephant skin	–	–	+	+	–	–	–	–	–	+	–	–	–	Lillywhite and Stein [100]
Succulent	–	–	+	+	+	–	+	+	+	–	+	–	+	Björn and Govindjee [117]

Figure 1.9. Examples of living systems with multi-function capabilities. The plus symbol (+) denotes the challenges carried out by pinnacles as obtained from the investigation; and the minus symbol (−) denotes that no investigation regarding the specific challenge was carried out, thus it is by no means an indication that the pinnacle is incapable of achieving the challenge. Credit: © L. Badarnah [37].

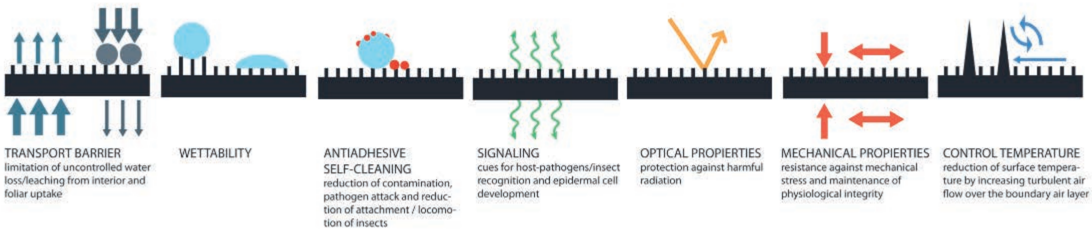


Figure 1.10. Multifunctional properties of the surfaces of plants leaves. Plants are highly functional surfaces that provide water, light, thermal, mechanical and aire regulation. Credit: M. Lopez [105].

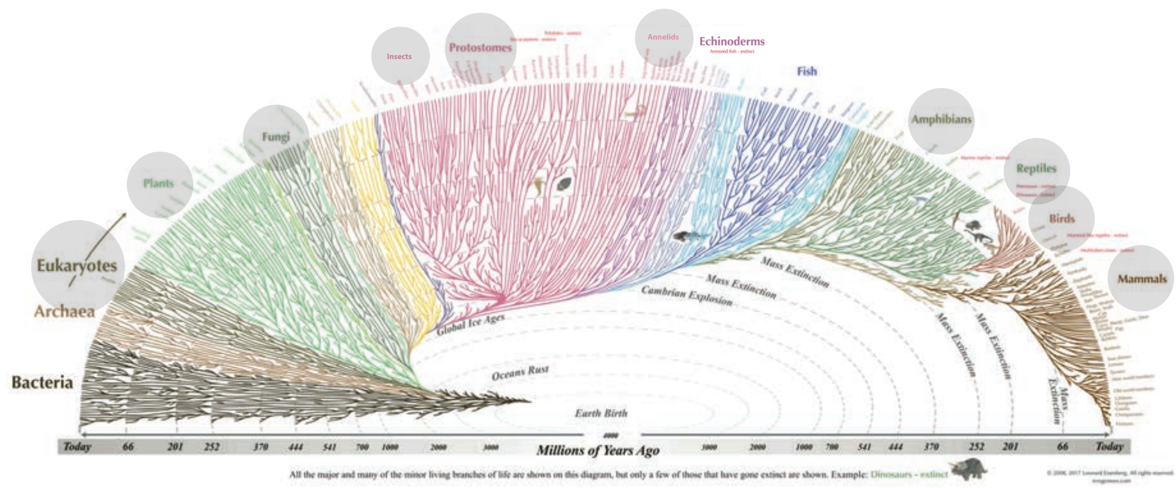


Figure 1.11. Terrestrial living envelopes studies throughout this research. The taxa studied within the research framework are circled in grey. Freshwater and marine animals such as annelids, molluscs, cnidarians and fish are not included in that research. Credits: © evogeneao.com [106].

1.5. Research questions and outlines

The main question addressed in this research is: *How to sort, compare and use biological knowledge to solve multi-criteria challenges in a technology pull biomimetic design process?*

To answer the main research question, the following sub-questions and sub-tasks are addressed in the subsequent chapters. The outlines of this thesis are presented as follow.

Chapter 2. Multi-regulation: a comparative review in biomimetics

In order to identify the main limitations to the development of multi-functional building envelopes, this chapter provides an overview of biomimetic design methods, the multi-regulation performances of biomimetic building skins and the multi-regulation capabilities of biological systems which inspired biomimetic building envelopes. The content of this chapiter is mostly based on two recent studies: *'Biomimetic adaptive building skins: Energy and environmental regulation in buildings'* by Kuru et al. (2019), and '*Design processes of bioinspired building skins: A comparative analysis'* by Cruz, Hubert et al. (2020). The first section compares the multi-regulation performances of thirty building envelopes based on literature review. The second section assesses the biomimetic design process with a focus on design phases related to biology. Data were collected during videoconference or face-to-face interviews. The third section compares the multi-regulation performances of the Bio-BS with the multi-functional performances of the biological model. Last section provides the concluding remarks for further investigations in the next chapters. In order to understand the main merits and limitations to the design of multi-functional building envelopes, the three following research questions are addressed in this chapter:

- How do existing biomimetics building skins meet with multi-function?
- What is the state of the art of current biomimetics methods and tools that can be used to design multi-functional building envelopes?
- How do biological envelopes cope with multi-regulation?

Chapter 3. BioMatrix : a multi-criteria tool to characterize the biological systems

To fill the gap between multi-functional capabilities of living systems and the development of mono-functional building envelopes, chapter 3 introduced a novel tool for a multi-criteria characterization of biological systems. This tool – called the BioMatrix - aims to increase the development of multi-functional biomimetic designs by abstracting several principles of biological systems. This matrix comprises four linked categories: 'Functions of regulation', 'Environment', 'Time' and 'Matter'. The circular representation of the matrix helps users to develop systemic thinking.

The research questions addressed in chapter 3 go as follow:

- What are the key concepts to understand biological systems as complex system?
- How to structure biological knowledge for a convenient access by designers?

Chapter 4. Biological envelopes : multi-criteria characterization

Chapter 4 provides a comparative and multi-criteria analysis of ten type of biological envelopes compared with the entries of the BioMatrix. This chapter synthesizes current knowledge in biological envelopes based on qualitative, and quantitative existing data. The results aim to help the architects to identify relevant biological models to combine according to their challenge(s). Chapter 4 applies the BioMatrix to a sample of terrestrial biological envelopes among the group of eucaryotes. The three following research questions are addressed in this chapter:

- What are the most relevant biological envelopes to regulate heat, light, water, air, noise and mechanical loads?
- What are the multi-regulation capabilities of biological envelopes?
- How to select the 'right' biological model?

Chapter 5. Discussion & Conclusion

The main developments and highlights of this PhD thesis – the BioMatrix, comparative tables and patterns - are concluded and discussed in chapter 5. These contributions have provided several tools to help designers in the initial building design phases during which investigation is undertaken to find relevant biological systems. Biomimetic approach can be integrated at all design steps of a building, from programming to construction administration, however, the approach is not widespread yet, especially over architectural practice. A discussion on the educational, research, design practices and politics brakes that can limit its integration within architectural practice is provided. This section presents a non-exhaustive overview of opportunities to enhance biomimetic illustrated with existing biomimetic buildings, research, and educational programs. The access to biological data was also found as one of the major challenges to enhance the development of biomimetic. This section discusses the strong taxonomic bias found throughout the research, and outlined in chapter 2 and 4. Likewise, a discussion on the lack of both qualitative and qualitative data is provided. Finally, the last section of the chapter discusses ethical aspects since biological data acquisition and biomimetic developments raise ethical question. These questions are discussed in the light of biomimicry's original philosophy, the current context of sustainability in architecture, and ecosystemic services.

1.6. References

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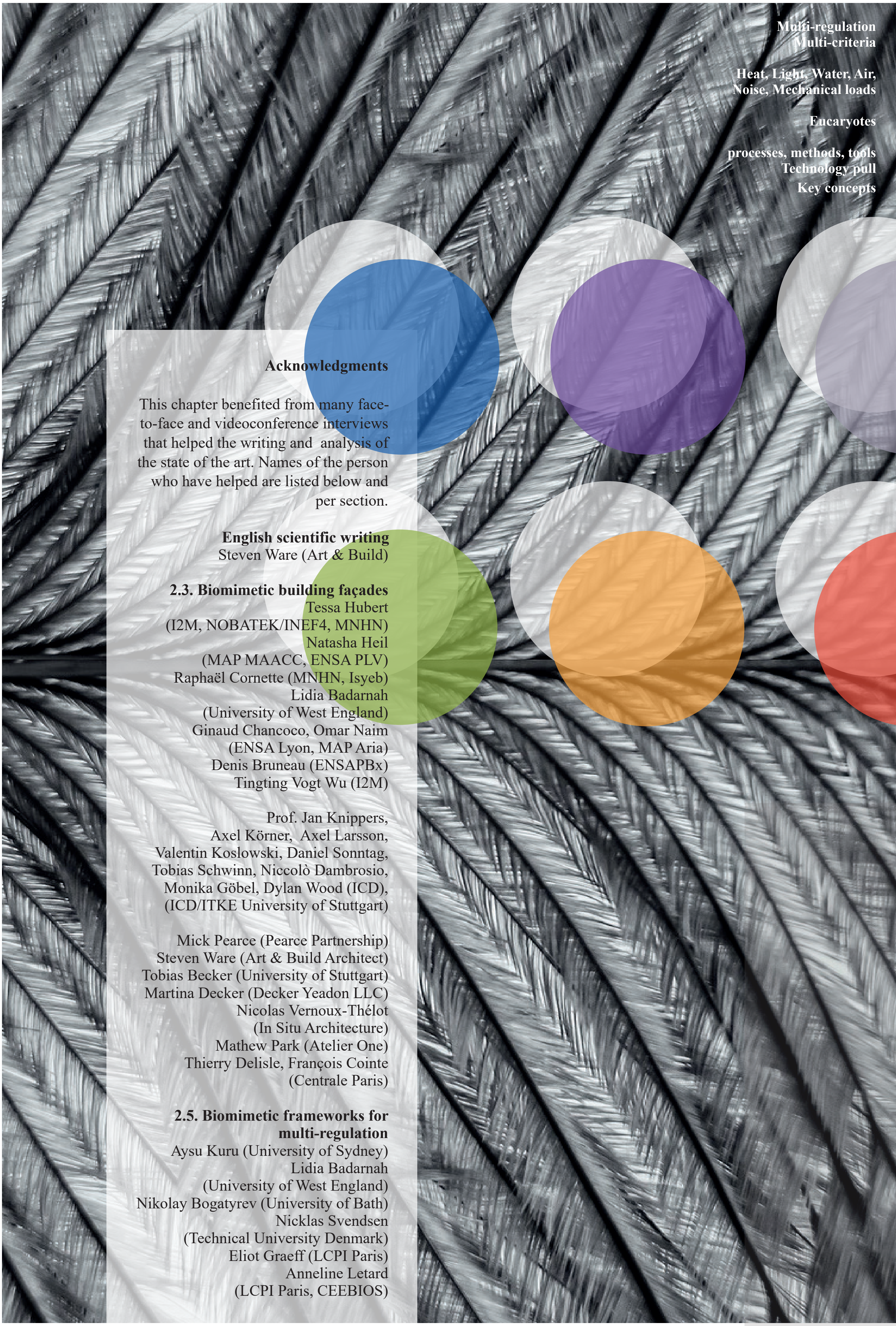

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Multi-regulation

Chapter 2

A comparative review

In order to identify the main limitations to the development of multi-functional building envelopes, this chapter provides an overview of biomimetic design methods, the multi-regulation performances of biomimetic building skins and the multi-regulation capabilities of biological systems which inspired biomimetic building envelopes. The content of this chapter is mostly based on two recent studies: 'Biomimetic adaptive building skins: Energy and environmental regulation in buildings' by Kuru et al. (2019), and 'Design processes of bioinspired building skins: A comparative analysis' by Cruz, Hubert et al. (2020). The first section compares the multi-regulation performances of thirty building envelopes based on literature review. The second section assesses the biomimetic design process with a focus on design phases related to biology. Data were collected during videoconference or face-to-face interviews. The third section compares the multi-regulation performances of the Bio-BS with the multi-functional performances of the biological model. Last section provides the concluding remarks for further investigations in the next chapters.

2.

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2.1. Introduction

2.1.1. Context

As outlined in chapter 1, the design of efficient building envelopes has recently caught the attention of academics and researchers given the importance of reducing building energy demand due to environmental challenges. Acting as a barrier, the envelope is expected to simultaneously filter many environmental factors such as heat, light, water, noise, mechanics stress and air to provide [1]. This multi-functional interface plays a key role in maintaining the building integrity and the occupants' internal comfort.

Despite biomimetic in architecture is not widespread yet[1], literature reviews have counted more than seventy proof-of-concepts of bioinspired building skins (Bio-BS) designed in the last two decades [2]–[5]. However, few of these cases address multi-criteria challenge, and most are inspired by a single function of one biological system according to [4], [5]. In addition, recent research assessed that the difficulty in adopting biomimetic within the architectural practice is due to the lack of clear methods and tools [6], [7].

In order to identify the limitations to the development of multi-functional building envelopes, this chapter provides an overview of the design methods and regulation performances of nineteen existing biomimetic building envelopes (Bio-BS). The content of this chapiter is mostly based on the first author's PhD peer-review published paper. The first section compares the multi-regulation performances of thirty building envelopes based on literature review. The second section assesses the biomimetic design process with a focus on design phases related to biology. Data were collected during videoconference or face-to-face interviews. The third section compares the multi-regulation performances of the Bio-BS with the multi-functional performances of the biological model. Last section provides the concluding remarks for further investigations in the next chapters.

2.1.2. Research questions

In order to understand the main merits and limitations to the design of multi-functional building envelopes, the three following research questions are addressed in this chapter:

- How do existing biomimetics building skins meet with multi-function?
- What is the state of the art of current biomimetics methods and tools that can be used to design multi-functional building envelopes?
- How do biological envelopes cope with multi-regulation?

[1] Less that hundred bioinspired buildings have been built over the past decade, while more than 400.000 housing units are for instance built per year in France [154]. (See Chapter 1, section 1.2. Current limitations and challenges).

2.1.3. Multi-regulation, multi-criteria and complexity

This section first introduces the key concepts of multi-regulation, multi-function, multi-levels, multi-criteria and complexity used throughout this research.

Complexity is a widely used term; it has different meanings according to the discipline, and the context [8]–[10]. From the Latin *complexus*, its means what is woven together. In philosophy, the complex through is a constant discussion between simplicity and complexity where simplicity is "*a short transition between several complexities*", and complexity "*a fabric of heterogeneous constituents inseparably associated: it poses the paradox of the one and the multiple"* [11]. In life sciences: *"Complexity science studies how a large collection of components spontaneously self-organize to exhibit non-trivial global structures and behaviours at larger scales, often without external intervention, central authorities or leaders"* [12].

The concept of 'complexity' encompasses the concept of multi-criteria, which, in turn, covers the concepts of multi-regulation, multi-function and multi-level. In fact, regulation, function, level are parameters which describe the state of a system. Their definitions, antonyms and examples founded in biomimetic literature go as follow in **Table 2.1.**

This research mainly focuses on multi-regulation and multi-function rather than complexity.

Concept	Definition	Examples in biomimetics
Complexity ≠ simplicity	Several definitions (see text above table 2.1).	[9] living systems considered as complex systems
Multi-criteria ≠ mono-criteria	Integrating several criteria	[13] Multi-criteria and trade-off analysis for biomimetic application [14] Development of a biomimetic tool based on multi-criteria requirements
Multi-level ≠ mono-level	Integrating several dimensions	[15] Hierarchy described as a natural design principle in architecture through the concept of multi-level
Multi-function ≠ mono-function	Having several different uses	[4] [16] Evaluation of building skins' multi-functionality [17] Evaluation of multi-functional surface structure of plants, [18], [19] for application in adaptive structure in engineering [20] Evaluation of multi-functional surface structure of animals for adaptive synthetic surfaces [15] [21] Multi-functionality described as a natural design principle [22] methodology to solve multi-functional challenges
Multi-regulation ≠ mono-regulation	Regulation of several factors	[23, Ch. 8] Assessment of living organisms' multi-regulation capabilities for the design of building skins.

Table 2.1. Overview of the main concepts related to complexity in biomimetic literature. Data is gathered from various sources: [4], [9], [21]–[23], [13]–[20].

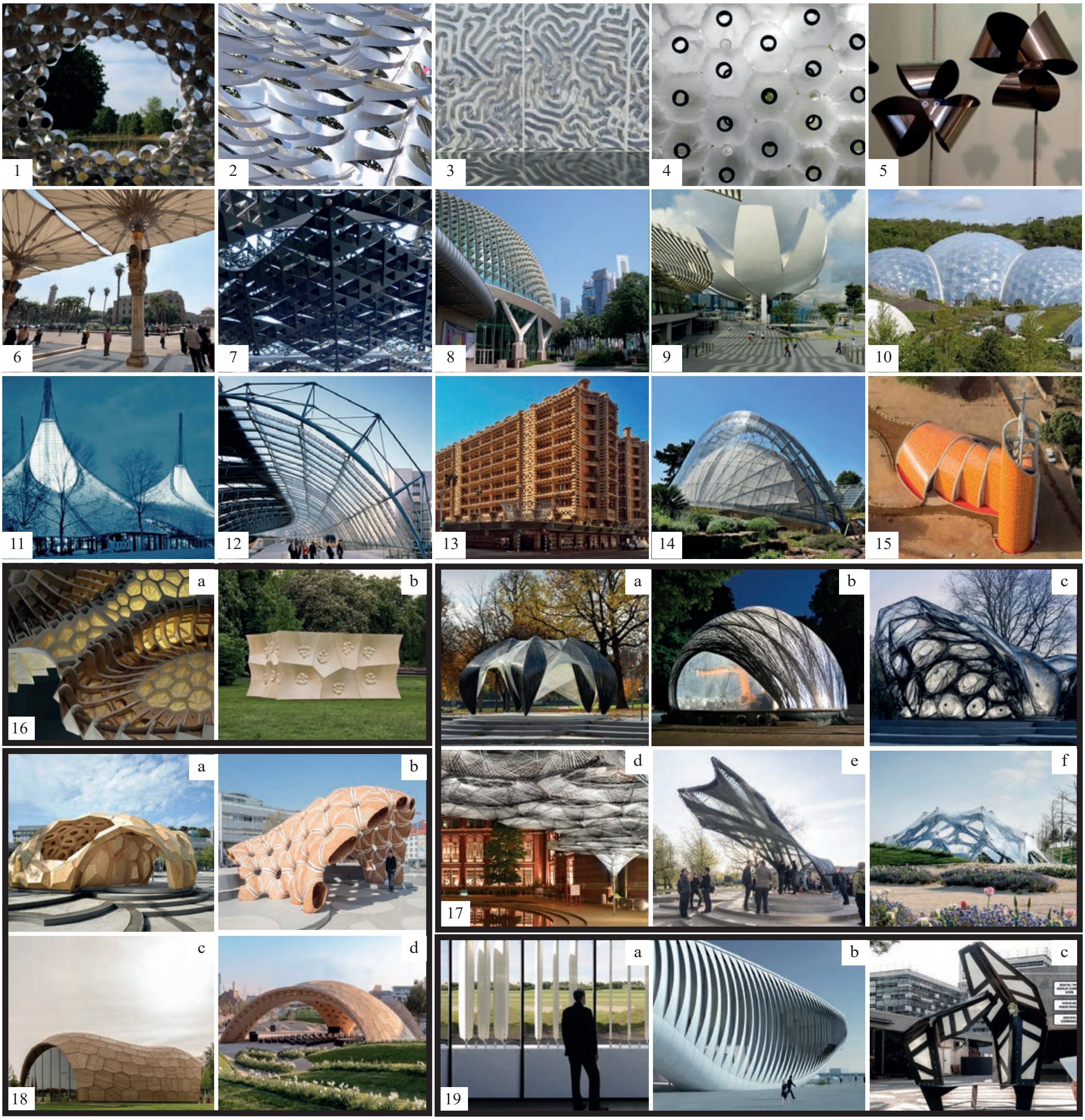


Figure 2.1. Overview of the 19 Bio-BS (projects from [5])

(1) Shadow Pavilion © PLY Architecture, **(2)** Bloom © DO SU Studio Architecture, **(3)** Homeostatic facade © Decker Yeadon LLC, **(4)** Breathing Skin pavilion © Tobias Becker, **(5)** Pho'liage Façade © Art and Build, **(6)** © Umbrella Al Hussein Mosque, SL Rasch, **(7)** Sierpinski Forest, CC BY SA 4.0 Creative Commons Estelle Cruz, **(8)** Esplanade Theatre Art Centre © Tom Ravenscroft, **(9)** ArtScience Museum © Tom Ravenscroft, **(10)** Eden project CC0 Creative Commons, **(11)** West German Pavilion © Frei Otto, **(12)** International Terminal CC 0 Creative Commons Licence, **(13)** Eastgate Centre © ARUP, **(14)** Davies Alpine House © Oast House Archive, **(15)** Nianing Church © Regis L'Hostis.

(16) Hygroscopic facades, **a.** HygroScope, **b.** HygroSkin © ICD/ITKE University of Stuttgart.

(17) Fibrous morphologies, a. Research pavilion 2012, **b**. Research pavilion 2014-15, **c.** Research pavilion 2013-14, **d.** Research pavilion 2015-16, **e.** Research pavilion 2017, **f.** BUGA Fiber © ICD/ITKE University of Stuttgart.

(18) Segmented shells, a. Research pavilion 2011, **b.** Research pavilion 2015-16, **c.** LAGA Research pavilion, **d.** BUGA Wood © ICD/ITKE University of Stuttgart.

(19) Compliant mechanisms. a. Flectofin, **b.** Thematic Pavilion, **c.** ITECH Pavilion © ICD/ITKE University of Stuttgart

2.1.4. Previous investigations into multi-functional biomimetic building skins (Bio-BS)

This chapter mostly relies on two comparative studies on multi-functional biomimetic building skins carried out by Kuru et al. (2019) [4] and Cruz, Hubert et al. (2020)[2] [5], literature review and interviews. These two researches were carried out one year apart, and without consultation with the authors.

Firstly, Kuru et al. (2019) assessed the performance and adaptability of 52 published Bio-ABS – Biomimetic Adaptative Building Skin – where more than half remain at a conceptual stage of development (53.8%). The study outlines that only 13,4% of the Bio-ABS are multi-functional while others only controlling a single environmental parameter. For instance, 84.7% focus on the control of single parameters such as daylighting with adaptive façade systems. In addition, very few quantitative analyses were found in terms of environmental or energy evaluation that assess the performance of biomimetic envelopes. In addition, the study outlined that Bio-ABS are mostly inspired by biological organisms which mostly belong to the kingdom of plants (40%) and animals (21%) [4].

Secondly, Cruz, Hubert et al. (2020) carried out a complementary study in order to assess the main obstacles of biomimetic design processes and their influence on the final design. This study especially identified the main challenges for the design of multi-functional biomimetic building skins (Bio-BS). While Kuru et al. (2019) gathered biomimetic envelopes from conceptual to mature stages (n=52), our study reduced the sample to only built biomimetic envelopes (n=19) (see **Fig. 2.1**). The sample also differs, since our study includes non-adaptative building envelopes. Thirty qualitative variables were defined to conduct a univariate analysis where results were expressed in percentages, and a multi-variate analysis using Multiple Correspondence Analysis (MCA) (see **Fig. 2.2**). These analyses 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%) [5].

These two studies are highly complementary since Cruz, Hubert et al. (2020) reinforced the previous findings on multi-regulation outlined by Kuru et al. (2019). Indeed, they shared 6 variables of analysis – corresponding to 17% of the variable sample of [5] - and 8 Bio-BS were found similar – 26% of the Bio-BS of [5]. Despite the differences between the two samples, the analysis of the shared variables resulted in convergent outcomes. **Table 2.2** summarizes the variables and parameters distribution in percentage for each study. Sections 2.2, 2.3 and 2.4 of this chapter deepen the main results related to multi-regulation from these two studies.

[2] Research conducted in the frame of this PhD. First authors: Estelle Cruz and Tessa Hubert. See section Publication at the end of the manuscript.

Performances of the biomimetic building skins

Number of functions of regulation provided by the building envelope

[4] : **86.6% Mono-functional** | 13.4% Multi-functional

[5] : **47% One function** | **30% Two** | 7% Three | 13% more than three

Environmental regulation provided by the envelope

[4] : **39% Light** | 21% Heat | 19% Water | 18% Air | 3% Energy

[5] : **30% Heat** | **26% Light** | 15% Water | 13% Air | 15% Mechanical load | 0% Noise

Performances targeted

[4] : **34% Thermal Comfort** | **28% Visual Comfort** | 22% Other | 15% Energy demand

[5] **: 34% Thermal Comfort | 28% Visual Comfort | 26% Mechanical stress resistance**
8% Indoor air quality | 4% Other | 0% Acoustic quality

[5] Building function: **63% Public building** (museum, office…) | **37% Pavilion** | 0% Housing

Biomimetic design process

Approach:

[4] **58% top-down** | 32% Bottom-up

[5] **63% Biology push** | 37% Technology pull

[5] Use of biomimetic design framework: **95% No** | 5% Yes

[5] Tools for abstraction: **73% NA** | 21% None | 6% Other | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm

[5] Tools for understanding biological models: **80% NA** | **20% none** | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm | Other

[5] Inputs of biologists from the design team Type of knowledge: **58% Existing for general public** | 40% for specialists | 12% created by specialists and/or by experimentation during the design process

[5] Inputs of biologists from the design team: **47% No interaction with any biologists** | 31% Biologists integrated in the design process | 21% Biologists consulted

[5] Number of biological models: **84% Single** | 16% Multiple

Biological models of inspiration

Biological models

[4] : **40% Plantae** | **44.5% Animalia** (including 13.4% of Arthropoda and 10% of *Homo Sapiens*) | 2% Microbe

[5] : **57% Animalia** | **36% Plantae** | 7% Protista | 0% Archaea | 0% Fungi | 0% Bacteria

[5] Number of biological models: **84% Single** | 16% Multiple

Table 2.2. Main results from [4] [5]. Kuru et al. (2019), n = 52 Bio-BS, and Cruz, Hubert et al. (2020), n = 19 Bio-BS.

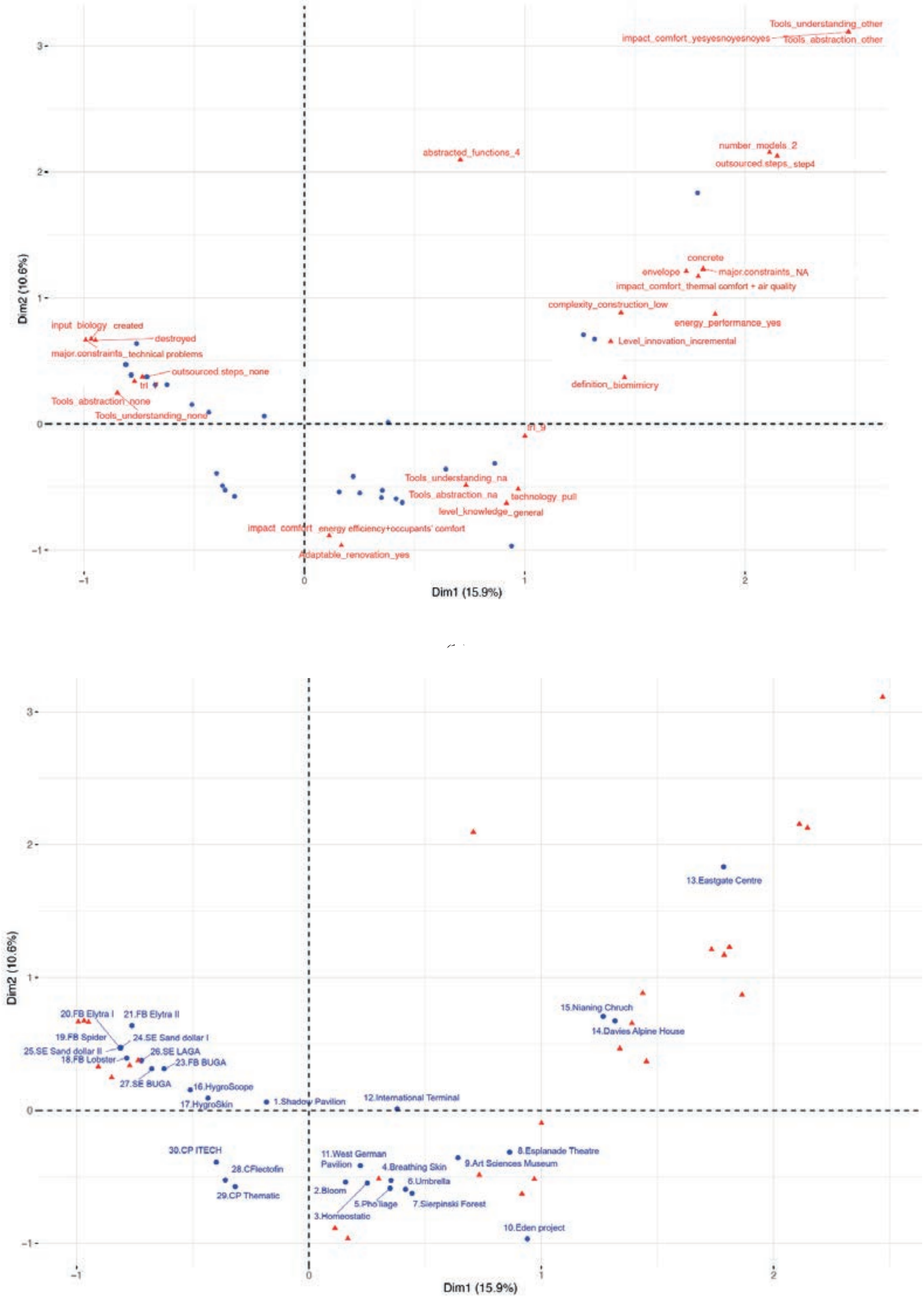


Figure 2.2. **MCA of 30 Bio-BS and 30 variables.** A multiple Correspondance Analysis is a descriptive technique of relationships between elements of a large qualitative dataset. MCA factor maps the 30 Bio-BS (blue points) and the 30 variables (red triangles). According to [5], this MCA outlined that the 30 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. Credits: reused from [5].

2.2. Method

Based on Cruz, Hubert et al. (2020), this section carried out further qualitative evaluations on the multi-functional properties of biomimetic building envelopes. Using the same data set of Bio-BS and several variables within the thirty, this section details the functions of regulation provided per envelope.

2.2.1. Overview of 19 biomimetic building skins

As detailed in [5], the thirty Bio-BS were chosen in the scientific literature and according to the three following criteria:

- The projects have a Technology Readiness Level (TRL) above 6, which means they are either a "system/subsystem model or prototype demonstration in a relevant environment" [24]. A TRL of 6 insured that the projects at least have enough run through the design process to provide feedback on the methodological aspects and on the building performances.
- The projects meet the definitions of either bioinspiration, biomimicry or biomimetics according to [25].
- 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 mostly designed by ICD and/or ITKE at Stuttgart University were included within the 19 Bio-BS since their TRL was found equal or above 6. Although performance of research pavilions highly differs from the building envelopes of public buildings, their biomimetic design processes remained relevant since they were designed beyond the limitations of the real-world constructions. The 15 projects of ICD/ITKE/Stuttgart University can be clustered in four groups: Hygroscopic façades (Ids. 16.a, b), Fibrous morphologies (Ids. 17, a, b, c, d), Segmented shells (Ids. 18, a, b, c, d, e, f), Compliant mechanisms (Ids. 19, a, b, c). To obtain more representative results on a global scale, these 15 projects were reduced to 4 projects as defined by the four clusters listed in **Table 2.3.**

2.2.2. Data collection

Cruz, Hubert et al. (2020) defined thirty qualitative variables which provided the context of the Bio-BS (location, climate, etc.), and the biomimetic design process (purpose, main tools, etc.). Within the thirty, this section only uses the eight following variables 'Number of abstracted functions of regulation', 'Building function', 'Performances targeted', 'Environmental factors regulated', 'TRL', 'Use of biomimetic design framework', 'Biomimetic design method', 'Type of biological models' and 'Number of biological models'. **Tables 2.5.a, b**, and **c** outlines the percentage distribution throughout the chapter.

The information was first collected going through literature, then reviewed with the designers for validation. The reviews were conducted by digital and face-to-face exchanges, videoconferences, discussions during conferences, and 2 weeks of participant observations at ITKE/ICD. Overall, 25 of the 30 Bio-BS data sheets received feedback from the designers. The collected data is available in an online report provides an overview of each project [27].

2.3. Biomimetic building facades (Bio-BS)

2.3.1. Building requirements

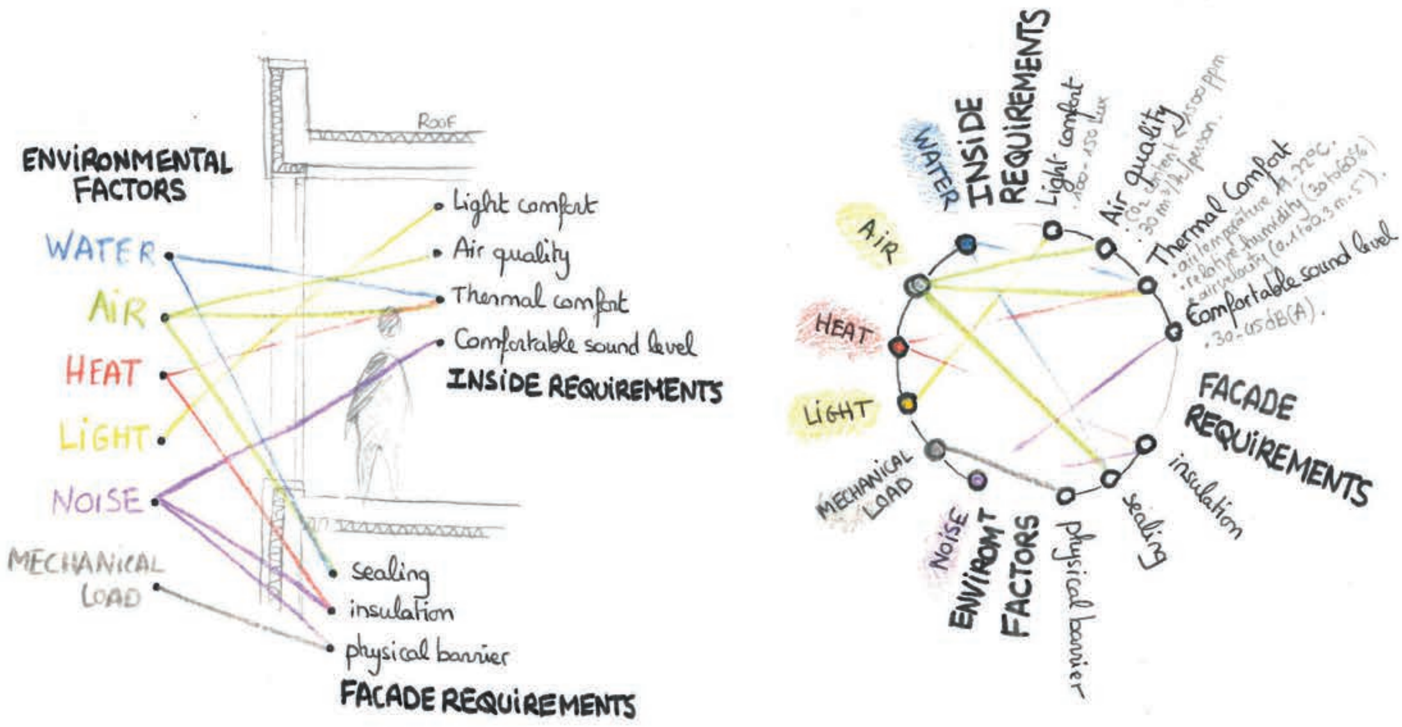
As outlined in chapter 1, building envelopes are complex systems that simultaneously filter several environmental factors to provide internal comfort conditions. Before ensuring comfort conditions, envelopes used to be effective barrier to protect *Homo Sapiens* against a hostile outside world. Diverse other requirements have been added throughout history such as visual relationship with the surroundings while allowing boundary between the private sphere and public areas, thermal and acoustic comfort within the occupied space. All these requirements can be divided into three groups according to [1, Ch. 2]: environmental factors, building inside requirements and facade requirements. All three interplay together and influence each other as illustrated in **Figure 2.3.** Diagram **A** and **B**.

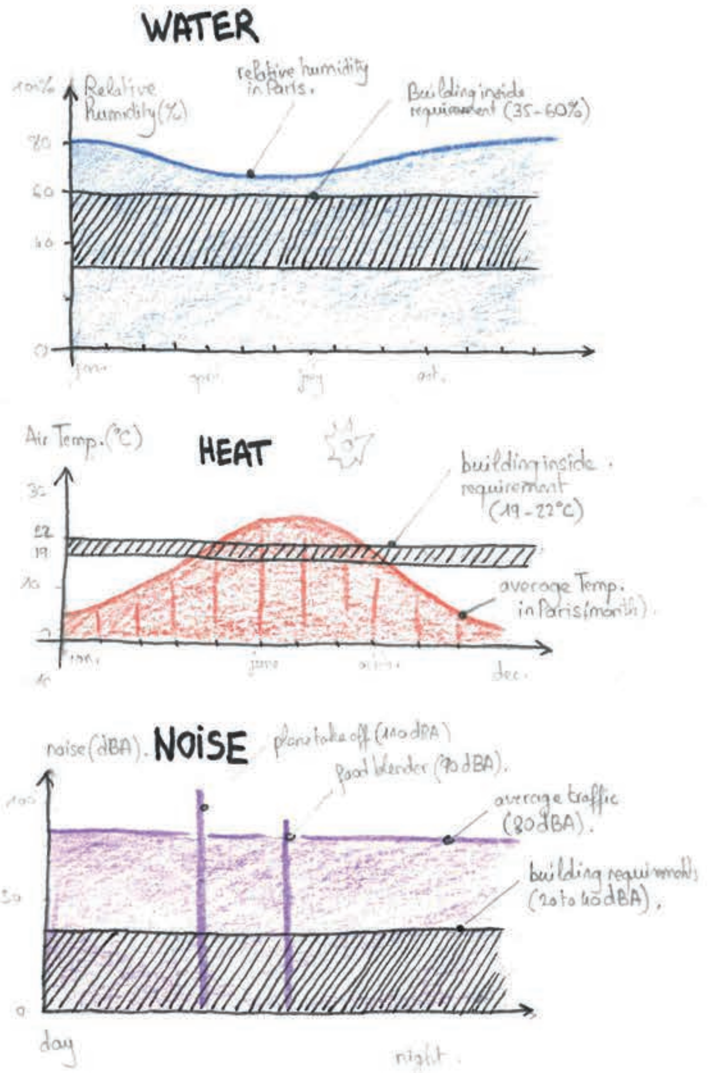
Environmental factors. The building façade is exposed to multiple external conditions such as solar radiation, temperature, humidity, precipitation, wind, mechanical loads, electromagnetic radiations, etc. For the purpose of this research on multi-regulation, this work only considers the six main environmental factors: heat, light, air, water, noise, and mechanical loads. They present severe fluctuations and different range of values vary according to daytime, seasons and building location.

Building inside requirements. In contrast with outside condition, the indoor requirements must constant internal conditions to provide acoustic comfort and thermal comfort (comfortable temperature and humidity range, and air velocity), indoor air quality, etc. There are no fixed target values for these variables since requirements varies according to countries, but there is general agreement on that operating ranges [28], [29].

Façade requirements. To provide the building inside requirements and constant comfort conditions, the building envelope should be able to handle climate-related tasks as comprehensively as possible. The building envelope must provide a physical barrier, insulation, sealing to air and water.

Current European construction standards require conditions of minimum internal comfort and overall energy performance of the building. The geometry, thickness, materials, and thermal, acoustic and visual performance of the building envelope is little constrained by building regulations. Indoor comfort and final energy performance of the building remain the main standards. **Table 2.3** lists non-exhaustive variables to qualify environmental factors buildings are exposed to. The city of Paris serves as a benchmark as a temperate climate and densely built city. The range of values are taken from [30]–[32]. The second section of the table lists indoor comfort requirements based on European standards [31, p. 23]. The last section of the table lists some building facades qualitative specifications.





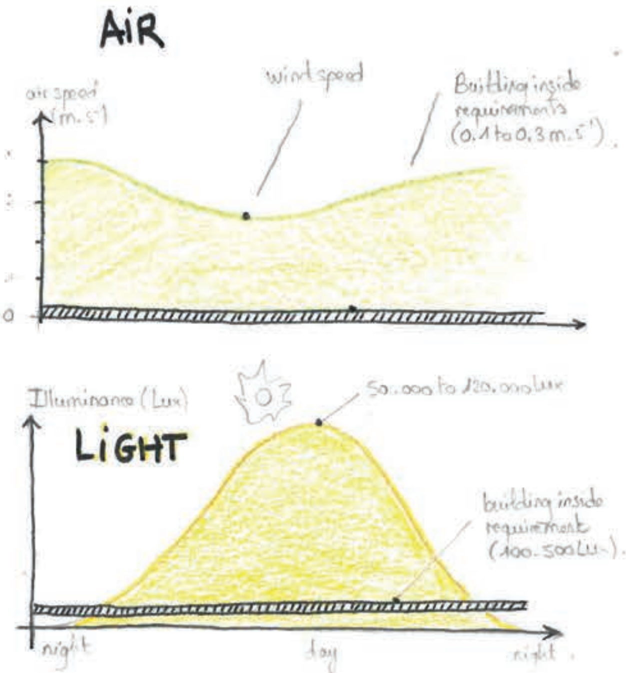


Figure 2.3. **Interplay between environmental factors, building and facade requirements.**

Figure 2.3. **Building requirements.**

Heat. Buildings must provide constant thermal comfort over days and seasons, despite thermal environmental fluctuations (air temperature, solar radiation intensity, etc). The term 'thermal comfort' sums up to a set of internal climatic conditions that can be measured by four quantitative variables: temperature of interior air (from 19 to 21°C), relative humidity of interior air (from 30 to 70%), airflow across the body (from 0 to 0.2 m/s), and surface temperature of building components (equal temperatures of 19.5 to 23°C for all surfaces enclosing the room) [31, p. 23].

Light. The sun is the main source of light which intensity varies over days and seasons. Buildings must achieve an amount of light as stable as possible despite the multiple timescales lighting environmental variations. This requirement is measured with the Daylight Factor in percentage ($2 < DF < 5\%$), or by Illuminance in Lux $300 < I < 750$ lx. Occupied building spaces must maintain lighting between a narrow range which also varies according to type of spaces [32]. During the day, the façade mostly acts as a filter to limit the excess of light. At night, artificial light compensates the lack of natural light by illuminates the occupied spaces. In both situations, the challenge is to provide a constant visual light comfort with little amount of energy for façade adaptation and artificial light production (see **Fig. 2.3.d**).

Water. The building skin is exposed to significant quantities of water in all three states - solid (ice), liquid (water), and gas (vapour). Accumulation of solid and liquid water lead to additional loads larger horizontal surfaces that have to be treated with drainage, waterproofing and insulation layers. The building skin shall be watertight on both sides. The outmost layer must protect the sub layers of the envelope from water runoff, rainwater, moisture, ice, snow and water vapour. Likewise, walls in contact with the occupied spaces must limit moisture formation and water vapour transfer from the internal spaces to the sub-layers of the envelope. Nowadays, the building façade is little involved to maintain a comfortable relative humidity range within the internal spaces. Controlled mechanical ventilation systems remain the main equipment to regulate both humidity and air quality (see **Fig. 2.3.a**).

Air. Ventilation in buildings is provided either naturally or mechanically. The air quality must assess several requirements such carbon dioxide rate below 1150 ppm. (see **Fig. 2.3.b**)

Noise. Sound is both an external condition and an internal requirement because sources of noise can be on either one or both sides of the envelope. For instance, footsteps on the floor propagate sound waves through the building components. Here we examine the sound transmission between the façade and the outdoor environment. The acoustic insulation depends on the prevailing external noise level and the permissible noise levels within the building. Noise levels, types and frequency highly vary according to the building location (city, town, village), and its surroundings (obstacles, (see **Fig. 2.3.e**)

Mechanical loads. The facade must safely withstand the horizontal and vertical forces to which it is subjected and transmit these to the loadbearing structure. Vertical loads are for instance dead loads of the structure itself, special loads (e.g., sun shading, plants), imposed loads (e.g., persons, furniture), snow and ice loads. Horizontal loads count wind load and imposed loads such as birds' impacts. Mechanical stress are temporary and permanent [33, p. 29]. 'Non-loadbearing' and 'loadbearing' facades are the two main types of building envelopes. 'Non-loadbearing' facades do not carry any loads nor assume any loadbearing tasks involving the stability of the building. They transmit the forces they are subject to to the bearing structure of the building (see **Fig. 2.3.f**).

Environmental factors	[30]–[32]	
Heat	air temperature	5 - 20 °C (year)
Light	illuminance of sunlight	0 - 120.000 Lux (day)
	hours of sunshine	50 – 230 hours (day)
Air	wind speed	10 – 15 km/h (year)
	air quality	-
Water	humidity	70 – 90 % (year)
	precipitation	40 – 60 mm (year)
Noise	noise level	0 – 110 dBA (day)
	frequency	(Hz)
Mechanical stress	wind load	5 – 90 daN/m^2
	building structure itself	-
	other loads (ice, water, birds …)	-
Indoor requirements	[31, p. 23], [34]–[36]	
Light comfort	illuminance[3]	300 – 750 Lux
	daylight Factor[4]	2 - 5%
Air quality	CO_2	1150 ppm
	fresh air	30 m^3 / h/ person
Thermal comfort	air temperature	19-21°C
	air relative humidity	30 to 70%
	airflow across the body	0 to 0.2 m/s
	temperature of building components	19.5 to 23°C
Acoustic comfort	noise level	0 to 50 dBA
Energy	building maximum consumption[5]	0 - 50 $kWhEP/m^2/year$
Façade requirements	[33]	
physical barrier	mechanical protection	-
insulation	thermal and acoustic barrier	-
sealing	air and water sealing	-

Table 2.3. Non-exhaustive dimensions and range of values to qualify and measure buildings and facades requirements, and the environmental factors. Information is gathered from various sources: [30]–[36]

[3] Daylighting legislations and illuminance-based standards vary according country. In France, Daylight levels are not described as being mandatory but preferred or recommended [32].

[4] The Daylight Factor (DF) is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies [1, p. 40].

[5] Maximum primary energy consumption requirement limited to 50 kWhEP/m2 in France. Five uses considered: heating, domestic hot water production, cooling, lighting, auxiliaries (fans, pumps) [34].

2.3.2. Multi-regulation performance

Table 2.3.a. presents the main results on multi-regulation performance from [4], [5].

	Performances of the biomimetic building skins
	Number of functions of regulation provided by the building envelope
[4]	: **86.6% Mono-functional** | 13.4% Multi-functional
[5]	: **47% One function | 30% Two** | 13% Three | 7% Four
	Environmental regulation provided by the envelope
[4]	: **39% Light** | 21% Heat | 19% Water | 18% Air | 3% Energy
[5]	: **30% Heat | 28% Light** | 15% Water | 13% Air | 15% Mechanical loads | 0% Noise
	Performances targeted
[4]	: **34% Thermal Comfort | 28% Visual Comfort** | 22% Other | 15% Energy demand
[5]	**: 34% Thermal Comfort | 28% Visual Comfort | 26% Mechanical stress resistance** 8% Indoor air quality | 4% Other | 0% Acoustic quality
[5]	Building function: **63% Public building** (museum, office…) | **37% Pavilion** | 0% Housing

Table 2.3.a. Main results on multi-regulation performance of building envelopes.

Both studies found that Bio-BS provide a limited number of functions of regulation. Results were unequally distributed between the environmental factors regulated by the biomimetic systems. For instance, Cruz, Hubert et al. (2020) found that 47% of the projects regulate one environmental factor, 30% two factors, 7% three and 13% four (see **Fig. 2.4**). None of the Bio-BS simultaneously addressed the regulation of more than four factors while the building envelope must regulate at least six environmental factors (see **Fig. 2.5**).

Multi-regulation of 19 Bio-BS. This section analyses the 19 Bio-BS selected by [5], and within the regulation of the six environmental factors - heat, light, air, water, noise, and mechanical loads. All existing buildings are expected to regulate at least simultaneously that six factors. This section only assesses the targeted environmental factors regulated by abstraction of biological systems properties. For instance, the envelope of the West German Pavilion (Id. 11) simultaneously provides water and light protection, however the abstraction of lightweight biological principles has only inspired regulation of mechanical loads. As a result, the West German pavilion only counts regulation of mechanical stress as outlined in **Table 2.4**. Likewise, the Breathing Skin pavilion (Id. 4) provides resistance to horizontal and vertical mechanical loads. However, the abstracted functions of regulation from the living systems – here the human skin – only allow the façade to regulate light, air and heat.

Table 2.4. outlines the results for each Bio-BS. The plus symbols (+) represent the main environmental aspects regulated by the Bio-BS as obtained from scientific literature. The minus symbols (-) denote that the factor is not, or little regulated by the biomimetic envelope. The mention (n/a) points that no indication was found within the literature; the function is deduced from geometrical properties and composition of the envelope. In addition, the column 'building function' presents the different building functions of the studied Bio-BS. This evaluation grid was adapted from L. Badarnah's nomenclature (see **Fig. 1.9**) [37].

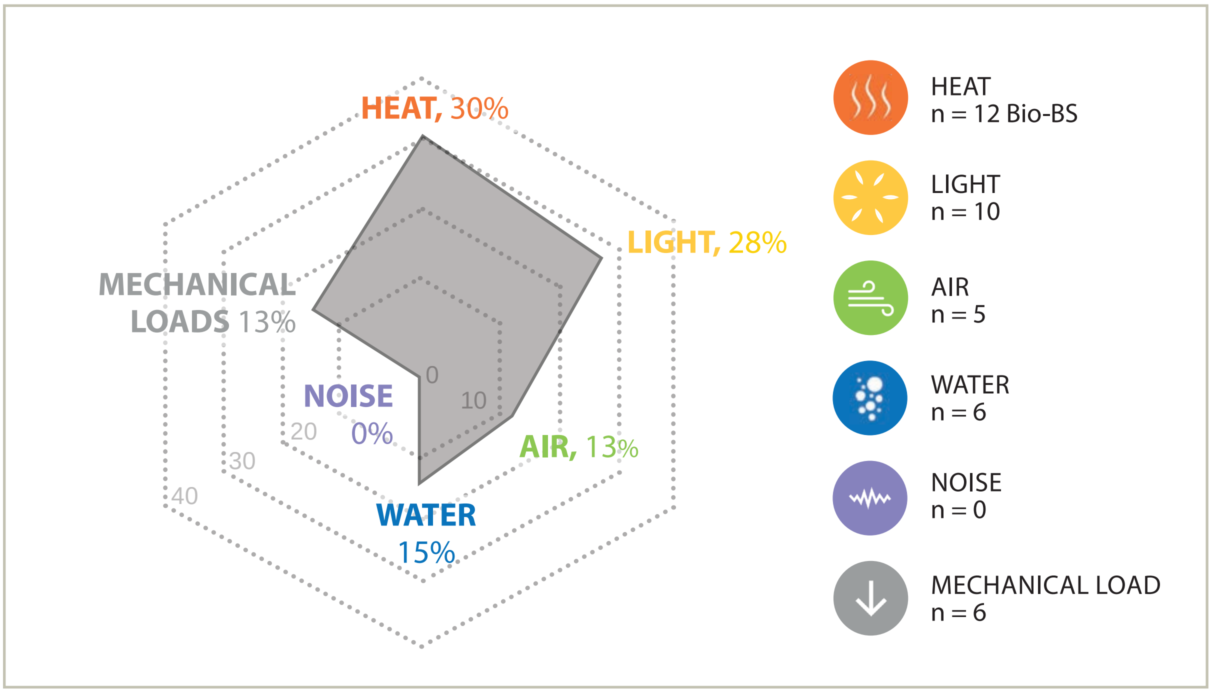


Figure 2.4. Distribution of the 19 Bio-BS according to the environmental factors. Distribution expressed in percentage. Credits: reused and adapted from [5].

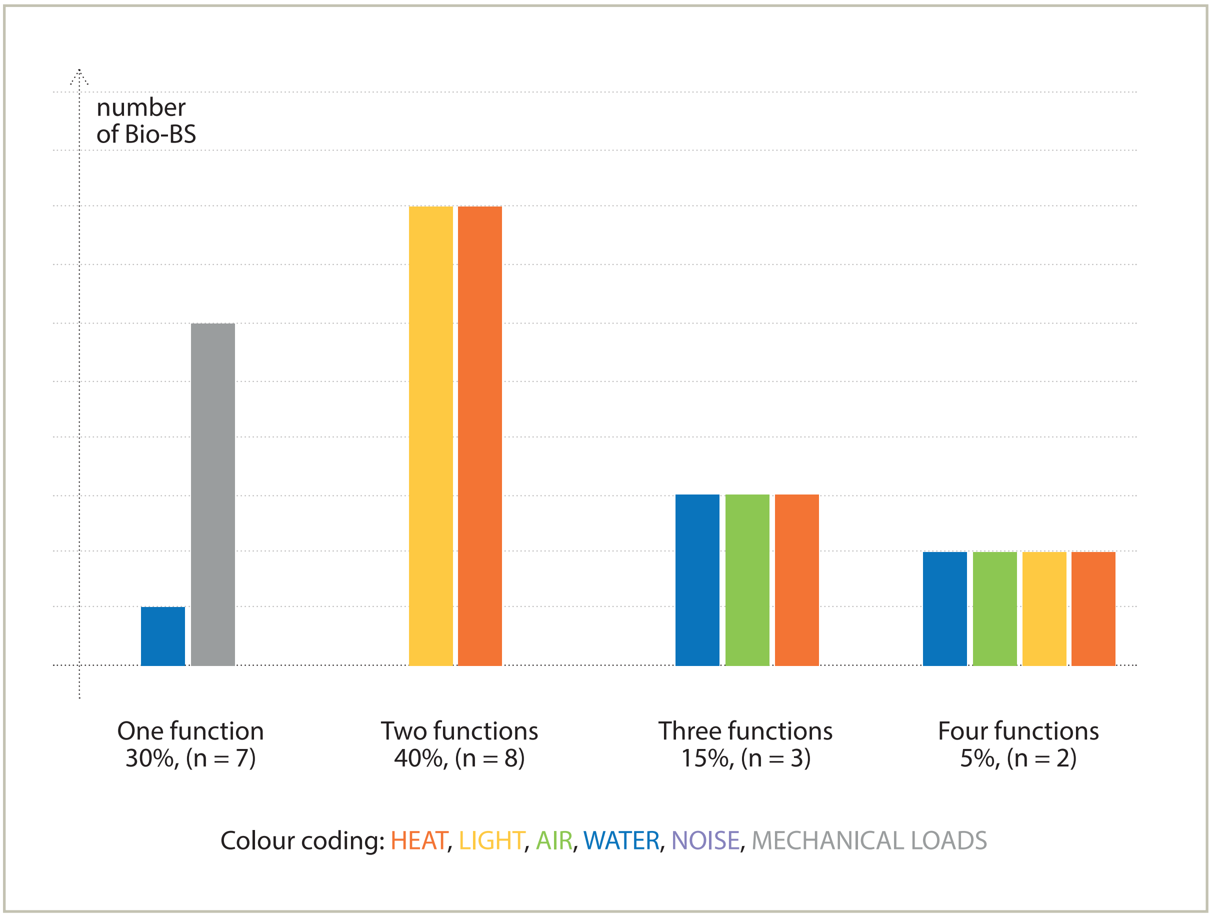


Figure 2.5. Distribution of the 19 Bio-BS according to the number of environmental factors regulated. Credits: reused and adapted from [5].

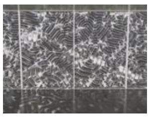
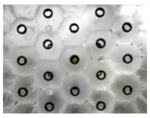
Id	Pictures	**Building envelopes** (Country, Date) Description of the bioinspired system	Building function	TRL	H	L	A	W	N	M
1		**Shadow Pavilion** (USA, 2009), Pavilion inspired by the concept of phyllotactic to optimize the geometry [38]–[40]	Pav.	6	-	-	-	-	-	+
2		**Bloom** (USA, 2011), Adaptive material inspired by adaptation mechanisms in nature [41]–[43]	Pav.	6	+	+	-	-	-	-
3		**Homeostatic facade** (USA, 2012), Adaptive shading system inspired by mammals' muscles to manage light and thermal comfort [44]–[46]	Pub.	6	+	+	-	-	-	-
4		**Breathing Skin pavilion** (Germany, 2015), Pneumatic façade component inspired by human skin for light, air and thermal regulation [47]	Pav.	6	+	+	+	+	-	-
5		**Pho'liage Façade** (France, 2020), Adaptive shading system inspired by opening and closing of flower petals and plants' stomata [48], [49]	Pub.	8	+	+	-	-	-	-
6		**Umbrella Al Hussein Mosque** (Egypt, 2000), Deployable shading system inspired by opening and closing of flower petals [50] [51]	Pub.	9	+	+	-	-	-	-
7		**Sierpinski Forest** (Japan 2019), Sun-shading façade component inspired by the fractal geometry of trees [52]–[55]	Pub.	9	+	+	-	-	-	-
8		**Esplanade Theatre Art Centre** (Singapore, 2002), Shading system inspired by the skin of the durian fruit for energy efficiency [56], [57]	Pub.	9	+	+	-	-	-	-
9		**ArtScience Museum** (Singapore, 2011), Building's shape inspired by the shape of the lotus flower to collect, harvest water [58], [59]	Pub.	9	-	-	-	+	-	-
10		**Eden project** (UK, 2001), Greenhouse inspired by soap bubbles for efficient subdivision of space and lightweight stability [60]–[63]	Pub.	9	-	-	-	-	-	+
11		**West German Pavilion** (Canada, 1967), Roof's pavilion inspired by the structure of web and biological light structures in general [64]–[66]	Pub.	9	-	-	-	-	-	+
12		**International Terminal** (UK, 1993), Façade component inspired by the pangolin scale to respond to changes in air pressure [67], [68]	Pub.	9	-	-	-	-	-	+
13		**Eastgate Centre** (Zimbabwe, 1996), Office building envelope inspired by termites' mounds ventilation system for energy saving [69]–[71]	Pub.	9	+	-	+	+		
14		**Davies Alpine House** (UK, 2006), Green house for thermoregulation and passive ventilation inspired by termite mounds [72], [73]	Pub.	9	+	-	+	+	-	-
15		**Nianing Church** (Senegal, 2019), Church inspired by the ventilation system of termites zzmounds for passive ventilation [74], [75]	Pub.	9	+	-	+	+	-	-

Table 2.4. Overview of the environmental factors regulated by 19 Bio-BS. Table content adapted from [5], and nomenclature adapted from [37].

16. ICD Hygroscopic facades - Responsive facade system inspired by pinecone

a		**HygroScope** (France, 2012), Responsive wood material within a glass case (in controlled humidity conditions) [76], [77]	Pav.	6	+	+	+	+	-	-
b		**HygroSkin** (France, 2013), HygroScope adaptation into a meteorosensitive pavilion in real conditions [78]–[80]	Pav.	7	+	+	+	+	-	-

17. ICD/ITKE Fibrous morphology pavilions - Lightweight structure inspired by morphology of arthropods

a		**Research pavilion** (Stuttgart, 2012) – Pavilion inspired by the highly adapted and efficient structure exoskeleton of the lobster [81]–[83],	Pav.	7	-	-	-	-	-	+
b		**Research Pavilion** (Stuttgart, 2014-15), Pavilion inspired by the web building process of the diving bell water spider [84], [85]	Pav.	7	-	-	-	-	-	+
c		**Research pavilion** (Stuttgart, 2013-14), Pavilion inspired by the Elytra, a protective shell for beetles' wings and abdomen [86], [87]	Pav.	7	-	-	-	-	-	+
d		**Research pavilion** (London, 2015-16), Pavilion inspired by the Elytra [88], [89]	Pav.	7	-	-	-	-	-	+
e		**Research pavilion** (Stuttgart, 2017), Pavilion inspired by construction logics of larvae spin silk of leaf miner moths [90], [91]	Pav.	7	-	-	-	-	-	+
f		**BUGA Fiber** (Heilbronn, 2019), Load-bearing structure inspired by beetle wings [92]	Pav.	8	-	-	-	-	-	+

18. ICD/ITKE Segmented shell Research Pavilions - Finger-joints inspired by the morphology of sand dollar

a		**Research pavilion** (Stuttgart, 2011), inspired by the morphology of the sand dollar built with extremely thin sheets of plywood [93], [94]	Pav.	7	-	-	-	-	-	+
b		**Research pavilion** (Stuttgart, 2015-16), Pavilion employing industrial sewing of wood elements on an architectural scale [95], [96]	Pav.	7	-	-	-	-	-	+
c		**LAGA research pavilion** (Stuttgart, 2014), structure entirely made of robotically prefabricated beech plywood plates [97], [98]	Pav.	8	-	-	-	-	-	+
d		**BUGA Wood** (Heilbronn, 2019) inspired by the plate skeleton morphology of the sand dollar [99], [100].	Pav.	8	-	-	-	-	-	+

19. ICD/ITKE Compliant mechanisms – Shading façade system to minimize energy for adaptive facade system

a		**Flectofin** (Germany, 2011), Adaptive hinge less louver system inspired by the opening mechanism of the bird paradise flower [101], [102]	Pav.	8	+	+	-	-	-	-
b		**Thematic Pavilion** (South Korea, 2012), Shading system for the façade of an exhibition hall which adapt the Flectofin system [103]–[105]	Pub.	9	+	+	-	-	-	-
c		**ITECH Pavilion** (Stuttgart, 2019) – Adaptive compliant structure inspired by the folding mechanisms of Coleoptera wings' [106], [107].	Pav.	8	+	+	-	-	-	-

Single regulation: mechanical stress. Almost third of the projects address mono-regulation, where the regulated environmental factor is the mechanical stress (30%, n=7). Within this sample, the Bio-BS were mostly designed to resist to the load bearing of the building itself. The ICD/ITKE research pavilions Fibrous morphologies (Ids. 16, a-f) and Segmented shells (Ids. 18, a-d) targeted lightweight structures in the legacy of the work of the German architect Frei Otto, and aligned with research of the SFB-TRR 141 [64]. Applying the evaluation grid of the targeted environmental factors regulated, these biomimetic projects respond to mono-functional approach.

Double regulation: light and heat regulation. Half of the projects simultaneously regulate heat and light (%, n=9). They are dependent environmental stimuli since they rely on solar radiations the building façade is exposed to. These two factors are mostly regulated by biomimetic shading systems which both flirter the thermal and light sun radiations. These systems are adaptive (Id. 2-6, 16, 19) or fixed (Id. 7, 8). For instance, the envelope of the Esplanade Theater of Singapore (Id. 8), inspired by the durian fruit was design to provide sufficient amount of natural light while protecting the building from overheating [56], [57]. Like the Sierpinski Forest project (Id. 7), the shading system is fixed [52]–[55]. Within the seven biomimetic shading systems, adaptation can be intrinsic (Id. 2, 5, 16) or extrinsic (Id. 3, 4, 6, 16) to the system according to the building envelopes' classification of [108]. Intrinsic control implies self-adjusting of the biomimetic system since the adaptive behaviour is automatically triggered by environmental stimuli. For instance, the alloy thermal responsive shading systems Pho'liage and Bloom allow low-cost operation and maintenance since the material adapt itself [41]–[43], [48], [49]. Extrinsic control implies first information retrieving and processing (from database, artificial intelligence) and then, the adaptation of the façade system.

Triple-regulation by ventilation systems. Simultaneous control of three environmental factors was addressed by only three biomimetic systems (Id. 13, 14, 15). The Eastgate Building (1996), the Davies Alpine House (2006), and the Nianing church (2019) which are inspired by the ventilation system of termites' mounds. As the mounds of Macrotermes, building ventilation systems simultaneously regulate three environmental factors which are air (quality, humidity, speed), heat (air temperature) and water (air humidity).

Quadruple regulation. This category counts two Bio-BS which are the Hygroscopic pavilions (Ids. 16, a, b), and the Breathing skin pavilion (Id. 4). The ICD Hygroscopic research pavilions of the University of Stuttgart are made of hygroscopic wood which adapt to moisture. As pinecone scales operate, the pavilion's openings close when the level of humidity is high, and open when is low. The envelope of the pavilion consists of an assembly of plywood plates with adaptive opening. Applying the evaluation grid of environmental factors, these pavilions provide an envelope that allow multi-regulation of environmental factors. However, these prototypes do not provide the expected multi-regulation for a building as they are pavilion. Similarly, the Breathing skin pavilion enables natural ventilation all over the façade. The permeability of the façade allows to control the flow of substances between the inside and the outside. Pneumatic muscles regulate the amount of incident light, views, and air passing through the façade.

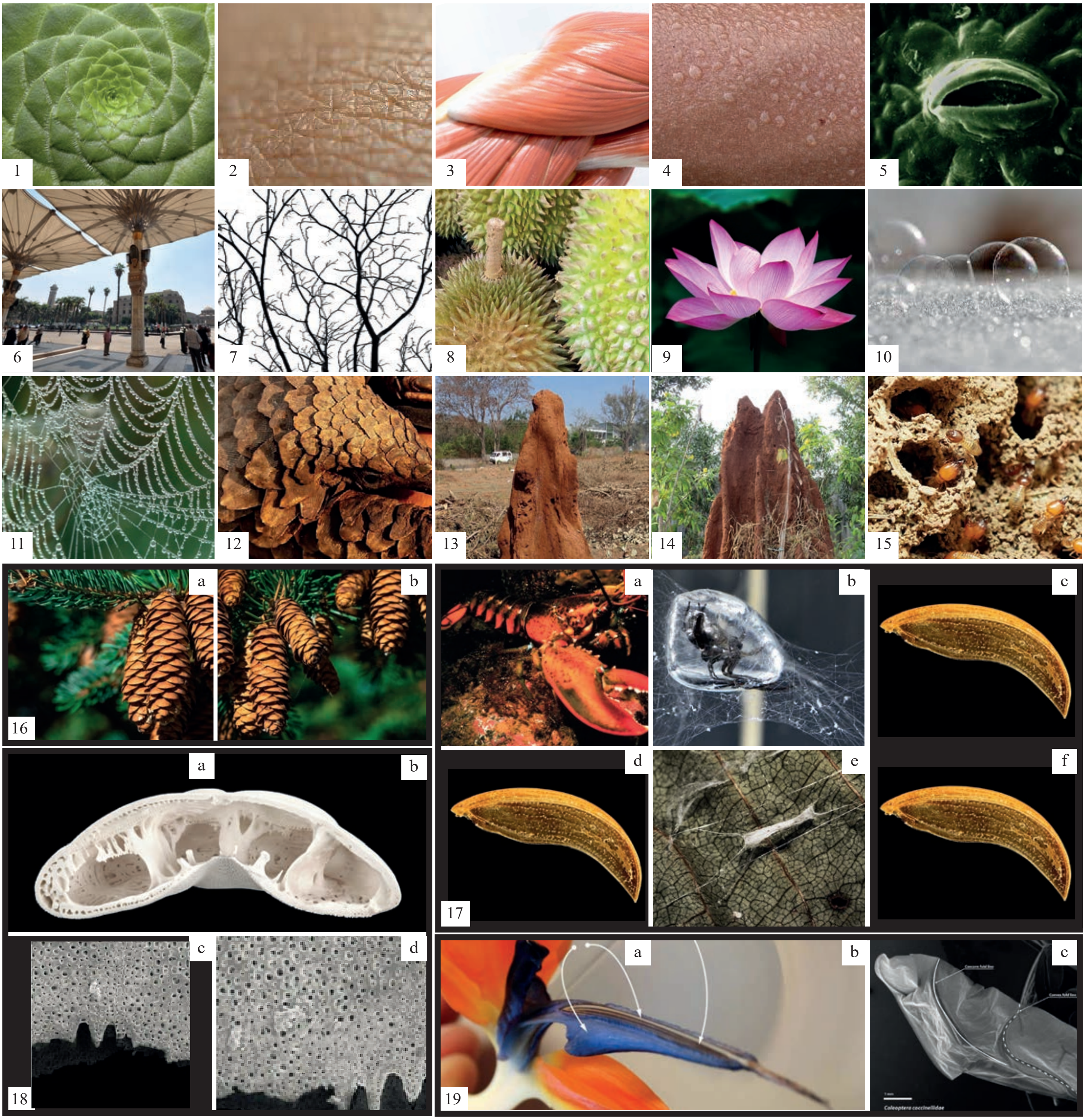


Figure 2.6. Overview of the 19 biological models which inspired the 19 Bio-BS

(1) Phyllotactic geometry of succulent, **(2)** Human skin, **(3)** Human muscle, **(4)** Human skin CC BY-SA 3.0, **(5)** Stomate BY-SA 3.0 **(6)** Opening and closing of flower petals, **(7)** Fractal geometry of trees, **(8)** skin of the durian fruit, **(9)** Shape of the lotus flower, **(10)** soap bubbles, **(11)** web of spiders, **(12)** pangolin scale, **(13-15)** termites mounds.

(16) a. and b. Scale of pinecone

(17) a. Exoskeleton of the lobster, **b**. diving bell water spider © ICD/ITKE University of Stuttgart, **c, d, f.** Elytra, protective shell for beetles' wings © ICD/ITKE University of Stuttgart. **e.** larvae spin silk of leaf miner moths © ICD/ITKE University of Stuttgart.

(18) a, b, c, d. Exoskeleton of sand dollar © ICD/ITKE University of Stuttgart.

(19) a. b. Bird paradise flower **c.** Coleoptera wings' © ICD/ITKE University of Stuttgart

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2.4. Biological interfaces

The previous section highlighted the need for the development of biomimetic building envelopes with multi-regulation capacities to address contradictory requirements. However, multi-functionality is intrinsic to biological systems as presented in section 2.1 of this chapter. In order to understand current limitations for the development of multi-functional building envelopes, this section qualifies multi-regulation capabilities of the 19 biological models gathered by Cruz, Hubert et al. (2020) [5]. **Figure 2.6** (previous page) presents these models using the same numbering as in Figure 2.1 and Table 2.4 in previous sections of this chapter.

2.4.1. Biomass and phylogenetic distribution

This section analyses the biological model(s) which inspired the Bio-BS selected in [5], and the Bio-ABS from [4]. **Table 2.3.b.** presents the main results from that two studies.

Biological models of inspiration	
	Biological models
[4]	: **40% Plantae | 44.5% Animalia** (including 13.4% of Arthropoda and 10% of *Homo Sapiens*) | 2% Microbe
[5]	: **57% Animalia | 36% Plantae** | 7% Protista | 0% Archaea | 0% Fungi | 0% Bacteria
[5]	Number of biological models: **84% Single** | 16% Multiple

Table 2.3.b. Main results on multi-regulation performances of building envelopes, data extracted from [4], [5].

Biodiversity distribution. Both studies found that plants (Plantae) and animals (Animalia) were the most studied biological models within the domain of eucaryotes. None of the biological models belong to the two other domains of archaea or eubacteria. Similarly, none of the Bio-BS are inspired by annelids, molluscs, cnidarians or fish. Cruz, Hubert et al. (2020) showed that the distribution of inspiring biological models is not proportionate to the distribution of estimated biomass on Earth (see **Fig. 2.7.A** [109], and **B** [110]**)**, nor proportional to the estimated and described species (see **Fig. 2.7.A, C** [111]). For instance, the specie *Homo sapiens* is over-represented in Bio-BS (33%) related to its proportion in the biomass (0,01%), and within the 1.7 billion of described species (0,0000005%). The distribution of Bio-BS inspired by arthropods is more representative to the biomass distribution and estimation of species as presented by **Figure 2.7.B**.

These results show that freshwater and marine animals such as annelids, molluscs, cnidarians or fish, less inspire architects than terrestrial organisms. Indeed, these marine organisms are not subject to the same environmental factors as buildings. We assure that terrestrial living systems that are exposed to the same environmental factors as building envelopes may have relevant adaptation to abstract compared to marine and freshwater species.

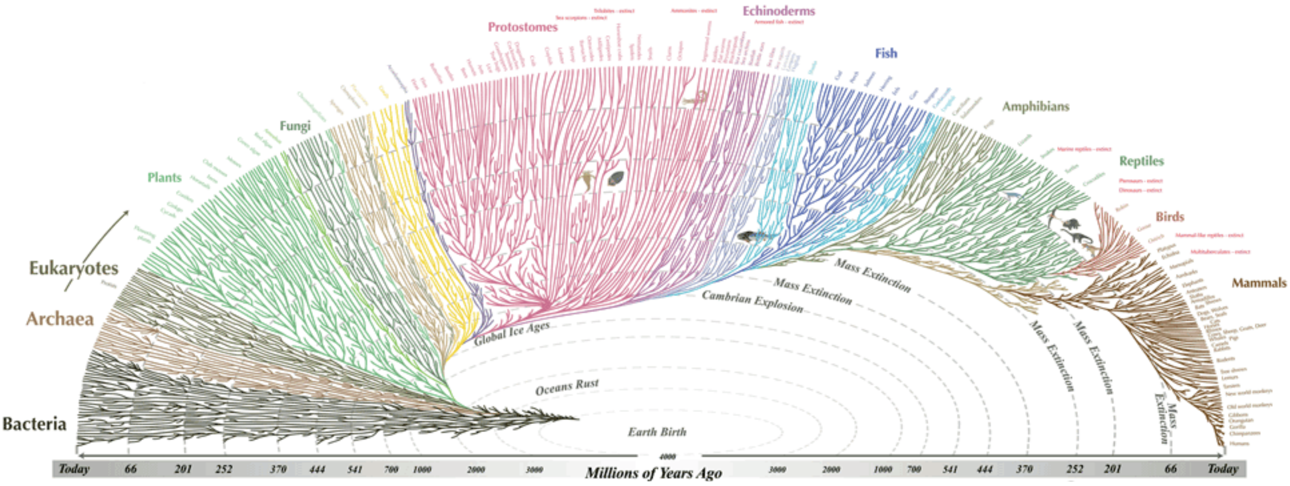


Figure 2.7.A. The Tree of Life, permission of reuse from [109], Credits: © evogeneao.com.

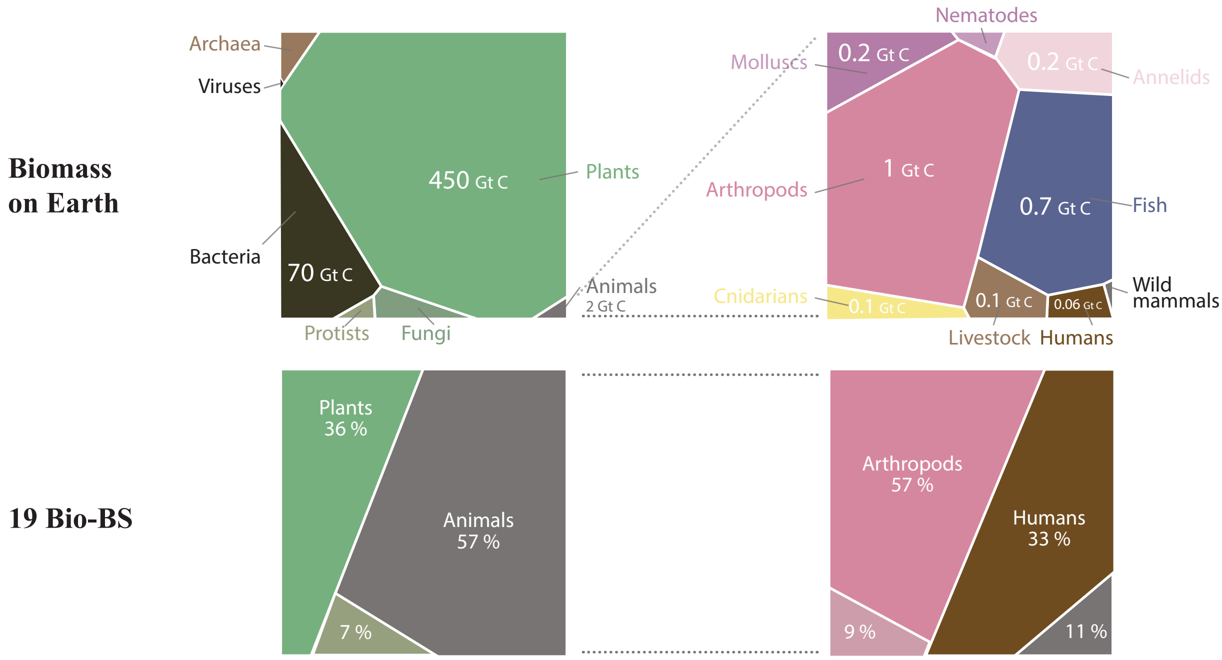


Figure 2.7.B. Comparaison of the 19 Bio-BS with biomass distribution. Distribution of the estimated biomass on earth in gigatons of carbon (GT C) (top), and distribution in percentage of the biological models which inspired the 19 Bio-BS (bottom). Credits: content adapted with permission from [5], [110]. Colour coding [109].

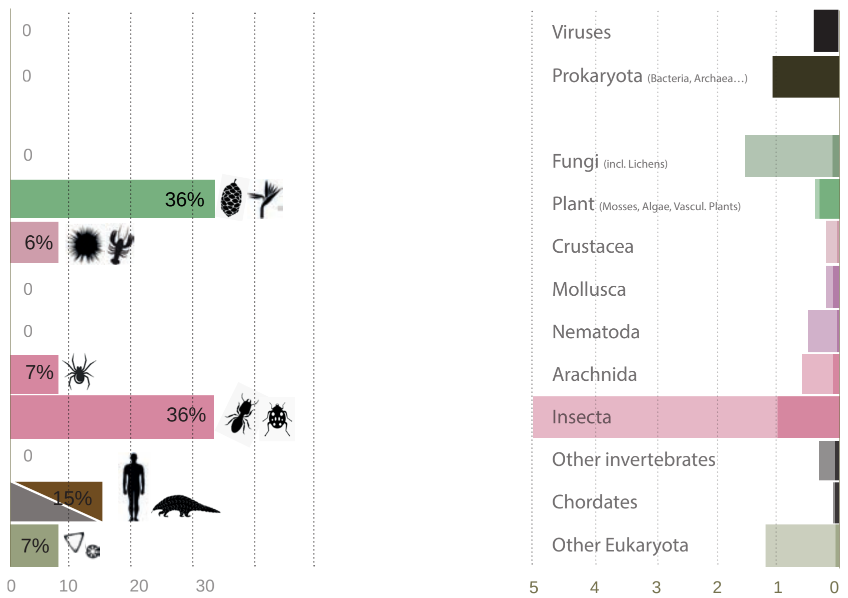


Figure 2.7.C. Comparaison of the 19 Bio-BS with distribution of estimated species on earth. Distribution of the major groups of biological models which inspired the 19 Bio-BS (left) according to the distribution of estimated species on earth (right).Credits: content adapted with permission from [5], [111]. Colour coding [109].

2.4.2. Multi-regulation performances

This section qualifies the multi-regulation capabilities of the 19 living systems which inspired the 19 Bio-BS cases analysed by [5] (see **Fig. 2.6**). The regulation of the six environmental aspects - heat, light, air, water, noise, and mechanical loads – is analysed for each living system.

Qualifying multi-regulation. A novel classification is introduced to qualify the level of regulation of the environmental factors provided by the living systems. This evaluation grid differs from the one used in **Table 2.4** and in **Figure 1.9** (chapter 1) with the symbols (+) and (-). Since most of the biological systems simultaneously regulate several environmental factors, there is a need for a finer nomenclature. The proposed nomenclature is comprised of four levels to qualify the involvement of the biological system within the regulation of each environmental aspect. **Table 2.5** and **Figure 2.8** presents each level illustrated by the performance of a cuticle of a ladybug (*Coccinella septempunctata*)

Level	Description of the functions of regulation	Example: ladybug cuticle (*Coccinella septempunctata)*
0	: the biological system is not involved in the regulation of the environmental factor	-
1	: the system is little involved in the regulation	**HEAT (1),** the cuticle little regulate thermal exchanges since insect are ectotherms[6]
2	: the system significantly contributes to regulate that factor	**LIGHT (2),** both cuticle and insect's displacement provide light regulation. **AIR (2),** both cuticle and trachea allow gas exchanges for breathing. **WATER (2),** the cuticle is watertight.
3	: only that biological system regulates the biological factor	**MECHANICAL LOADS (3),** the mechanical resistance of the cuticle allow shocks absorption and dissipation of mechanical energy
n/a	: not applicable. No indication was found or can be deduced within the literature	**NOISE (?),** the acoustic absorption of ladybug cuticle is not yet known.

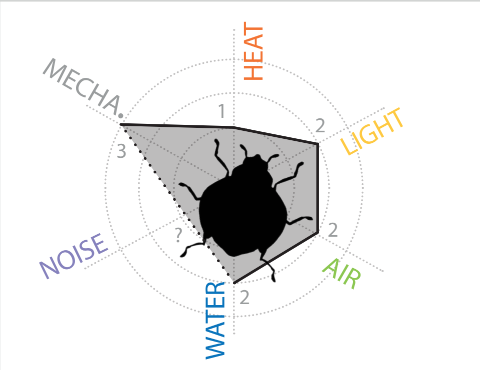
Table 2.5. Level of regulation of environmental factors provided by the biological system. The cuticle of the ladybug *Coccinella septempunctata* illustrates the introduced nomenclature.

Applying the novel classification as presented in Table 2.5, **Table 2.6** and **Figure 2.9** provides a qualitative evaluation of the multi-regulation performances of each biological system. Results are displayed in radar chart to provide a graphical overview of all environmental factors regulated. Data is gathered from various sources such as handbooks in biology [112], [113], and the scientific papers that described the Bio-BS. The regulation of the environmental factor 'noise' is deduced from geometrical properties and composition of the biological system (see chapter 4, Noise for key concepts in acoustic). . Indeed, little basic research in biology have assess acoustic properties of living systems.

[6] Ectotherm: organism with body temperature that depends on external sources of heat, directly or indirectly from the sun [155]

Id.	**Biological system.** Description of the biological principle abstracted for the design of the Bio-BS	**H**	**L**	**A**	**W**	**N**	**M**
1	**Geometry of plants,** phyllotactic leaves' arrangement	2	2	0	0	0	1
2	**n/a,** inspired by 'animals' skins in general	-	-	-	-	-	-
3	**Mammals' muscles,** deformation of the muscles	2	0	0	1	2	2
4	**Human skin,** gas exchange, light and thermal regulation	2	2	1	2	1	2
5	**Stomata,** openings that regulate heat, air, humidity	2	0	3	2	0	0
6	**Flower petals,** opening and closing	2	2	0	1	0	1
7	**Fractal geometry of trees,** structure to enhance heat loss	2	2	2	0	0	2
8	**Durian,** geometry of the envelope of the fruit	3	3	3	3	1	3
9	**Lotus flower**, shape to collect and harvest water	0	0	0	2	0	0
10	**n/a,** inspired by various lightweight nature principles	-	-	-	-	-	-
11	**n/a,** inspired by various lightweight nature principles	-	-	-	-	-	-
12	**Pangolin scale,** flexible scale arrangement	2	2	0	2	1	2
13-15	**Termites' mounds**, ventilation system	2	3	3	3	2	3
16, a-b	**Scale of pinecone**, opening and closing mechanism	1	1	1	3	1	3
17 (a)	**Exoskeleton of the lobster,** lightweight structure	1	1	1	1	1	3
17 (b)	**Diving bell water spider**, building process	-	-	-	-	-	-
17 (c, d, f)	**Insects' elytra,** lightweight and resistant structure	1	2	3	2	1	3
17 (e)	**Miner moths,** construction logics of larvae spin silk	-	-	-	-	-	-
18 (a-d)	**Sand dollar,** high load bearing capacity of the plate skeleton morphology	1	1	1	1	1	3
19 (a-b)	**Bird paradise flower,** opening mechanism of etamines	3	3	3	3	1	2
19 (c)	**Coleoptera wings'**, folding mechanisms	1	2	3	2	1	3

Table 2.6. Overview of multi-regulation capabilities of the 19 biological models. Qualitative assessment of the regulation performances of each biological system, according to Table 2.5 classification.



HEAT (1), the cuticle little regulate thermal exchanges since insect are ectotherms

LIGHT (2), both cuticle and insect's displacement provide light regulation.
AIR (2), both cuticle and trachea allow gas exchanges for breathing.
WATER (2), the cuticle is watertight.

MECHANICAL LOADS (3), the mechanical resistance of the cuticle allow shocks absorption and dissipation of mechanical energy

NOISE (?), the acoustic absorption of ladybug cuticle is not yet known.

Figure 2.8. Multi-regulation provided by an insect cuticle. Here the ladybug - *Coleoptera coccinellidae*.

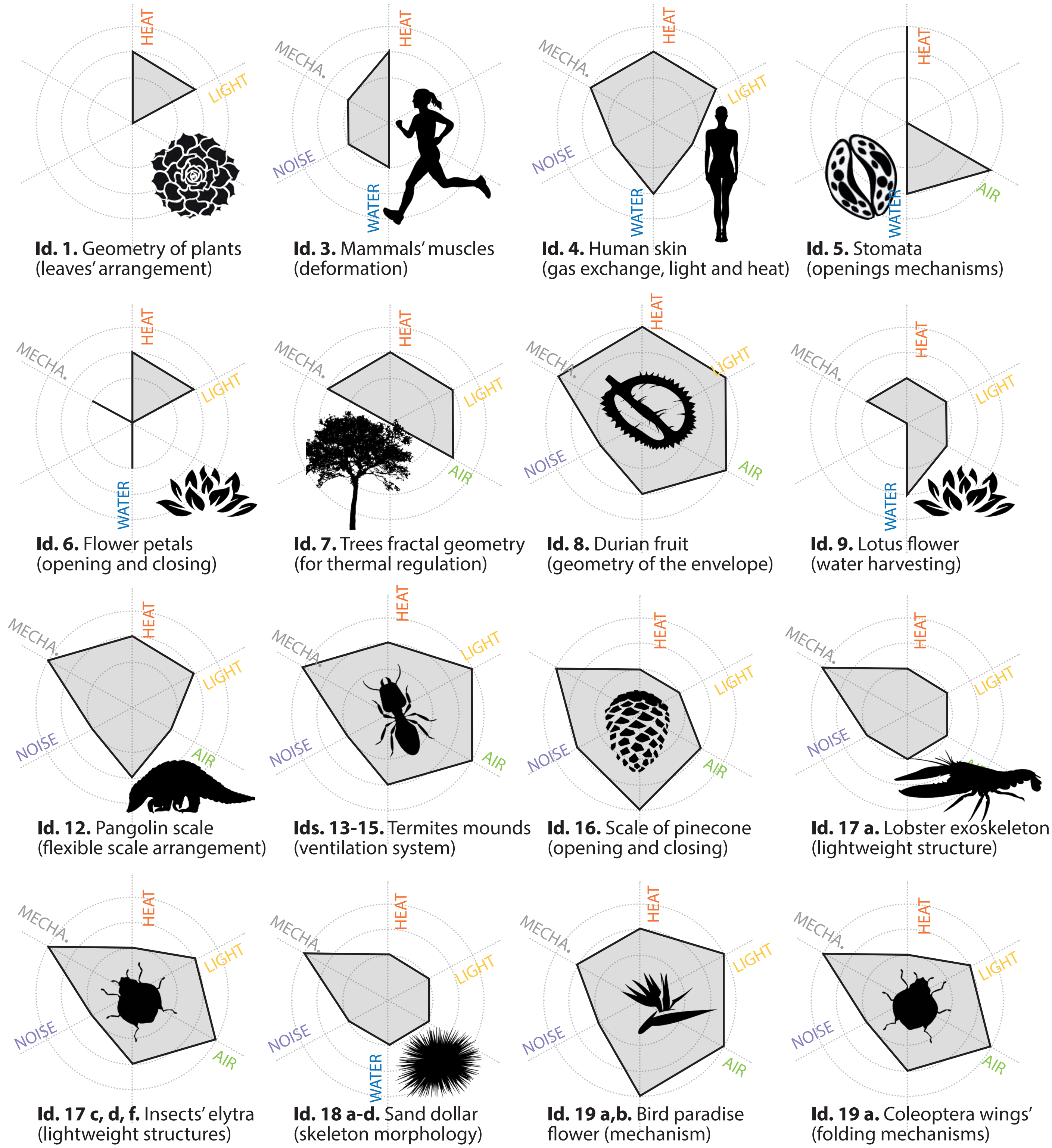


Figure 2.9. Overview of multi-regulation capabilities of the 19 biological models.

Abstraction of single biological 'feature'. Previous section '2.4.1. Distribution within biodiversity' highlighted a disperse distribution of the 19 biological models across the five kingdoms. Here, the results show a diversity in the type of 'strategy'[7] abstracted from the selected biological models. None of the Bio-BS was inspired by the whole biological system. Each Bio-BS abstracted a specific feature such as one or several functions of regulation, geometry, physiological adaptation, etc. Most of the 19 Bio-BS resulted from abstraction of morphological adaptations of living systems (Ids. 1, 5, 7-9, 17-19). These results are aligned with Kuru et al. (2019) since the study outlined that 59.6% of the fifty-two Bio-ABS provide morphological adaptations, 17.3% physiological, 11.5% behavioural and 11.5% combination [4].

Multi-regulation across kingdoms. Some Bio-BS were inspired by different species of flowering plants (Angiosperm) (Ids. 1, 5, 6, 8, 9, 19.a). Each abstracted a specific feature resulting of a diversity within the regulation performance of environmental aspects. For instance, the arrangement of plant organs around a central axis – known as phyllotaxy – optimises the regulation of heat and light while providing mechanical stability [114] (Id. 1). Stomata – mostly found in the epidermis of leaves and stems - controls the rate of gas exchange which contribute to air quality, thermal and humidity regulation (Id. 5) [112, Ch. 10]. Durians – fruits of the tree species belonging to the genus *Durio* – simultaneously provides mechanical protection, heat and light regulation (Id. 8) [115]. Indeed, within the taxa Angiosperm, there is a diversity of features to regulate several environmental factors. This result also suggests that a multi-criterion mapping of living system can reveal multi-regulation capabilities, beyond the 'obvious' biological features. The same reasoning can be applied to the other kingdoms.

Variety of multi-regulation performances. These preliminary results show that the 19 biological systems have multi-functional capabilities. First, none of them simultaneously regulate all the environmental factors as expected for the building envelope. Acoustic remains the less performed environmental aspect since few living systems protects from sound level and intensity[8].

The application of the four levels provided by the previous classification in Table 2.4 outlines different level of performances across the biological models. For instance, some living systems regulate all the environmental aspects, however, the aspects are little regulated such as the sand dollar' and lobster's exoskeleton (Ids. 18. a-d, 17.a). One the other hand, some living systems such as the termites' mounds (Ids. 13-15) or biological envelopes such as the pangolin scale or the human skin (Ids. 4, 8, 12) have a wider range of regulation. In addition, some biological systems regulate contradictory requirements.

Biological interfaces. This mapping of biological models also outlined that some Bio-BS were inspired by biological envelopes such as the pangolin' scales (Id. 12), the cuticle of the durian fruit (Id. 8), or arthropods exoskeleton (Ids. 17, 18, 19.a). Radars charts of these envelopes cover a larger area compared to other biological features. Indeed, there has been a surge of interest in biological interfaces for biomimetic applications as outlined by [116]–[119]

[7] See Chapter 1, section 'Towards the 'right' level of information'.

[8] See Chapter 4, Noise.

2.5. Biomimetic frameworks

Previous sections outlined that most of the biomimetic building envelopes – Bio-ABS or Bio-BS – regulate single or linked environmental aspects such as heat and light. On the other hand, the biological systems have multi-regulation capacities to address contradictory requirements. The terrestrial living systems are promising models since they cope with the same environmental factors as buildings do.

In order to understand current limitations for the development of multi-functional building envelopes, this section first assesses the biomimetic frameworks, tools and methods used to design the 19 Bio-BS as gathered by Cruz, Hubert et al. (2020) [5]. Secondly, this section aims at structuring and mapping the existing frameworks from the perspective of achieved multifunctionality in building skins.

2.5.1. Methods, tools, and processes

Biomimetics developments have increased with the development of tools and methods. The first framework to facilitate transfers from life to design sciences was published in the 1987 [120]. Indeed, design sciences have attracted attention of academic researchers and industry since the 1970s. Before that time, design was regarded closer to art than to engineering due to insufficiency of knowledge. Nowadays, design sciences is widely taught in engineering schools and industrially applied [121]. For this purpose, academics have provided three key concepts: 'process', 'method' and 'tool' as summarized by [122]**.** These concepts have different level of abstraction and can overlap as discussed by the scientific [123]. Their definitions illustrated with application in biomimetics go as follow. The designation 'framework' covers the contributions describing the hole development process such as process, method, tools [124].

Process. A process is a framework that allow to organize the generic steps to follow during the design practice. It has a high level of abstraction; it allows to mobilize a large range of methods and tools as appropriate to the design phases [125]. In biomimetics, two processes have been defined: 'technology pull' BID Process (Biologically Inspired Design) and 'biology push' BID Process. The ISO standard 2015:18458 [126], [127] has provided the following definitions:

- The biology push BID 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'. Like the technology pull BID, this pattern also follows a sequence of six stages, but the starting point is a particular biological solution (see **Fig. 2.10. B**)

- The technology pull BID 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 of technology pull *BID* follows a progression of six steps from the technical problem to the improved biomimetic product (see **Fig. 2.10. A**)

The figures show linear development, however these processes are highly dynamic and can include several feedback loops [128], [129].

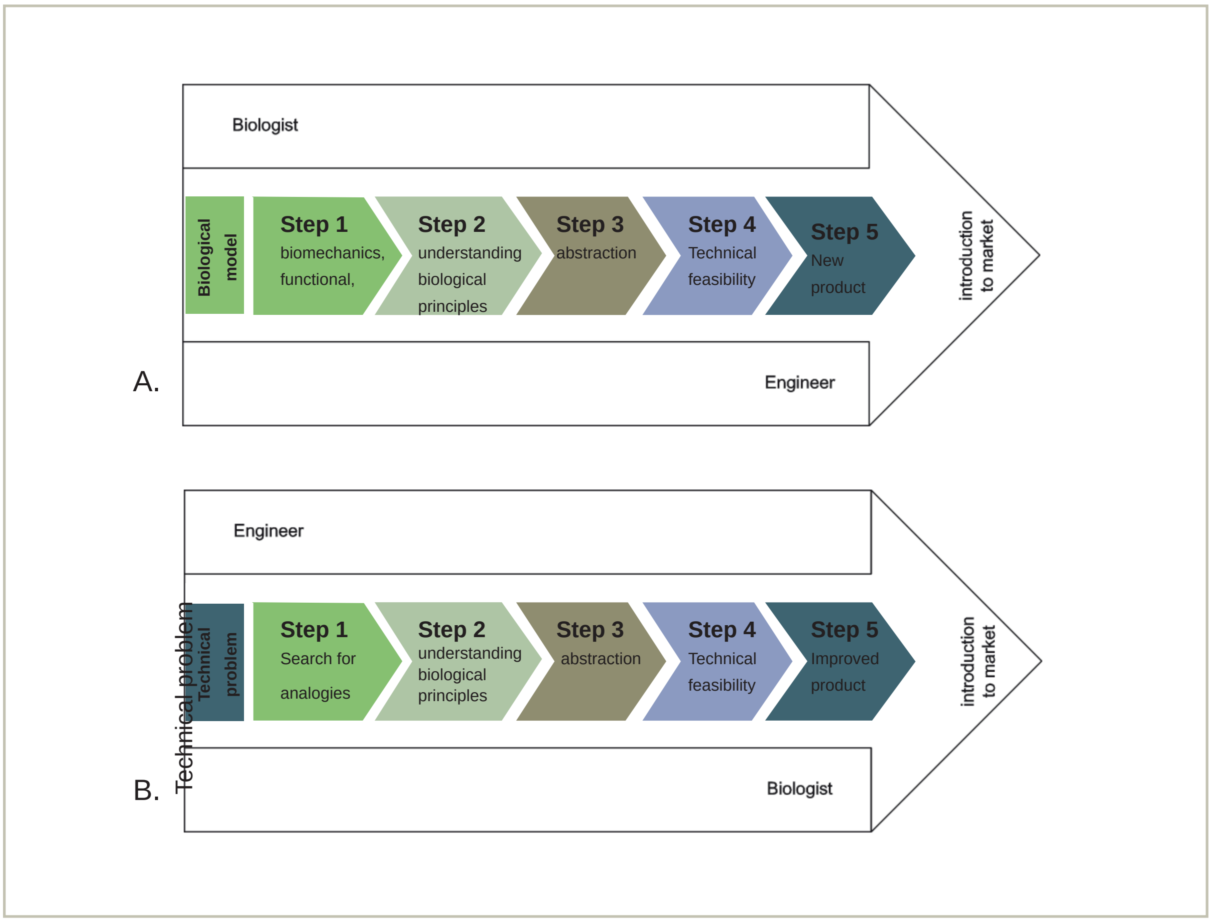


Figure 2.10. Biomimetic development process. A. Biology push, **B.** Technology pull. Credits: adapted with permission from ISO standard 2015:18458 [23] and [27].

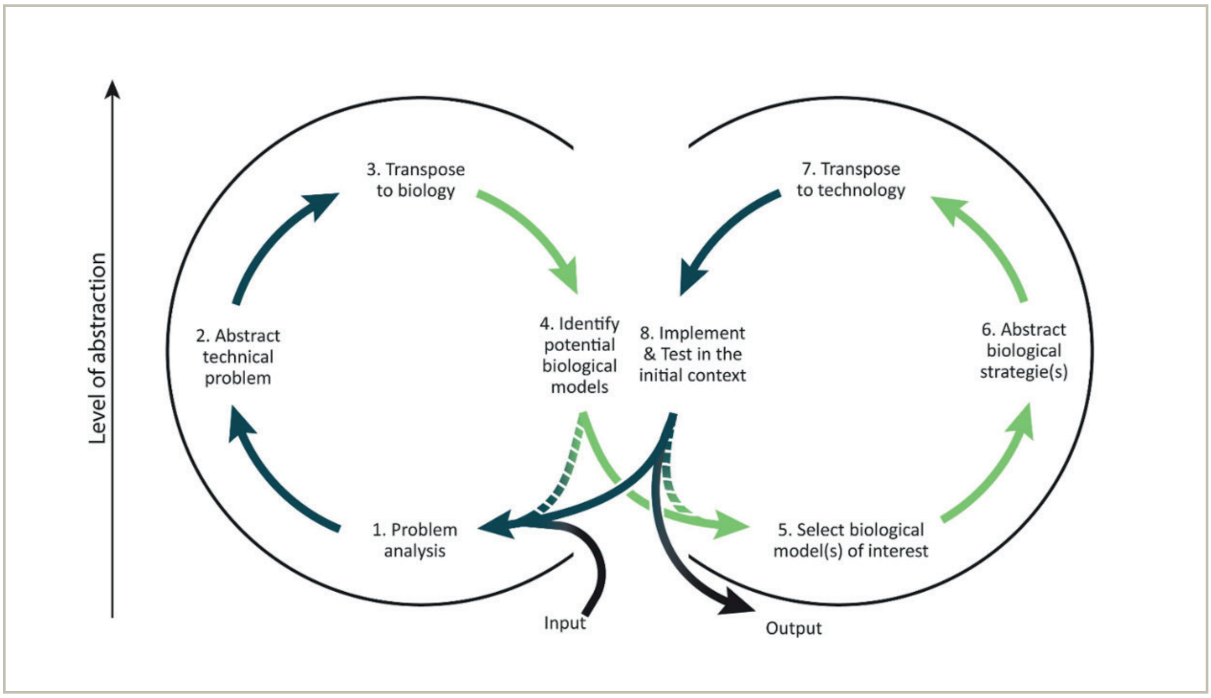


Figure 2.11. The eight steps of the unified problem-driven biomimetic design processes. Credits: reuse with permission from Fayemi (2015) [2].

Method. A method is a set of specific steps that guide the design process. A method relies on knowledge, know-how and tools [122]. It has a lower level of abstraction compared to the process. In biomimetics, dozens of methods have been developed over the past decades. They mostly belong to the problem-driven approach since the transfer from industry to biology remains one of the key challenges [120].

Tool. A tool is a framework that allows practitioners to go through the various steps determined by the method. There is a wide diversity of tools such as ontology, thesaurus, databases, algorithms, taxonomy. In biomimetics, more than 43 tools have been founded in the literature as reviewed by [120] in 2017. They are mostly stage-specific tools to facilitate the tasks of the technology pull BID. More than half can be used for the technology push BID. However, no tools have only been design to facilitate the biology push BID approach [120]. Wanieck *et Al.,* have also outlined that half of these tools help for the identification of biological systems which corresponds to the step 2 and 3 of the technology pull BID. In fact, recent studies have suggested that the identification of the relevant biological model(s) remains a main steps to work over the next decades [14], [130].

Main trends. The formalisation of biomimetic processes, methods, and tools, has been focusing on the technology pull BID approach since the transfer from industry to biology remains the main challenges. Furthermore, over 18 'technology pull' processes and 43 methods and tools have been developed for this purpose such and a 'unified technology pull biomimetic process' by Fayemi et al, (2017) [120], [126], [131], [132] (see **Fig. 2.12**). This process break up the technology pull BID process into 8 steps rather than 6. Today, the unified technology pull biomimetic process is used as a reference rather than the technology pull BID developed by ISO 18458:2015 [126]. In addition, the diversity of BID tools and methods can create confusions since the users do not have a clear vision of the available tools and the step they facilitate.

In addition, some tools were specifically proposed to support designers in applying biomimetic in architecture, such as *BioGen* developed by Lidia Badarnah (2012) [23], *Multi-functional biomimetic adaptive façad*e (2018) developed by A. Kuru [4], [133], [134] or *Biomimetic principles for the development of adaptive architectural envelopes* (2015) developed by M. López [18], [135].

2.5.2. Methods and tools for the biological steps

This section analyses the biomimetics frameworks used to design the 19 Bio-BS, and the relationship between biological knowledge selected in [5]. **Table 2.3.c.** presents the main results from that two studies.

Biomimetic design process	
	Approach:
[4]	**58% top-down** | 32% Bottom-up
[5]	**63% Biology push** | 37% Technology pull
[5]	Use of biomimetic design framework: **95% No** | 5% Yes
[5]	Tools for abstraction: **73% NA** | 21% None | 6% Other | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm
[5]	Tools for understanding biological models: **80% NA** | **20% none** | Database | Ontology | Taxonomy | Thesaurus | Method | Algorithm | Other
[5]	Inputs of biologists from the design team Type of knowledge: **58% Existing for general public** | 40% for specialists | 12% created by specialists and/or by experimentation during the design process
[5]	Inputs of biologists from the design team: **47% No interaction with any biologists** | 31% Biologists integrated in the design process | 21% Biologists consulted
[5]	Number of biological models: **84% Single** | 16% Multiple

Table 2.3.c. Main results that describe biomimetic design processes, data extracted from [4], [5].

Approach. The Bio-BS can result from two design processes: 'technology pull' and 'biology push' BID. In most cases, the Bio-BS were designed following a biology push approach. 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 [136]. 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 [131] (see **Fig. 2.11** see previous pages).

Use of design framework. 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.

Tools for understanding biological model is a variable based on [137] 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. 18-19). Projects that benefited from the involvement of biologists clearly compensated this lack: for instance, ICD/ITKE design teams 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.

Tool for abstraction. Likewise, the interviews did not provide detailed information on this step of the biomimetic design process 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. For instance, the Sierpinski Forest (Id. 7) is the result of an opportunity rather than the use of specific tools for abstraction [138], [139].

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 (see **Fig. 2.12**): 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) [69], [140]. However, although the Eastgate is a beautiful example of what bioinspiration or biomimicry can promote, his analysis was eventually proved erroneous [70]. 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 [106], and according to the interviews, lead to co-discoveries.

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).

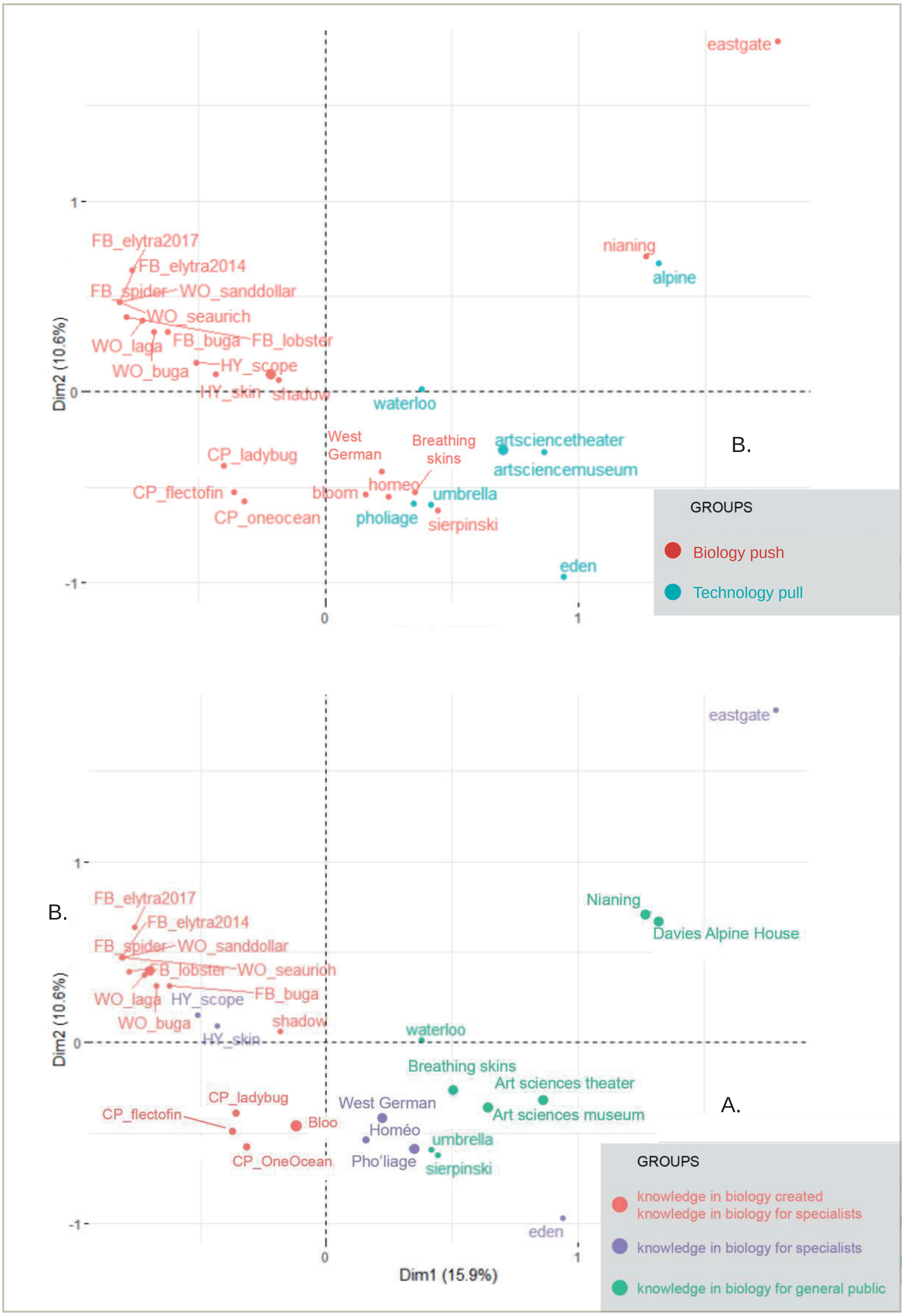


Figure 2.12. **MCA of the 19 Bio-BS distinguished by the variable**
(A) Biomimetic approach, (B) Biologists' inputs. Credits: reused from [4].

2.5.3. Methods and tools for multi-regulation

Previous section demonstrates that very few Bio-BS consciously followed a biomimetic design framework, and most of them are mono-functional. However, eight biomimetic methods and twelve stage-specific biomimetics tools have been designed to address multi-functionality as reviewed by [6], [141]. For instance, the Georgia Institute of Technology has developed a technology pull biomimetic design methodology with addition of several phase-specific tools to solve multi-functional challenges [22], [142]–[144]. Other frameworks such as BioTRIZ developed by Vincent et al. [145], the Biocards developed by [146], [147], and researches carried out at Macquaire University and the University of New South Wales [148] have integrated the concepts of multi-function or multi-regulation within biomimetic design processes. Similarly, the 'Nature-inspired solution guide' developed by KARIM network, [21] has integrate multi-regulation within the 22 properties biological systems to abstract.

Most of these frameworks, provide support for a functional decomposition of the challenge into sub functions. This step is followed by a number of parallel solutions searches corresponding to the number of sub functions [6], [141].

Within these frameworks, three of them have focused on the design of biomimetic building envelopes. Since this research focuses on the development of multi-functional building envelopes, this section provides a comparative evaluation these three biomimetic frameworks. **Table 2.7** presents then compared these three biomimetic frameworks with four main variables such as the approach, the number of cases of study that have used the design framework. The table also qualifies the cases of study resulting of the framework's application: the number of cases, their maturity and multi-functionality capacities. The table a was reviewed by the authors of the developed frameworks.

Ref.	Frameworks	Approach	Cases	Maturity	Multi
[149], [150]	i. **BioGen**, 9 steps technology pull BID	technology pull	4	numerical modelling	mono
[4], [133], [134]	ii. **Multi-functional biomimetic adaptive façade**, 3 main steps technology pull BID	technology pull	1	numerical modelling	multi
[18], [135]	iii. **Biomimetic principle for envelopes**,	biology push	2 1	concepts numerical modelling	mono multi

Table 2.7. Existing biomimetic frameworks for the development of building envelopes.

i. BioGen (2012), developed by L. Badarnah [149], [150] is a 9 steps technology pull BID method for the design of building "living envelopes" concepts. The developed framework covers the whole technology pull BID process, from the problem analysis to the generation of digital prototypes. It first qualifies the four main environmental factors that building envelopes have to manage: heat, light, water, air. Then each is separately addressed resulting in 4 cases of numerical prototype. In addition, the author has also developed specific phase tools as the *exploration model*, *pinnacle analysis, pinnacle analysis matrix*, *design path matrix*. The application of BioGen resulted in the development of four numerical modelling of building living envelopes design by L. Badarnah. Each case address the regulation of one single environmental factor rather than several.

ii. Multi-functional biomimetic adaptive façade (2018), developed by A. Kuru [4], [133], [134] - is a framework for designing multi-functional biomimetic adaptive façades. The framework covers the whole technology pull BID process in 3 main steps: (i) *definition of boundary conditions as functional requirements*, (ii) *selection and mapping of corresponding multi-functional biological models*, and (iii) *design generation for multi-functional biomimetic adaptive façades*. The step 2 includes a novel tool to map multi-functional biological models developed by A. Kuru. Applying these frameworks a multi-functional adaptive façade was designed by the author. This case transfers morphological and physiological adaptations found in the barrel cactus (*Echinocactus grusonii*) to a dynamic façade. Quantitative simulations have demonstrated improvements of thermal and visual comfort, and energy consumption when incorporating the biological solution.

iii. **Biomimetic principles for the development of adaptive architectural envelopes** (since 2015) developed by M. López [18], [135] – is a biology push BID methodology for the design of adaptive building façades. The methodology covers the whole design process in four steps: (i) the data collection then the design concept generation divided into three sub-steps: (ii) *application ideas*, (iii) *innovation* then (iv) *design concept generation*. This framework focuses on plants since they lack movement and remain to a specific location like buildings. Two mono-functional and theoretical design cases, and one multi-functional resulted from the application of the methodology.

These three frameworks ended up with cases of study. None of them cases were developed beyond the concept or numerical prototype. In fact, they have been designed in academic contexts such as PhD thesis, master or undergraduate courses. They remain at a conceptual stage of development. These findings are aligned with recent study in BID which highlighted the gap between theoretical and real-world up-take [4]. Both multi-functional and mono-functional cases resulted from the BID frameworks. Multi-regulation is addressed since the BID design meet at least two functions of regulation. The descriptions of frameworks to solve multi-functional challenge has also suggested that the integration of multi-regulation in BID needs a functional decomposition. Multi-functionality breaking down the problem into single sub-problems. Sub-problem represents a single function that is, at first, studied separately, and later jointly implemented into the product. These methods assume that the solution to the overall engineering problem can be found by using the super positioning principle where solutions for each of the required functions are combined [141].

Id	Frameworks	Characterization of biological models				Environmental factors regulated						
		Matter	**Time**	**Functions of regulation**	**Environment**	H	L	A	W	N	M	Other
1	BioGen (L. Badarnah) [149], [150]	nano, micro, meso, macro	adaptation	gain, retain, dissipate, prevent, exchange, move, conserve, lose, transport, filter, illuminate, harness	Köppen-Geiger classification [151]	+	+	+	+	-	-	-
2	Multifunctional biomimetic adaptive façade (A. Kuru) [4], [6], [133], [134]	cell, tissue, organ, organism, ecosystem	adaptation, performance	gain, loose, maintain, filter, exchange	Qualified with light, air, heat, water, energy	+	+	+	+	-	-	energy
3	Biomimetic principle for envelopes (M. Lopez) [18], [135]	macro, micro	adaptation	Exchange, gain, retain, dissipate, prevent, conserve, transport, lose, regulate	Worldwide bioclimatic classification system [152]	+	+	+	+	-	-	carbon dioxide

Table 2.8. Overview of the three biomimetic frameworks. Environmental factors regulated by the biological models: H (Heat), L (Light), A (Air), W (Water), N (Noise), M (Mechanics). The symbols (+) denote that the framework allows to assess the biological models' ability to regulate this factor. The minus symbols (-) shows that the framework does not allow to assess the biological models' ability.

In addition, **Table 2.8** assesses the steps related to biology within the tree frameworks through different categories: time, matter, function of regulation and environment. The information was first collected going through literature, then reviewed by the researchers who designed the method for validation.

Functions of regulation. All the frameworks created for the design of building envelopes qualify several functions of regulation of one or several biological systems. In fact, building envelopes are quite standard designs with similar functions of regulation whatever the building location. For this purpose, biological systems are studied through several functions of regulation.

Time. The concept of time is not clearly presented by embedded throughout the three frameworks.

Matter. One of the frameworks qualify the size of the biological models. Some frameworks use variables which refer to the field of physics such as "nano, micro, meso, macro" while other use variables referring to the hierarchical organization of living systems in life sciences like "tissue, organ, organism, cell, ecosystem".

Environment. Almost half of the frameworks define the environment of the studied biological system. Among them, none use the same environmental classification. They belong to different fields such as climatology (Köppen-Geiger classification [151], Id. 1) or botanic (worldwide bioclimatic classification system [ref], Id. 2) which provide both quantitative and qualitative data on the climates.

Environmental factors. The most assessed environmental factors are light, heat, air and water (Ids 1, 2, 3**)**. Atmosphere carbon dioxide concentration (carbon dioxide) and energy one time. Mechanical stress and noise are mentioned by these three frameworks.

Access to biological data. All these three frameworks create their own data collection of biological models rather than using existing data base or data collections. These data collections are filled by the research teams using the scientific literature. The size of the data collection highly varies from a few dozen biological models (Id. to more than hundred (Ids. 1,2).

2.6. Conclusion

How do existing biomimetics building skins meet with multi-function?

- The existing biomimetic building skins have limitation in addressing multi-regulation of unlinked environmental factors, as third of the Bio-BS (n=19) addressed single-regulation of environmental factors (30%) or double-regulation mostly of light and heat (40%).
- the evaluation grid of multi-regulation has limitation since it does not provide a qualitative and quantitative assessment. For instance, the research pavilions HygroSkin and HygroScope regulate four factors applying the previous grid. However, they are far from assessing multi-functionality as expected for a building envelope.

How do biological envelopes cope with multi-regulation?

- Living envelopes outline a variety of multi-regulation performances since they regulate simultaneously many environmental factors. However, none of them simultaneously regulate all the environmental factors as expected for the building envelope. Acoustic remains the less performed environmental aspect since few living systems protects from sound level and intensity. In addition, some biological systems regulate contradictory requirements while building envelopes mostly provide multi-regulation of linked environmental factors

What is the state of the art of current biomimetics methods and tools that can be used to design multi-functional building envelopes?

- There are three main frameworks that have been developed to design biomimetic multi-function building envelopes. However, this analysis demonstrates that current frameworks are not adapted to provide a global understanding of living systems. The biological systems are mainly characterized through the functions of regulation provided by the biological system without time and environment contextualization.
- 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 author would not be aware.
- 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).

Combining the results of this chapter led to the following statements:

- These is a need for the development of biomimetic building envelopes with multi-regulation capacities to address contradictory requirements. These systems have to address multi-regulation of unlinked environmental factors such as noise and light. The terrestrial biological systems are promising models since they cope with the same environmental factors as buildings do. There is a need for the development of both qualitative and quantitative grid of evaluation of multi-regulation for building envelopes. The grid has to include the different levels of regulation for each environmental factor.
- The diversity of environmental aspects regulated within a single living organism suggest that abstracting and then combining different biological features can enhance multi-regulation within biomimetic design. This result also suggests that a multi-criterion mapping of living system can reveal multi-regulation capabilities of living systems, and beyond the ‘obvious’ biological features.

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2.8. Annexes

List of annexes

- **Annexe A.** Data sheet Davies Alpine House, p. 29-31, from [5]
- **Annexe B.** Data sheet ITECH / ITKE / ITFT Pavilion p. 26-88, from [5]
- **Annexe C.** Research poster ‘From biological interfaces to building multi-regulation’ [153]

Davies Alpine House, 2006. England

The Davies Alpine House, located in Kew Gardens, London, England is inspired by the ventilation system of termites mounds. The building was designed in 2006 by Wilkinson Eyre, Dewhurst MacFarlane and Atelier Ten.

The building was designed to avoid energy intensive refrigeration typically needed for the display of alpine plants. It instead uses a stack effect to cool the interior passively, while essentially remaining a glass house with high rates of air circulation. A removable shading sail is included in the design to prevent too much sunlight reaching the plants. The stack effect is enhanced through the high internal space created by the double arches, sequential apex venting as temperature increases, by vents at the bottom of the glass structure, and through a Barossa termite inspired decoupled thermal mass labyrinth below the building. The concrete block labyrinth is set between a double concrete slab that also acts to resist the forces exerted by the tension rods that support the glass ceiling. The air that is cooled within the labyrinth is recirculated so it cools the low level plants. The labyrinth is vented at night to take advantage of cooler temperatures, meaning the mass remains at a temperature usually cooler than that required for the space itself.

Name: Davies Alpine House
Year of construction: 2006
Climate: Temperate (Cfb)
City: London
Country: England

Surface: 70 m²
Cost (£/m²): £800,000 total cost, (£11 430 / m²)
Project use: green house (tertiary private)
Renovation: No

atelier ten

WilkinsonEyre

Data sheet completed by Estelle Cruz & Tessa Hubert (literature)

Data sheet reviewed by Patrick Bellew
patrick.bellew@atelierten.com

References

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- Pawlyn, M. (2011). Biomimicry in Architecture. (R. Publishing, Ed.)
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Annexe A. Data sheet Davies Alpine House, pages 29-31.
Credits: Ceebios / Mecadev / Vicat / NOBATEK/INEF4

Biomimetic

Definition
- ○ Biomimetics
- ○ Bioinspiration
- ● Biomimicry

Approach
- ● Biology-push
- ○ Technology-pull

Origins of bioinspiration
- ● Random opportunities
- ○ Interdisciplinary collaborations
- ○ Call for projects
- ○ Other

Targeted performance
- ● Thermal comfort
- ● Visual comfort
- ○ Acoustic comfort
- ● Air quality
- ○ Mechanical stress resistance
- ○ Water regulation

Integration scale of biomimetics
- ○ Material (facade component)
- ○ Facade system
- ● Building

Link to biology

Model kingdom
- ● Animalia: termites mounds
- ○ Plantae
- ○ Fungi
- ○ Bacteria/Archaea
- ○ Protozoa
- ○ Chromista / Ecosystems

Number of models
- ● One
- ○ Two
- ○ More

Type of knowledge
- ● Existing for general public
- ○ Existing for specialist
- ○ Created during the design process

Inputs in biology
- ● Background of the designer
- ○ Acquisition during the design
- ○ Biologists integrated in the process

Design process

Use of design framework
- ○ Yes
- ● No

Eco-design approach
- ● Yes
- ○ No

Major constraints
- ○ Lack of funds
- ○ Use of biomimetic tools
- ○ Law regulations
- ○ Technical problems
- ● Other

Design complexity
- ○ High (software, design process)
- ● Low (well-known design)

Outcome

Technology readiness level
- ○ TRL6 - demonstrated in relevant environment
- ○ TRL7 - system prototype demonstration in operational environment
- ○ TRL8 - system complete and qualified
- ● TRL9 - actual system proven in operational environment

Overtime performance
- ● Still operating
- ○ Not operating yet
- ○ Destroyed

Construction complexity
- ○ High (new technology)
- ● Low (existing technology)

Main component of the building envelope
- ○ Polymers
- ○ Alloys
- ○ Textiles
- ○ Wood
- ● Concrete
- ○ Carbon-glass fiber

Level of innovation
- ○ Breakthrough innovation
- ● Improvement of existing systems

Adaptable to renovation
- ○ Yes
- ● No

Adaptatibility

Adaptation to stimuli
- ○ Yes
- ● No

Type of trigger (input)
- ○ Mechanical (e.g. wind load)
- ○ Thermal (e.g. air temperature)
- ○ Electromagnetic
- ○ Optical (e.g. daylight level)
- ○ Air quality (e.g. humidity)
- ○ Occupancy
- ○ Other (internet data, BMS, etc.)

Type of actuator (output)
- ○ Mechanical
- ○ Pneumatical
- ○ Electromagnetic
- ○ Thermal
- ○ Chemical
- ○ Other

Control
- ○ Intrinsic (auto-reactive)
- ○ Extrinsic (external control)

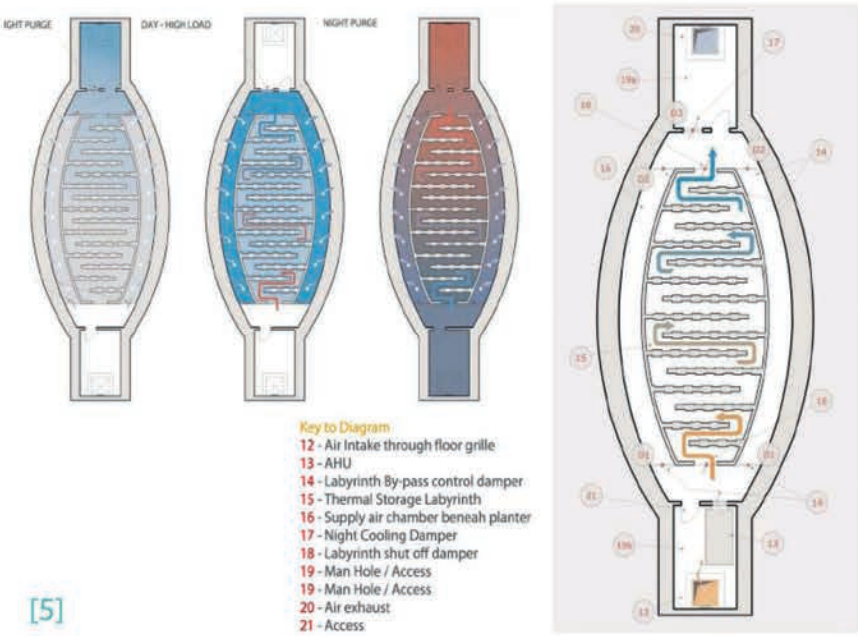
Response time
- ○ Seconds
- ○ Minutes
- ○ Hours
- ○ Days
- ○ Weeks
- ○ Months

Spatial adaptation
- ○ Nanometers
- ○ Micrometers
- ○ Millimeters
- ○ Centimeters
- ○ Meters

Material adaptation
- ○ Elasticity
- ○ Inflatable
- ○ Bi-material
- ○ Other

Degree of adaptability
- ○ On-Off
- ○ Gradual

Annexe A. Data sheet Davies Alpine House, pages 29-31.
Credits: Ceebios / Mecadev / Vicat / NOBATEK/INEF4



Pictures and credits

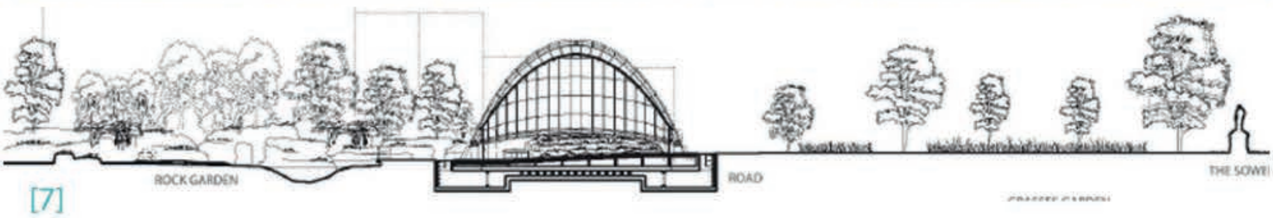
[1] Exterior of the greenhouse
© Oast House Archive

[2] [5] Labyrinth under construction for thermal regulation system used by permission from © Atelier Ten

[3] [4] Ventilation mouths inside the greenhouse used by permission from © Atelier Ten

[6] Blinds going up used by permission from © Joshua Molnar

[7] Elevation of the greenhouse used by permission from © WilkinsonEyre



Annexe A. Data sheet Davies Alpine House, pages 29-31.
Credits: Ceebios / Mecadev / Vicat / NOBATEK/INEF4

ITECH Research Demonstrator, 2018-19. Stuttgart, Germany

The ITECH research demonstrator 2018/19 investigates large-scale compliant architecture inspired by the folding mechanisms of the Coleoptera coccinellidae (Ladybug) wings. The demonstrator is composed of two adaptive folding elements made of carbon and glass fibre-reinforced plastic.

The demonstrator is first to employ industrial tape-laying technology for an automated fabrication of large-scale compliant mechanisms. Their kinetic behaviour is achieved through distinct compliant hinge zones with integrated pneumatic actuators. An interactive control system, consisting of integrated sensors, online communication, and backend computational processing, facilitates interactive and user-controlled adaptation.

https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/itech-research-demonstrator-2018-19/

Name: Research Pavilion ITECH
Year of construction: 2018/2019
Climate: Temperate (Cfb)
City: Stuttgart
Country: Germany
Surface (m²): < 2 m²
Cost (€): na
Project use: Pavilion
Renovation: No

ITECH Integrative Technologies & Architectural Design Research M.Sc. Programme — itke Institute of Building Structures and Structural Design — ITFT Fiber Based Visions

University of Stuttgart
Germany

Data sheet completed by Estelle Cruz & Tessa Hubert during a research exchange of three weeks at ITKE, University of Stuttgart.

Data sheet reviewed by Axel Körner
axel.koerner@itke.uni-stuttgart.de

References

• Ruggiero, Michael A., Dennis P. Gordon, Thomas M. Orrell, Nicolas Bailly, Thierry Bourgoin, Richard C. Brusca, Thomas Cavalier-Smith, Michael D. Guiry, and Paul M. Kirk. 2015. "Correction: A Higher Level Classification of All Living Organisms." PLOS ONE 10 (6): e0130114.

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Annexe B. Data sheet ITECH / ITKE / ITFT Research pavilion, pages 86-88.
Credits: Ceebios / Mecadev / Vicat / NOBATEK/INEF4

Biomimetic

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- ● Facade system
- ○ Building

Link to biology

Model kingdom
- ● Animalia: Coleoptera coccinellidae
- ○ Plantae
- ○ Fungi
- ○ Bacteria/Archaea
- ○ Protozoa
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Number of models
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Design process

Use of design framework
- ○ Yes
- ● No

Eco-design approach
- ○ Yes
- ● No

Major constraints
- ○ Lack of funds
- ○ Use of biomimetic tools
- ○ Law regulations
- ● Technical problems
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- ○ Low (well-known design)

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- ○ Weeks
- ○ Months

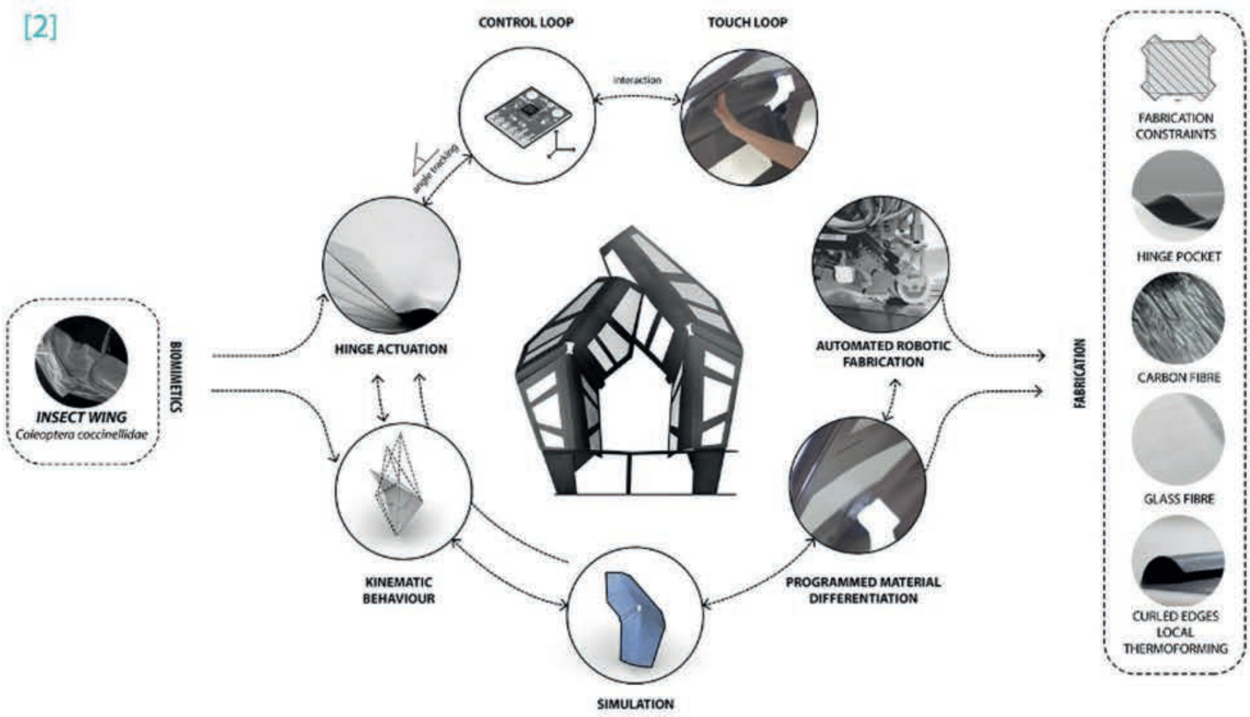
Spatial adaptation
- ○ Nanometers
- ○ Micrometers
- ○ Millimeters
- ● Centimeters
- ○ Meters

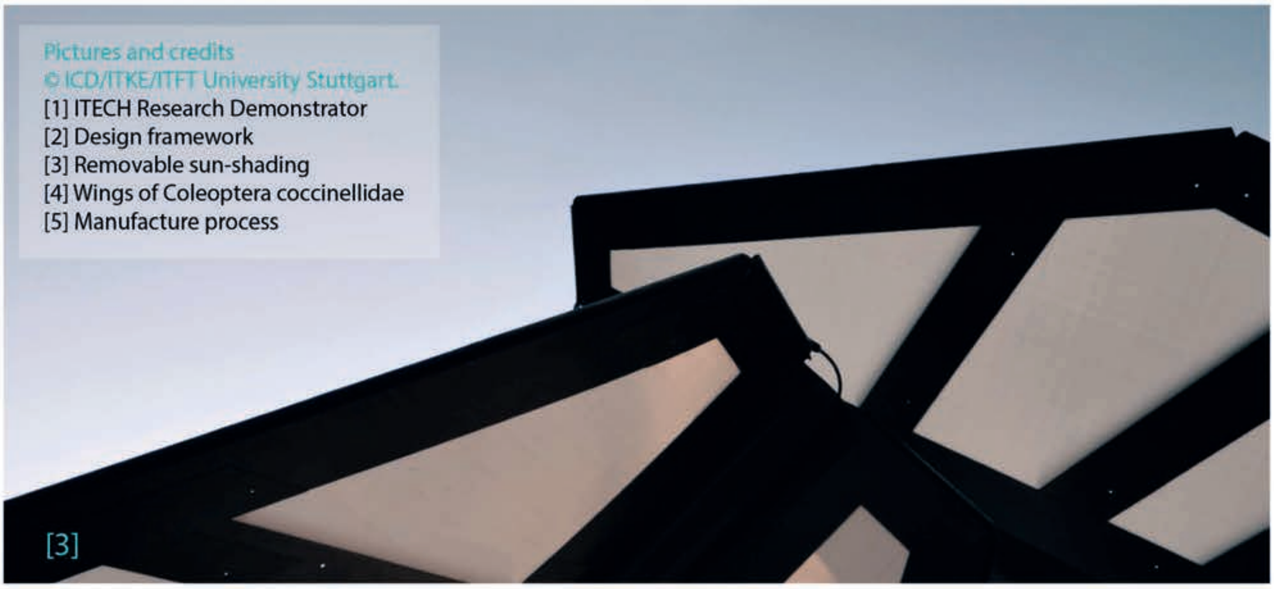
Material adaptation
- ○ Elasticity
- ○ Inflatable
- ○ Bi-material
- ● Other

Degree of adaptability
- ○ On-Off
- ● Gradual

Annexe B. Data sheet ITECH / ITKE / ITFT Research pavilion, pages 86-88.
Credits: Ceebios / Mecadev / Vicat / NOBATEK/INEF4

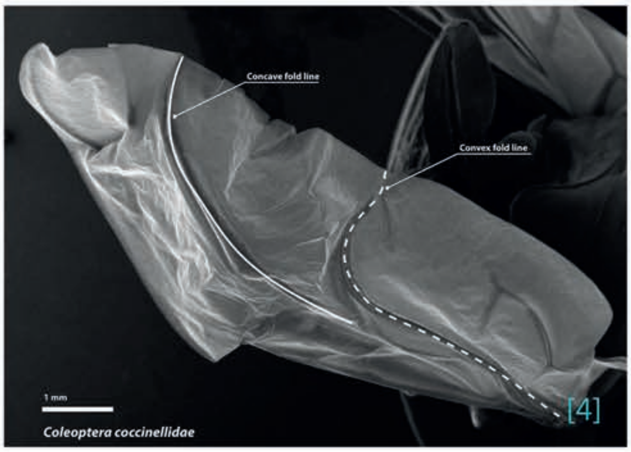
[2]





Pictures and credits
© ICD/ITKE/ITFT University Stuttgart.
[1] ITECH Research Demonstrator
[2] Design framework
[3] Removable sun-shading
[4] Wings of Coleoptera coccinellidae
[5] Manufacture process

[3]



[4]

[5]

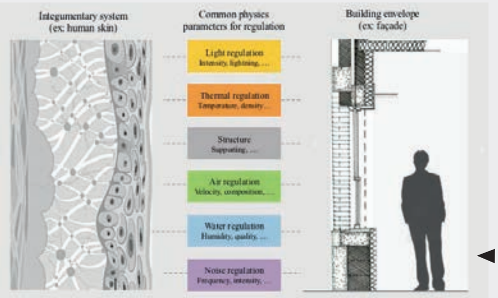
Annexe B. Data sheet ITECH / ITKE / ITFT Research pavilion, pages 86-88.
Credits: Ceebios / Mecadev / Vicat / NOBATEK/INEF4

From biological interface to building multi-regulation

Estelle Cruz[a),b)*], Amandine Bonnet[b)], Tarik Chekchak[e)], Pierre-Yves Henry[b)], Caroline Gilbert[b)], Christophe Goupil[d)], Lidia Badarnah[e)], Kalina Raskin[a)], Fabienne Aujard[b)]

a) CEEBIOS, European Centre in Biomimetics, France, (corresponding author: estelle.cruz@ceebios.com)
b) MECADEV UMR CNRS 7179, National Museum of Natural History of Paris, France
c) Institut des futurs souhaitables, Paris, France
d) LIED UMR 8236, Interdisciplinary Energy Research Institute Paris, France
e) University of New England, Bristol, UK

1. Constat: buildings and living organisms cope with the same abiotic factors

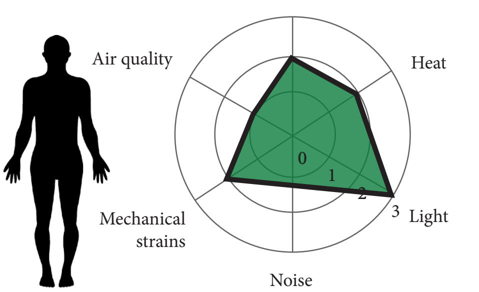


As interfaces between the indoor and outdoor environment, building envelopes must be multi-functional and adaptive through days and seasons to achieve multi-regulation. Shaped by environmental pressures, biological organisms have developed sophisticated adaptations, specifically through their interfaces called teguments. Teguments of living organisms, as diverse as skin, hairs, cuticles, can manage the same environmental factors as building envelopes. Their thermal, acoustic, light, humidity and air regulation capacities can be quantified using physical parameters such as hygrometry, thermal conductivity, porosity, compacity, etc.

◄ **Figure 1,** Common abiotic factors to which biological and built envelopes have to cope with. Adapted from Lidia Badarnah PhD thesis, 2012

2. Method: a tool to qualify multi-regulation of "living" interfaces

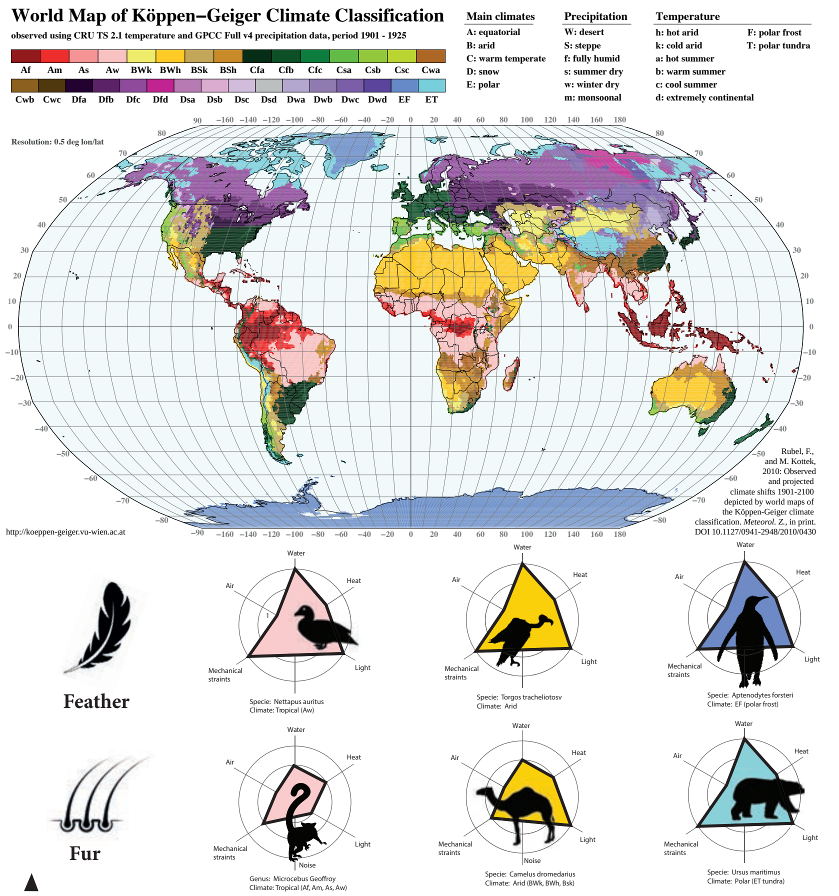
Multi-regulation rating scale of abiotic factors
0 = the tegument is not involved the regulation
1 = the tegument contributes very weak to the regulation
2 = the tegument significantly contributes to the regulation but is not the only
3 = the tegument regulates itself



▲
Figure 2, Qualitative evaluation of human skin regulation. Climate: all. Subspecie: Homo Sapiens Sapiens.

Water (2): the human skin ensures water tightness and allows the evacuation of excess water by sweating
Heat (2): the human skin allows the regulation of the heat by perspiration and cold by shuddering
Light (3): the human skin stumps for UV protection (melanin production)
Noise (?): No data
Mechanical strains (2): the elasticity of human skin allows the absorption of shocks
Air quality (1): human skin contributes little to gaseous exchange ensured by the lungs

3. Results: a tool to assess multi-regulation of "living" interfaces



▲
Figure 3, Qualitative analysis of multiregulation of fur and feather based on Köppen classification

4. Conclusion

- **Lack of contextualization** of the adaptive response (qualitative analysis not correlated with abiotic factors and the needs of the organism). Figure 5.a

- Move **from qualitative to quantitative analysis**. Radar charts are useful to compare different types of teguments. They are unprecised to compare different types of feather or fur. Figure 5.b.

5. Discussion

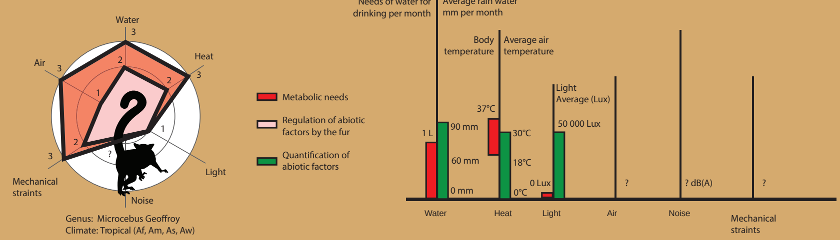
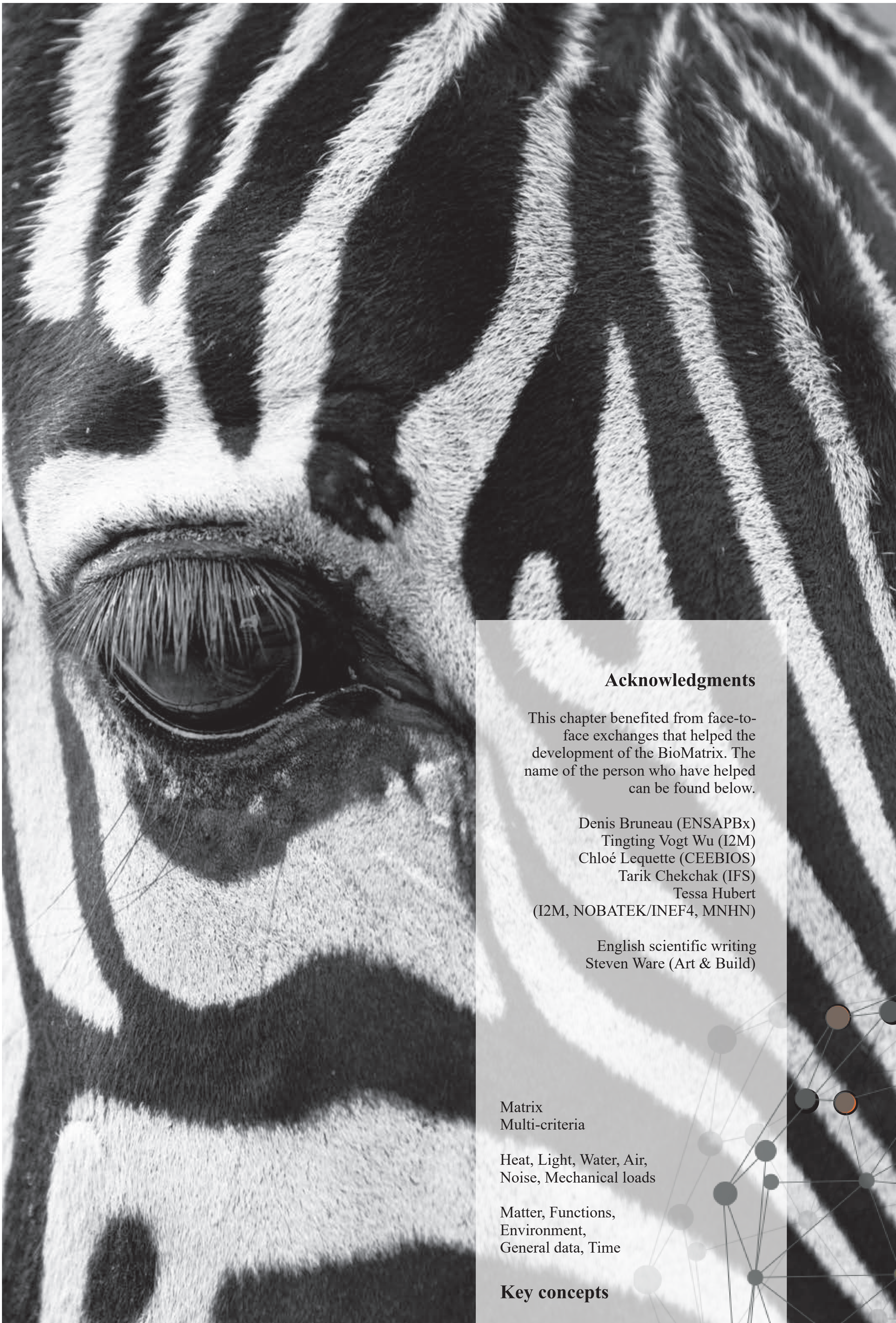


Figure 5.a. and 5.b Qualitative multi-regulation of *Microcebus Geoffroy fur* according to it metabolism needs (5.a). Quantitative multi-regulation of *Microcebus Geoffroy* fur according to it abiotic factors

Annex C. Research poster. Colloque Poils et Plumes, MNHN, Sorbonne, 2019.



Acknowledgments

This chapter benefited from face-to-face exchanges that helped the development of the BioMatrix. The name of the person who have helped can be found below.

Denis Bruneau (ENSAPBx)
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Chloé Lequette (CEEBIOS)
Tarik Chekchak (IFS)
Tessa Hubert
(I2M, NOBATEK/INEF4, MNHN)

English scientific writing
Steven Ware (Art & Build)

Key concepts

Matrix
Multi-criteria

Heat, Light, Water, Air,
Noise, Mechanical loads

Matter, Functions,
Environment,
General data, Time

BioMatrix

Chapter 3

A multi-criteria tool to characterize the biological systems

To fill the gap between multi-functional capabilities of living systems and the development of mono-functional building envelopes, chapter 3 introduced a novel tool for a multi-criteria characterization of biological systems. This tool – called the BioMatrix - aims to increase the development of multi-functional biomimetic designs by abstracting several principles of biological systems. This matrix comprises four linked categories: 'Functions of regulation', 'Environment', 'Time' and 'Matter'. The circular representation of the matrix helps users to develop systemic thinking.

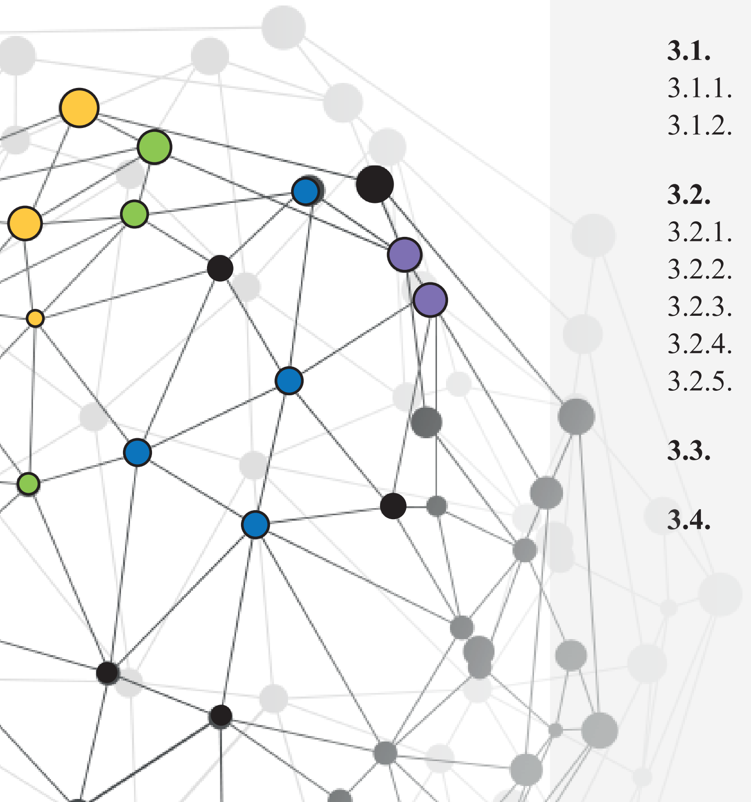


Table of contents

3.

3.1. Position of the BioMatrix

3.1.1 Context

Chapter 2 and Cruz, Hubert et al. (2020) demonstrate that thirty existing biomimetic building envelopes are mono-functional and mostly abstracted from a single property of a biological system [1]. For instance, each ICD/ITKE research pavilions developed at the University of Stuttgart are inspired by a single biological principle abstracted from a single biological system. These research pavilions are also mono-functional since the ICD / ITKE laboratories focus on light structure [2], [3].

However, living organisms are multi-criteria systems with multi-functional properties at all scales [4]–[6]. For instance, the molluscs' or crustaceans' shells support multiple functions such as communication, protection, reproduction, gas exchanges. Cells' membranes also provide multifunctional interfaces between the cell and its surroundings. Multi-functionality is intrinsic to life [5], [7].

In addition, Cruz, Hubert et al. (2020) showed that the distribution of inspiring biological models is not proportionate to the distribution of estimated biomass on Earth, nor proportional to the estimated and described species. For instance, within existing biomimetic envelopes, three of them - Eastgate building (Zimbabwe), Nianing church (Senegal) and the Davies Alpine House (United Kingdom) - are inspired by the ventilation system of the termites' mounds.

Moreover, several researches have outlined that the understanding, accessibility and the selection of biological data remains a challenge [8]. Gruber *et Al.* (2008) highlighted that superficial research or lack of information from life sciences can result to failure in transferring natural processes into a design [9].

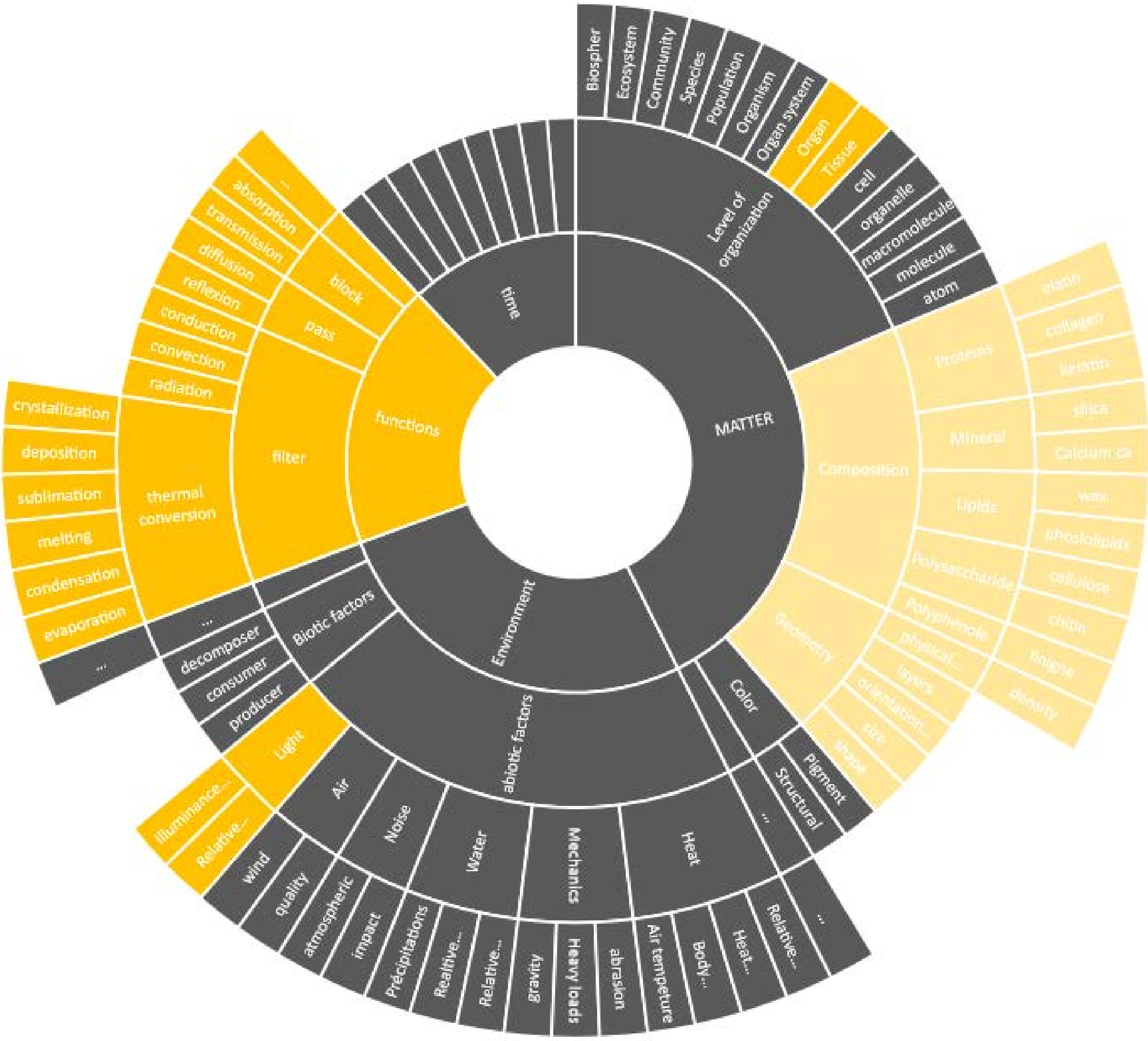
The research questions addressed in chapter 3 go as follow:

- What are the key concepts to understand biological systems as complex system?
- How to structure biological knowledge for a convenient access by designers?

3.1.2. Method

Several research methods are used in this chapter to develop a tool for multi-criteria characterisation. These methods include the following:

- Literature review, and comparative analysis of the existing biomimetic design frameworks to achieve multi-regulation and design biomimetic building facades (see Chapter 2 section 'Biomimetic frameworks')
- Collaboration with T. Chekchak - head of the biomimetic department of IFS – which has developed 4 –day - professional training in biomimetics based on the 'unified problem driven biomimetic design process' enriched with the key concepts of complexity [10].
- Collaboration with the department 'Industrial studies' of the Ceebios which responds to industrials technical challenges with a biomimetic approach.


MATTER
Level of organization
Biospher
Ecosystem
Community
Species
Population
Organism
Organ system
Organ
Tissue
cell
organelle
macromolecule
molecule
atom
Composition
Proteins
elastin
collagen
keratin
Mineral
silica
Calcium ca
Lipids
wax
phospholipids
Polysaccharide
cellulose
chitin
Polyphenole
lingnine
Geometry
physical...
density
layers
orientation...
size
shape
Color
Pigment
Structural
...
Environment
abiotic factors
Heat
Air tempeture
Body...
Heat...
Relative...
...
Mechanics
gravity
Heavy loads
abrasion
Water
Precipitations
Realtive...
Relative...
Noise
impact
Air
wind
quality
atmospheric
Light
Illuminance...
Relative...
Biotic factors
producer
consumer
decomposer
...
functions
filter
thermal conversion
crystallization
deposition
sublimation
melting
condensation
evaporation
...
radiation
convection
conduction
reflexion
diffusion
pass
transmission
block
absorption
...
time

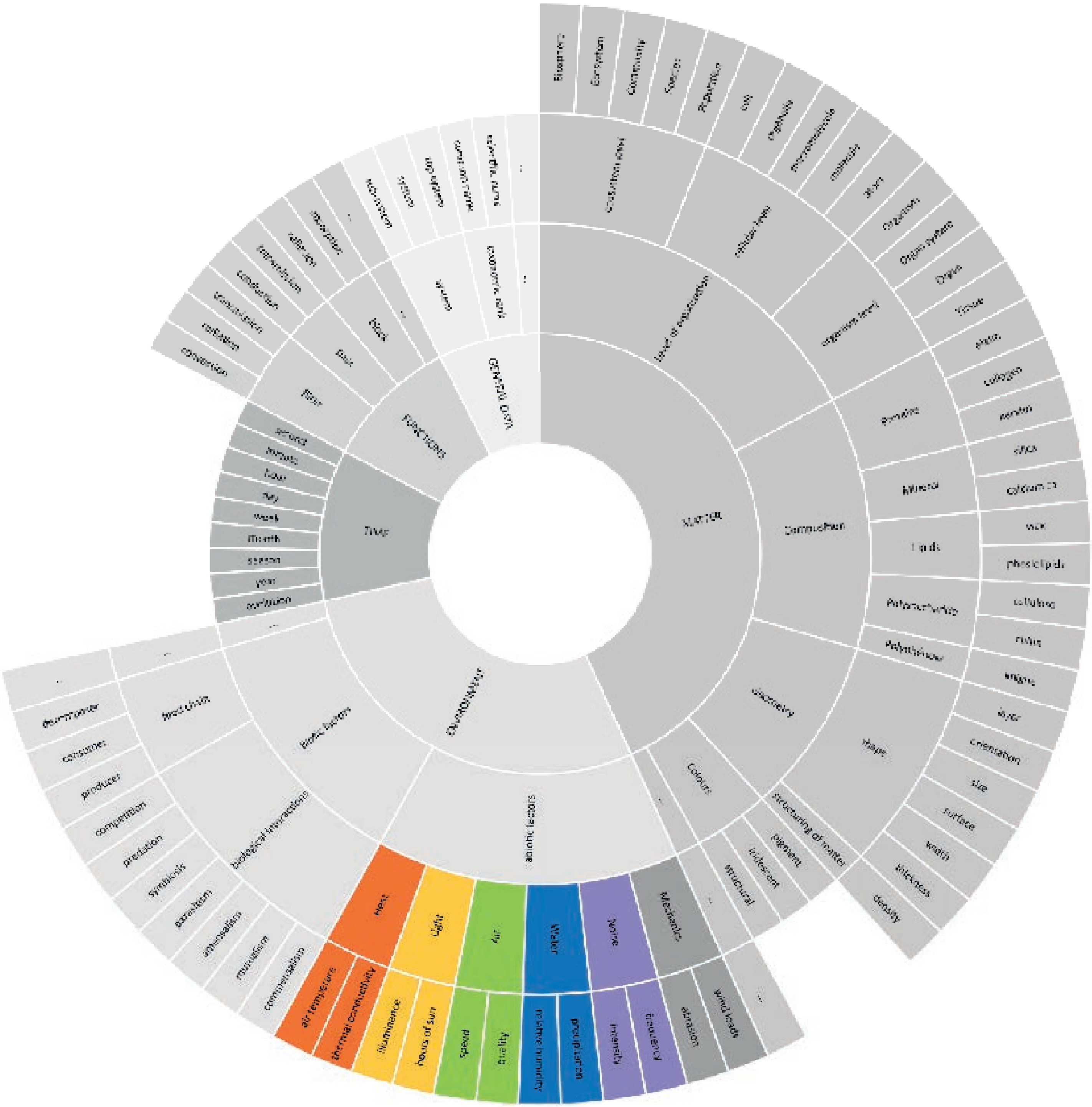


Figure 3.1. Entries of the Matrix. Overview of category, sub-category, variable and parameter. Content adapted from Table 3.1.

3.2. BioMatrix's entries

To fill the gap between multi-functional capabilities of living systems and the development of mono-functional building envelopes, this section introduces a tool for multi-criteria characterization of a biological system. This tool – called the BioMatrix - aims to increase the development of multi-functional biomimetic designs by abstracting several principles of biological systems.

3.2.1. Overview

The BioMatrix provides a systemic framework to map the regulation of the environmental factors provided by the living organisms. The classification is comprised of five categories outlined in **Table 3.1**. The first three column describes the categories, sub-categories, variables, and parameters which help to both qualify and quantify the living systems. The last column points the tools, database, handbooks, and frameworks that help to map the biological knowledge.

This matrix comprises five linked categories: 'General data', 'Functions of regulation', 'Environment', 'Time' and 'Matter'. The environmental aspects – category 'Environment' - and the functions of regulation – category 'Functions' are central of this mapping since the development of multi-functional biomimetic building envelopes is the main objective of this research. The categories Time' and 'Matter' enriched the understanding of the regulation of the environmental factors provided by the living organisms.

The main objective of this mapping is to provide a systemic understanding of living organisms beyond the understanding and then abstraction of single function of regulation. This tool is designed to gather biological data during step 2 – Understanding biological principles - in the biology push or technology pull biomimetic design process [11]. Aligned with networking thinking, and in order to overcome reductionist thinking, living systems are considered as complex systems [12] [13]. According to Cilliers (1998), a complex system has three main criteria: it consists of a large number of elements that interact dynamically; it is non-linear; and it interacts with the environment [14].

Applying these key concepts, **Figure 3.1** presents a circular representation of the matrix which helps the user to develop systemic thinking. Indeed, circular mappings encourages to make connections across different topics rather than linear representations [15].

The following sections linearly describe the categories to map the biological knowledge, however each category is linked to the others.

GENERAL DATA			
Subcategory	**Variables**	**Parameters**	**Resources**
Taxonomic rank	Scientific name	-	[16] Textbooks
	Common name	-	[17]–[19] Database
System	Top system	-	[20], [21]
	System	-	
	Sub-system	-	

ENVIRONMENT			
Biotic factors	**Food chain**	Producer, consumer, decomposer	textbooks [7], [22]
	Biological interactions	competition, predation, symbiosis, parasitism, amensalism, mutualism, commensalism	textbooks [7], [22] biomes [23], [24]
Abiotic factors	**Heat**	air temperature (°C) thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	climate [25], [26]
	Light	illuminance of sunlight (Lux) hour of sun (h/day)	climate [25], [26]
	Air	composition speed ($m.s^{-1}$)	climate [25], [26]
	Water	relative humidity (%) precipitation (mm)	land cover [27] biomes [23], [24]
	Noise	intensity (dBA) frequency (Hz)	land cover [27] biomes [23], [24]
	Mechanical stress	abrasion wind load ($N.m^{-2}$)	land cover [27] biomes [23], [24]

FUNCTIONS OF REGULATION			
Functions of regulation	**Block**	absorption, reflexion, …	Scientific literature
	Filter	transmission, conduction, …	Scientific literature
	Pass	transmission, radiation, convection, …	Scientific literature

MATTER

Subcategory	**Variables**	**Parameters**	**Resources**
Levels of organization	**cellular level**	Atom, molecule, macromolecule, organelle, cell	Textbooks [7], [22]
	Organism level	Tissue, organ, organ system, organism	
	Ecosystem level	Population, species, community, ecosystem, biosphere	
Colours	**-**	Structural, pigment, iridescent	Specialized literature [28]
Composition	**Proteins**	Keratin, collagen, elastin, chitin, cellulose, …	Textbooks [7], [22]
	Lipids	phospholipids, wax, …	
	Mineral	Calcium, silica, …	
Geometry	**Shape**	Thickness, width, surface, size, orientation, layer, …	Textbooks [7], [22]
	Structuring of matter	Density, porosity, …	

Table 3.1. Entries of the Matrix. Overview of category, sub-category, variable and parameter.

3.2.2. General data

The category 'General data' comprises three sub-categories as outlined in **Table 3.1.a.**

Subcategory	Variables	Parameters	Resources
Taxonomic rank	Scientific name	-	[16] Textbooks
	Common name	-	[17]–[19] Database
System	Top system	-	[20], [21]
	System	-	
	Sub-system	-	

Table 3.1.a. General data. Overview of sub-category, variable and parameter to define the biological system.

Taxonomic rank. In biological classification, taxonomic rank is the relative level of a group of organisms (a taxon) in a taxonomic hierarchy. The main taxonomic ranks are species, genus, family, order, class, phylum, kingdom, domain [16] As outlined in chapter 2, biomimetic designs can abstract properties from a single specie e.g. Eastgate building inspired by *Ondontotermes Transvaalensis* (rank specie) - or from a common character shared by a group of organisms e.g. Bloom pavilion inspired by animals' skins (rank kingdom). Defining the taxonomic rank of the studied systems helps the user to consider the biological system within the Tree of Life.

Most of the species have both a scientific name and one or several common name(s). The common name, also known as a vernacular name, is based on the normal language of everyday life. They highly contrast with the scientific names which are based on binominal nomenclature. Binominal nomenclature is a formal system which consist of two names derived from Latin[1]. The formal introduction of this system is credited to Carl von Linné with his work Species Plantarum in 1753 [29]. The first part of the name – the generic name – refers to the genus to which the species belongs, while the second part – the specific name – identifies the species within the genus. For instance, humans belong to the genus Homo and within this genus to the species *Homo sapiens*. One single scientific name is attributed per specie in order to avoid confusion. In botanic, this is particularly relevant since botanists estimate 391 000 species of vascular plants where only 23% are edible [30].

System. In addition to the taxonomic rank, the description of the system in sub system, system and top system narrow the scope of analysis of a taxa or group of taxa. This classification has been developed by T. Chekchak [20], [21] to facilitate the abstraction between biological systems and man-made designs. For instance, the system which inspired the ICD/ITKE research pavilion Elytra[2] is the elytra of the beetle [31], [32]. Top systems can be is the exoskeleton of the insect, the whole organism. Sub systems can be the different layers which compose the elytra of the insect. This subcategory 'system' is strongly linked with the category 'level of organization' as outlined in **Table 3.1.**

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[1] They can be derived from other languages too.

[2] See chapter 2, Bio-BS, Table 2.3. Overview of the environmental factors regulated by 19 Bio-BS.

3.2.3. Environment

The category 'Environment' comprises two sub-categories 'biotic factors' and 'abiotic factors' as outlined in **Table 3.1.b.** That section focuses on the abiotic factors defined as heat, light, water, air, noise and mechanical loads since the building envelope must simultaneously regulate that environmental aspects. Parameters listed in the third column allow quantify these abiotic environmental aspects. The last column points the available resources in order to quality and / or quantify the biotic and abiotic factors a living specie is subject to.

Subcategory	Variables	Parameters	Resources
Biotic factors	**Food chain**	Producer, consumer, decomposer	textbooks [7], [22]
	Biological interactions	competition, predation, symbiosis, parasitism, amensalism, mutualism, commensalism	textbooks [7], [22] biomes [23], [24]
Abiotic factors	**Heat**	air temperature (°C) surfaces thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	climate [25], [26]
	Light	illuminance of sunlight (Lux) hour of sun (h/day)	climate [25], [26]
	Air	composition speed ($m.s^{-1}$)	climate [25], [26]
	Water	relative humidity (%) precipitation (mm)	land cover [27] biomes [23], [24]
	Noise	intensity (dBA) frequency (Hz)	land cover [27] biomes [23], [24]
	Mechanical stress	abrasion wind load ($N.m^{-2}$)	land cover [27] biomes [23], [24]
…	…	…	…

Table 3.1.b. Environment. Non-exhaustive overview of sub-category, variable and parameter to describe the environment of biological systems.

The concept of 'Environment' has different meanings according to the context. According to [33], an environment is defined as "the circumstances, objects, or conditions by which one is surrounded". Applied to biology, the following definition can be given: "an environment is the total set of surrounding; the ecological complex of physical, chemical and biological factors that act upon an organism, population or an ecological community and ultimately influence its form, functions and survival". Indeed, living systems and their environments are highly interrelated as described by the literature [34] [35, Ch. 5]. Several famous examples such as the Wallace's sphinx moth (*Xanthopan morgani praedicta*) or the Darwin's finches outlined that strong relationship between living species populations. Living organisms cannot be understood without understanding their environment.

Historically, life sciences researchers have developed various classifications systems in order to describe Earth's environments and living systems communities. These attempts have resulted of the development of several concepts such as biome, climate, land cover, etc. They provide different types of information and vary in scale from local to regional scale. There is, however, no universal truth when it comes to environments' classifications. They are simplifications of reality that are constructed for organising knowledge on the structure and functioning of the world's ecosystems [36]. In order to describe the immediate surrounding environment of living organisms, the concepts of biotic and abiotic factors have developed by scientists. They are both environmental components which affects the living systems at all stages of development.

Biotic factors refer to any living systems that affect another living organism. Usually this concept is illustrated with the concept of food web where living organisms are assigned to a role of producer, consumer or decomposer (see **Fig. 3.2**) The interaction between them are defined as competition, predation, symbiosis, parasitism, amensalism, mutualism, commensalism [7]. This concept plays a key role to understand biological systems as illustrated by the example of the co-evolution of heliconiine butterflies and Passiflora plants. It cannot be understood without studying their predation relationship. They both have developed[3] several successive physiological and morphological adaptations to survive[4] [37] (see **Fig. 3.3**). Likewise, biomimetic designs often cite the zebras' stripes as a relevant model for thermal regulation [38]–[40]. However, there are several theories that seek to explain this pattern. T. Caro has reduced the complexity of these theories by clustering them into six headings: predation and crypsis, predation and aposematism, predation and confusion, ectoparasitism, intraspecific communication, and temperature regulation [41] (see **Fig. 3.4**). Indeed, analysing the biotic factors which influence the development of a living system helps to contextualize the biological strategies to avoid 'wrong' selection for biomimetic inspirations.

[3] 'have developed' see Chapter 1, section 'the right level of information'

[4] Heliconiines butterflies exclusively feed on Passiflora plants during the larval stage. In order to protect from this predation, botanists observed major adaptations such as variation of leaf shape within the genus; the occurrence of yellow structures mimicking heliconiine eggs; and their extensive diversity of defence compounds. Entomologists discovered major adaptation of Heliconiines butterflies in response to Passiflora's adaptations.

Abiotic factors refer to all the non-living chemical and physical factors on Earth that affect living systems. Within a terrestrial ecosystem, abiotic factors include air, weather, water, temperature, humidity, altitude, the pH level of soil, type of soil and more (see **Fig. 3.2,** [42]). In an aquatic ecosystem, abiotic examples include water salinity, oxygen levels, pH levels, water flow rate, water depth and temperature.

The BioMatrix focuses on the six terrestrial main abiotic factors as defined in chapter 1 'Scope of exploration', i.e. heat, water, light, air, noise and mechanical loads. Biologists use different classification such as climate, biomes and land cover description to describe the different abiotic factors livings organisms are subject to. Information is gathered from various sources and from different domains.

Table 3.2 shows that none of these environmental classifications provide both qualitative and quantitative description of the abiotic factors. The symbols (++) denote that the classification provides quantitative data on the abiotic factor. The plus symbol (+) denotes that the classification provides a qualitative description of the abiotic factors. The minus symbols (-) shows that the classification does not provide information.

Type	**Examples of classifications**	**H**	**L**	**A**	**W**	**N**	**M**
Climate	Köppen-Geiger Figure [25], [43]	++	+	+	++	-	-
Biome	Leslie Holdridge's Life Zone [23]	++	+	+	++	-	+
	WWF Global ecoregions [24], [44]	+	+	+	+	-	+
Land cover	Corine Land Cover [27], [45]	+	+	+	+	+	+

Table 3.2 Overview of the main environments' classifications and information provided of the 6 selected abiotic factors. H (Heat), A (Air), W (Water), L (Light), N (Noise), M (Mechanical constraints).

Climate. Scientists define climate as the average weather for a particular region and time period, usually taken over 30-years [46]. Climates' classifications are long-term patterns of weather in particular areas. The 'Köppen-Geiger classification' remains the most popular scheme based on seasonal precipitation and temperature patterns (see **Fig. 3.3**). Wladimir Köppen developed this classification first published in 1884. The classification provides five main climates based on seasonal precipitation and temperature patterns: tropical (A), dry (B), temperate (C), continental (D), and polar (E) [25], [43]. The main environmental descriptors are related to heat (average, highest and lowest temperatures per months in Celsius) and water (average precipitation in millimetres). This classification does not provide any evaluation of the environmental factors noise, mechanics and air. Sun exposure can be deduced from the factor heat crossed with the climates' mapping provided by this classification.

Biome can be defined as community of living organisms that have common characteristics for the environment, they exist in. Life zone, ecosystem, ecozone, ecoregion can be considered as synonymous since their definitions are still discussed [23]. Biomes classification counted several attempts over the last century where the WWF biome map remains the most frequently used [44].

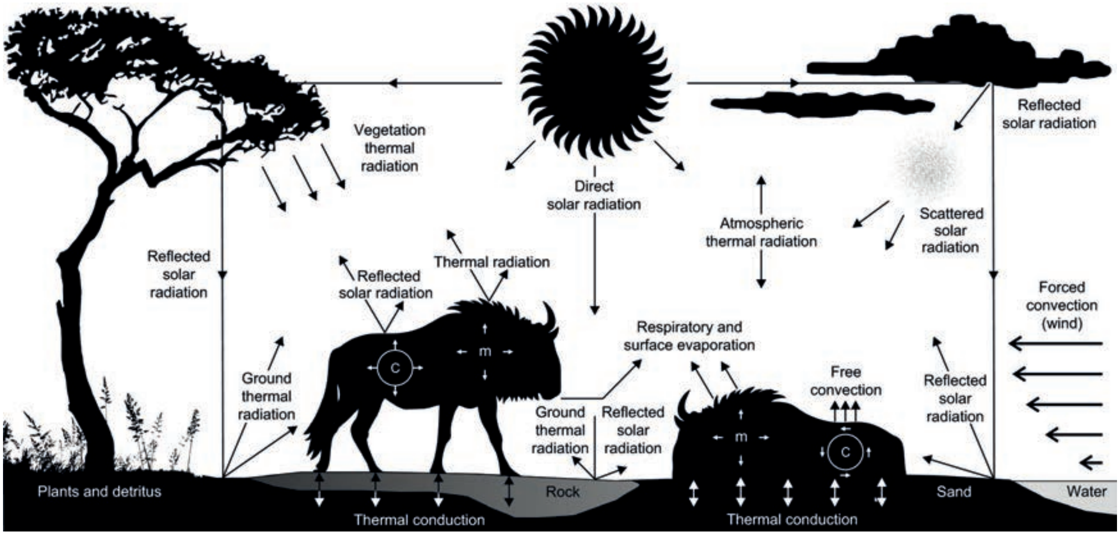

Figure 3.2. Abiotic factors. Abiotic factors refer to all the non-living chemical and physical factors on Earth that affect living systems. Living systems are exposed to a wide range of environmental aspects. Credits: [42].

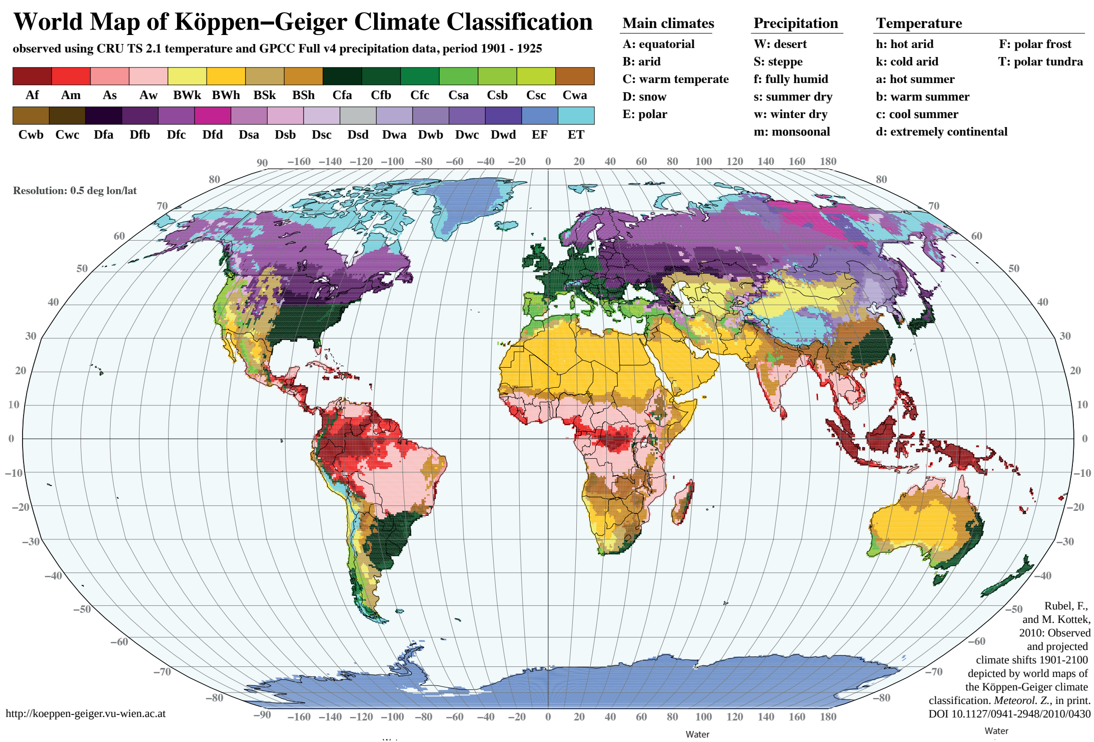

Figure 3.3. Environments classifications. 'Wladimir Köppen climate classification'. Five main climates based on seasonal precipitation and temperature patterns: tropical (A), dry (B), temperate (C), continental (D), and polar (E). Credits: [25], [43].

The ‘WWF global ecoregions classification’ is an attempt to sort environments according to the definition of 26 major habitat types so-called ecoregions. They are "large unit of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions" [24], [47]. They reflect the distributions of a broad range of fauna and flora across the entire planet from terrestrial to marine and freshwater areas. Similarly, the ‘Holdridge Life Zone classification’ is a global climatic scheme for the classification of land areas. It was first published in 1947 by the botanist Leslie Holdridge. This three-dimensional classification is based on year averages of precipitations (in millimetres), biotemperature[5] (in Celsius) and the ration of annual potential evapotranspiration to total annual precipitation. The following further indicators are incorporated into the classification: humidity province, latitudinal regions and altitudinal belts. The only two quantify environmental criteria are related to heat and water. Sun exposure can be deduced from the crossing of the factors biotemperature and altitudinal belts.

Land cover is the physical material at the surface of the earth. It included artificial surfaces, wetlands, forest areas, etc. The ‘Corine Land Cover (CLC)’ is one of the most used classification to qualify land covers.

None of these classifications simultaneously qualify or quantify the six main environmental factors searched for the design of building envelopes. They need to be combined in order to describe the several environmental factors a biological system is subject to.

3.2.4. Functions of regulation

The category ‘Functions’ comprises three sub-categories ‘block’, ‘filter’ and ‘pass’ as outlined in **Table 3.1.c.** That section focuses on the regulation of the abiotic factors defined as heat, light, water, air, noise and mechanical loads. The last column points the available resources in order to quality and / or quantify the function of regulation.

Subcategory	Variables	Parameters	Resources
Functions of regulation	**Block**	absorption, reflexion, …	Scientific literature
	Filter	transmission, conduction, …	Scientific literature
	Pass	transmission, radiation, convection, …	Scientific literature

Table 3.1.c. Functions. Exhaustive overview of sub-category, variable and parameter to describe the functions of regulation of abiotic factors.

[5] *Biotemperature* refers to all temperatures above freezing, with all temperatures below freezing adjusted to 0 °C, as plants are dormant at these temperatures. Holdridge's system was created for the use of botanists.

3.2.5. Matter

The category 'Matter' at least comprises four sub-categories 'level of organization', 'colours', 'composition' and 'geometry' as outlined in **Table 3.1.d.** The last column points the available resources in order to describe the geometry.

Subcategory	Variables	Parameters	Resources
Levels of organization	**cellular level**	Atom, molecule, macromolecule, organelle, cell	Textbooks [7], [22]
	Organism level	Tissue, organ, organ system, organism	
	Ecosystem level	Population, species, community, ecosystem, biosphere	
Colours	-	Structural, pigment, iridescent	Specialized literature [28]
Composition	**Proteins**	Keratin, collagen, elastin, chitin, cellulose, …	Textbooks [7], [22]
	Lipids	phospholipids, wax, …	
	Mineral	Calcium, silica, …	
Geometry	**Shape**	Thickness, width, surface, size, orientation, layer, …	Textbooks [7], [22]
	Structuring of matter	Density, porosity, …	

Table 3.1.d. Matter. Exhaustive overview of sub-category, variable and parameter to describe the matter of the living system.

Level of biological organization. Biologists defined three level of hierarchical organization of living things: from small and simple, to large and complex, within cells (cellular level), multi-cellular organisms (organism level) and among organisms (ecosystem level). Each level contains sub-levels. The level organism can be divided into four sub-levels: organism, organ system, organ and tissue [7].

Colour refers to the spectral qualities of the light emitted or reflected from every living or non-living organisms. The colours are formed in two different ways, from either pigment (chemical composition) or from light refraction caused by the structure of the surface (matter organisation at the nanometre scale) [48], [49]. In some cases, surfaces colours are the result of a combination of pigment and structural colours. For instance, the greens of some birds' feather are the result of yellow pigments overlying the blue-reflecting characteristic of the feathers [50].

Composition. Biological material result from hierarchization of a narrow range of elements (C, N, O, H, Ca, P, S, Si …). Nevertheless, biologists count a wide range of biological materials with different properties (self-repair, adaptation, self-assembly), and manufactured at low temperature and pressure [51], [52]. The high diversity of functions and properties arise from multi-scale hierarchical structuring. For instance, the mechanical properties are, in general, adapted by a modification of the hierarchical structure rather than by a different chemical composition [53]. Biological materials count two main families: organic and inorganic material. At the molecular level, organic materials can be classified into 4 groups of molecules: proteins, polysaccharides, lipids and polyphenols; and inorganic material into mineral.

Geometry. The study of geometry refers to the evaluation of the shape (thickness, width, surface ...), and the structuring of the material (density, layers, ...). These data are both qualitative and quantitative.

3.2.6. Time

The category 'Time' describes the different scales of time from seconds to evolution as outlined in the BioMatrix.

3.4. Conclusions

This chapter answered to the following questions.

- **What are the key concepts to understand biological systems as complex system?**

This chapter has provided a systemic framework to map the regulation of the environmental factors provided by the living organisms. The classification is comprised of five categories: 'General data', 'Functions of regulation', 'Environment', 'Time' and 'Matter'. This tool is designed to gather biological data during step 2 – Understanding biological principles - in the biology push or technology pull biomimetic design process.

- **How to structure biological knowledge for a convenient access by designers?**

Aligned with networking thinking, and in order to overcome reductionist thinking, the BioMatrix provides a circular representation to helps the users to develop systemic thinking. This representation provides a permanent discussion between the categories in order to connect key concepts between them.

This chapter offered a non-exhaustive classification of biological systems. Further investigations in collaboration with biologists and designers must complete the proposed matrix, and as carried out by current researches [54], [55] Indeed, Life sciences count more than hundred subdisciplines distributed among anatomy, biomechanics, systematic, botany, chronobiology, ecology, genetics, epidemiology, etc.

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Key concepts

Multi-regulation
Operating range

Heat, Light,
Water, Air, Noise,
Mechanical loads

Eucaryotes
Terrestrial living organisms

Biomimetic methods frameworks and tools
Problem driven

Chapter 4

Multi-criteria characterization of biological envelopes

Previous chapters demonstrated a gap between multi-functional capabilities of living systems and the development of mono-functional building envelopes. For this purpose, chapter 3 introduced a novel tool for a multi-criteria characterization of biological systems. To enhance the development of multi-functional building envelopes, Chapter 4 provides a comparative and multi-criteria analysis of ten type of biological envelopes compared with the entries of the BioMatrix. This chapter synthesizes current knowledge in biological envelopes based on qualitative, and quantitative existing data. The results aim to help the architects to identify relevant biological models to combine according to their challenge(s). Chapter 4 applies the BioMatrix to a sample of terrestrial biological envelopes among the group of eu-caryotes.

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4.1. Introduction

Chapter 2 provided a state of the art on the multi-regulation capabilities of biological interfaces and building envelopes.

Biological envelopes such as furs, feathers or plants' surfaces provide a wide diversity of functions such as mechanical protection, thermal regulation, light management to regulate the environmental stress they are subject to. They are exposed to multiple environmental factors whilst maintaining the physical properties of their envelopes and stabilizing the internal environment. Many regulatory mechanisms such as morphological, behavioural, and physiological are involved to maintain this 'steady state', called homeostasis [1, Ch. 40]. These outmost layers of their body exhibit a high level of diversity: skin, exoskeleton, shells, cuticle, fur, feathers, scales [2]. As a result, they have attracted great attention for applications in engineering and architecture since the functionality of skins, surfaces, membrane, or interface in nature bears similarities with the functions of building facades. Both are subject to similar environmental stress (light, heat, noise, water, mechanical stress, …) while they have to maintain constant their internal conditions [3]–[5].

However, existing biomimetic building facades have shown limitation for the regulation of several environmental factors. Two main studies highlighted their lack of multi-functionality compared to biological systems [6], [7]. In addition, most of the biomimetic building envelopes have been inspired by a limited number of taxa as presented in chapter 2 (see section 2.4.1. Biomass and phylogenetic distribution, chapter 2). Biomimetic designs are often inspired by the same biological systems. For instance, the specie *Homo sapiens* is over-represented within biomimetic building skins related to its proportion in the biomass (0,01%), and within the 1.7 billion of described species (0,0000005%). Aligned with [6], [7], chapter 2 also outlined that most of these cases address regulation of a single environmental factors through their envelope while the biological interfaces have multi-functional capabilities. We assume that the lack of tools and methods to provide a systemic understanding of living systems results of a limited comprehension of living systems.

To fill the gap between multi-functional capabilities of living systems and the development of mono-functional building envelopes, chapter 3 introduced a novel tool for a multi-criteria characterization of biological systems. This tool aims to increase the development of multi-functional biomimetic designs by abstracting several principles of biological systems (see chapter 3).

To enhance the development of multi-functional building envelopes, Chapter 4 provides a comparative and multi-criteria analysis of ten type of biological envelopes compared with the entries of the BioMatrix. This chapter synthesizes current knowledge in biological envelopes based on qualitative, and quantitative existing data. The results aim to help the architects to identify relevant biological models to combine according to their challenge(s). Chapter 4 applies the BioMatrix to a sample of terrestrial biological envelopes among the group of eucaryotes.

Research questions. The sub-questions addressed in Chapter 4 go as follow:

- What are the main types of Eucaryotes' living envelopes in terrestrial ecosystems?
- What are the multi-regulation capabilities of biological envelopes?
- How to select the 'right' biological model?

4.2. Method

Several research methods are used in this study to provide a multi-criteria qualification of living envelopes. These methods include the following:

- Literature review, synthesis, and comparative analysis of the biological envelopes
- Application of the BioMatrix as presented in chapter 3
- Multi-regulation classification (radar charts) as presented in chapter 2

4.2.1. Data collection

Data is gather going through literature (handbooks, encyclopaedia, scientific papers) and online databases. Encyclopaedia and handbooks in biology such as [1], [8] first help to gather qualitative data and characters shared by many taxa. For instance, all birds (Aves) have feathers which is a well described appendage in biology. Both encyclopaedia and textbooks describe their main characteristics such as thermal and mechanicals properties, geometry, colors, adaption throughout evolution, etc. This literature mostly provides ranges of values whereas scientific papers and data bases usually give quantitative data per species or group of species. These two levels of information are complementary.

4.2.2. BioMatrix

Categories and sub-categories of the BioMatrix. The environmental aspects – category 'Environment' - and the functions of regulation – category 'Functions' are central of this mapping to provide a comparative analysis of biological envelopes. The category 'Time' and 'Matter' enriched the understanding of the regulation of the environmental aspects ensured by the living envelopes. **Figure 4.1.** illustrates the categories and sub-categories mainly used throughout this chapter.

Read direction. As outlined in the section 'user' of chapter 3, the BioMatrix can be filled starting with any variable or category. Similarly, the six sections Heat, Light, Water, Air, Mechanical stress, and Noise can be read in any direction.

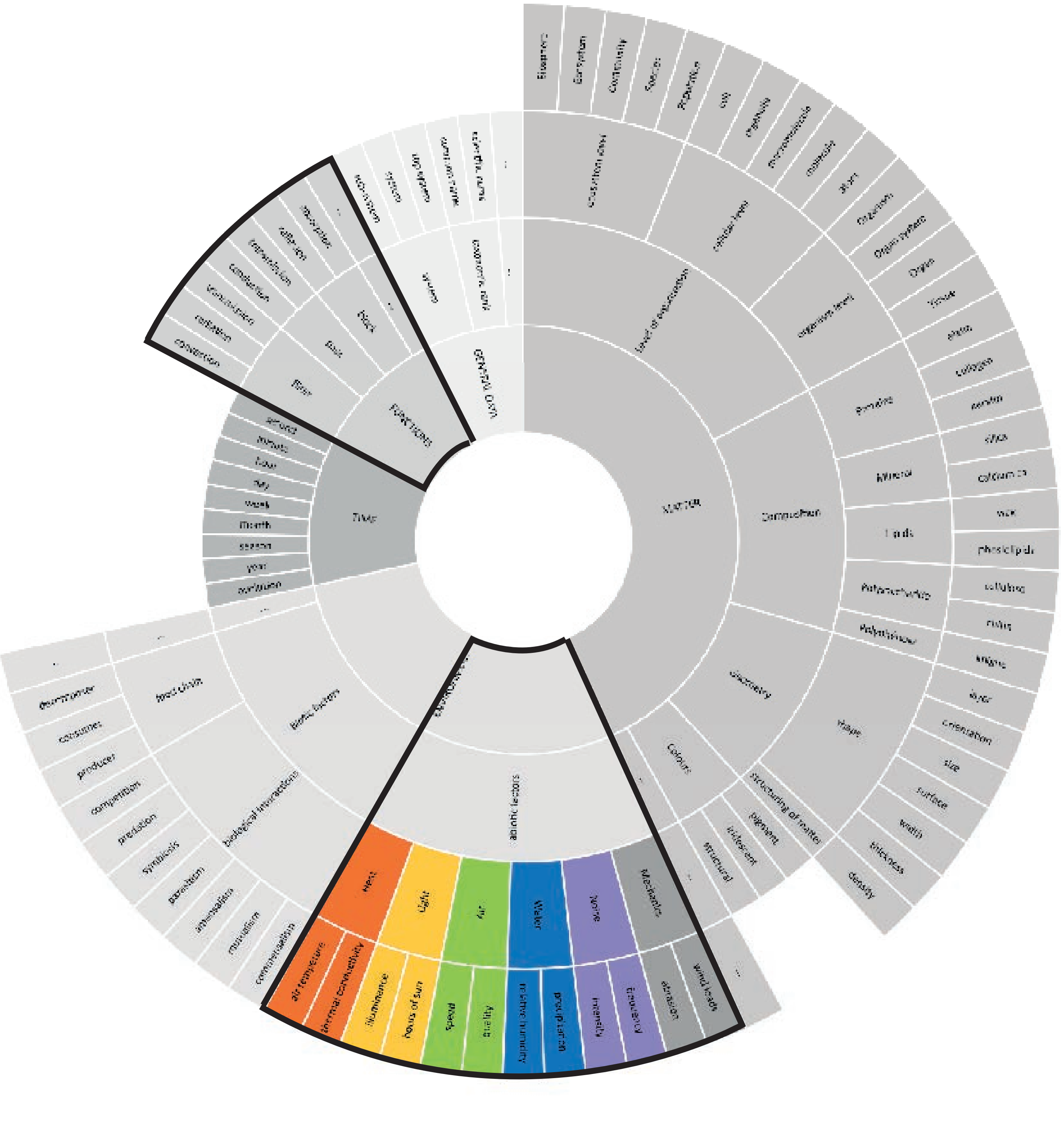

Figure 4.1. BioMatrix to describe the multi-regulation capabilities of biological envelopes. Main categories used within this chapter are cicurled in black.

4.3. Biological envelopes

As outlined in chapter 1, the concept of the 'envelope', also referred to as the 'membrane', 'skin' or 'interface', can be applied to every living or non-living system. Acting as a barrier, it filters the flux of matter, information and energy exchanged between the inside and the outside [9]. Shaped by both environmental pressures and natural selection, biological organisms are adapted to their environment. They can adapt their phenotype[1] – e.g. morphology, behaviour, physiology - from days to seasons to maintain their internal environment in a stable state [8, Ch. 20].

The diversity of biological envelopes is extensive. Animals' skin, plants' leaves, fungi' cuticles have also displayed multi-functional properties since they can simultaneously regulate various environmental aspects. Their composition, structure and adaptation behaviour allow them to overcome contradictory requirements to maintain the integrity of their body.

4.3.1. Criteria of selection

In order to find applications for building envelopes, ten types of biological envelopes are selected based on common analogies between living organisms and buildings (i, ii), and the availability of biological data (iii, iv, v).

(i) **Terrestrial environments.** This research focuses on terrestrial organisms found within terrestrial environments. They are exposed to the same range of environmental conditions as buildings (see chapter 2, section 2.4). As a result, only land gastropods are considered within the taxa gastropods (Gasteropoda[2]). The selection also counts amphibious species (Amphibia) which both live on marine and terrestrial environments

(ii) **Outermost biological tissues**. Both organisms and buildings are surrounded by an outmost envelope involved in maintaining the system integrity. These interfaces act as a filter between the surroundings and inside the system. By analogy with building façades, this sample of biological envelope focuses on the outmost layers of the body of the biological organisms. Indeed, this research does not analyse mucous membranes within bodies such as the lining of the intestine.

(iii) **Living envelopes.** Animal architectures such as egg, mound, nest, burrow, cocoon [10], correspond to the two previous criteria. They provide a non-living outermost layer for some living organisms. These envelopes are exposed to terrestrial environmental aspects. Despite they are found relevant by the author and several architects[3], they are not analysed to limit the scope of this research[4].

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[1] Phenotype: The realized expression of the genotype; the observable manifestation of a trait (affecting an individual's structure, physiology, or behaviour) that results from the biological activity of the DNA molecules.

[2] The taxa gastropods includes freshwater and marine animals.

[3] See chapter 2, Biomimetic building façades. The biomimetic buildings - Eastgate building, the church Nianing and the Davies Alpine House – are inspired by termites' mounds.

[4] Further investigations are undertaken by Tessa Hubert on animals' architectures for the design of multi-functional building envelopes. See chapter 1, section 'Collaborations'.

About 8.7 million[5] of eucaryotes[6] species on Earth have been estimated with 6.5 million species on land and 2.2 million in oceans. In spite of 250 years of taxonomic classification and over 1.2 million species already catalogued in a central database, recent studies suggest that some 86% of existing species on land and 91% of species in the ocean still await description [11], [12].

The three previous criteria (i, ii) reduce the field of exploration to around 845.000 species which correspond to the 13% of described species on land. To reduce the sample to study, two additional criteria related to the availability of biological data are added:

(iv) **Multi-cellular organisms**. The tree of life consists of three domains: Archaea, Bacteria, and Eukaryotes [13, Ch. 1]. Living organisms within the domain of Archae and Bacteria are not studied. Indeed, little number of species within Archaea and Bacteria have been described. Likewise, unicellular species within eucaryotes are not included since they are little described. For instance, only 0.9% of estimated species within the kingdom of procaryotes (Prokaryota) have been described by the literature [14]. In addition, buildings can be considered as the "humans' third skin", or its "extended organism" according to [15], [16]. This research assumes that the more living organisms share characters[7] with mammal humans, the more they may regulate the same environmental factors to maintain the homeostasis of their body.

(v) **Ten biological envelopes.** The four previous criteria narrow the scope of exploration. However, there is still a wide diversity of living systems which correspond to previous criteria. For this purpose, ten biological envelopes which meet the five previous criteria are arbitrarily chosen. Each type is illustrated in **Figure 4.2** and **4.3,** and listed in **Table 4.1** This non-exhaustive selection covers a wide diversity of taxa within the domain of eukaryotes.4.4

[5] There is a scientific consensus around that number (give or take 1.3 million), however estimates of the total number of species in the world vary from 5 to 50 million since the counting method is still discussed within scientists. This number excludes bacteria and virus which are too complicated to count [11], [12].

[6] Eucaryotes (Eucaryota): 5 domains Animalia, Chromista, Fungi, Plantae, and Protozoa

[7] Characters: any observable attribute in an organism [13]

4.4. Matter

This section compares the ten living envelopes based on the category 'Matter' of the BioMatrix. The following sections compare their level of biological organisation, composition, geometry and colours per type of envelope. This descriptive section does not include concepts related to function of regulation, environmental factors and time.

4.4.1. Levels of hierarchical organization

As a detailed in chapter 3, biologists count three level of hierarchical organization - within cells, multi-cellular organisms and among organisms – where each level contains sub-levels. The level organism can be divided into four sub-levels: organism, organ system, organ and tissue [1].

By analogy with building façades and for the purpose of this work, biological envelopes are the outmost layers between the body and the surroundings of the living organism. The envelope is a tissue[8] made of several layers and covers some organs[9] or organ systems[10] of an organism. For instance, the system 'bark' counts cellulose, lignin as sub-systems and the whole tree and the forest as top system.

This framework can be applied to the ten biological envelopes. The biological envelope is not yet considered as an isolated component, but as part of a part of a complex system.

4.4.2. Geometry

This section compares geometrical features of the envelopes such as shape (thickness, width, surface...), structuring of matter (density, layers, ...) and the size of the biological envelope. These data are both qualitative and quantitative. **Table 4.2** describes the different layers for each type of envelope. **Figure 4.3** provides additional schematic cross-sections and diagrams.

The comparative analysis of geometrical features outlines that these biological envelopes are:

(i) made of two main layers: appendages and tissues. Appendages such as trichomes, feathers, hairs, spine or shell, constitute the outermost layer of the body of the organism. They are produced by the deep tissues.

(ii) The layer 'tissue' can be divided into conceptual sub-layers which performs a specific function. For instance, plants' cuticle can be divided into several sub-layers such as the epicuticular waxes, cuticle proper, cuticular layer.

(iii) The layer continuously covers some parts of the living organisms' body by adapting to the surface

(iv) Energy and matter exchanges occur through specialized apertures that punctually pierce the layer, e.g. leave' stomata and insects' spiracles for gas exchanges, skin pores for water evacuation.

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[8] Tissue: a group of specialized cells that work together for a particular function [1]

[9] Organ: a distinct structure made up of different tissues that have a specific function [1]

[10] Organ system: group of organs that work together as a biological system to perform one or more functions [1].

Geometrical features vary among species, the type of organ covered and the body's location. For instance, birds (Aveas) shows the varied of appendages such as feathers and scales on the feats Likewise, trichome length and density vary among vascular plants (Tracheophytes).

Envelope	Ref.	Description of the layers
Plants' cuticle	[17]–[19]	**Cuticle**: continuous layer which cover the epidermis of the leaf **Tissues**: epicuticular waxes, cuticle proper, cuticular layer **Appendage**: trichome
Plants' bark	[1]	**Bark:** outermost layers of stems and roots of woody plants
Fungi's cuticle	[1]	**Cuticle:** uppermost layer of the cap of fungal fruit body. **Tissues**: cutis, trichoderm, epithelium, hymeniderm **Appendage**: trichoderm
Cuticle, setae	[20]–[22]	**Cuticle**: uppermost layer of the exoskeleton of arthropods **Tissues**: epicuticle, exocuticle, endocuticle **Appendage**: setae
Skin, feather	[1]	**Skin, feather**: continuous layer pierce by feathers which covers the body of birds. **Tissue**: epidermis, dermis, hypodermis **Appendage**: feather and down feather
Skin, scale	[1]	**Skin, scale**: continuous layer which cover the body of reptiles **Tissues**: horny epidermal scale, stratum corneum epidermis, dermis, hypodermis **Appendage**: scale
Skin, hair	[1]	**Skin, hair**: continuous layer of tissue and hairs which covers mammals' body **Tissue**: epidermis, dermis, hypodermis **Appendage**: hair / wool / fur and down hair
Skin, spine	[23]	**Skin, spine**: layer pierce by spine which covers the back of the body of hedgehog, porcupine and spiny anteaters. **Tissue**: epidermis, dermis, hypodermis **Appendage**: spine
Skin, mucous	[1]	**Skin, mucous**: continuous layer of several tissues which amphibians and roundworms body **Tissue**: epidermis, dermis, hypodermis **Appendage**: no appendage
Skin, shell	[1]	**Skin, shell** **Tissue**: **Appendage**: shell

Table 4.1. Description of the layers for each type of envelope

Figure 4.2. Overview of the ten types of biological envelopes studies in this chapter. Credit: under pixabay licence.

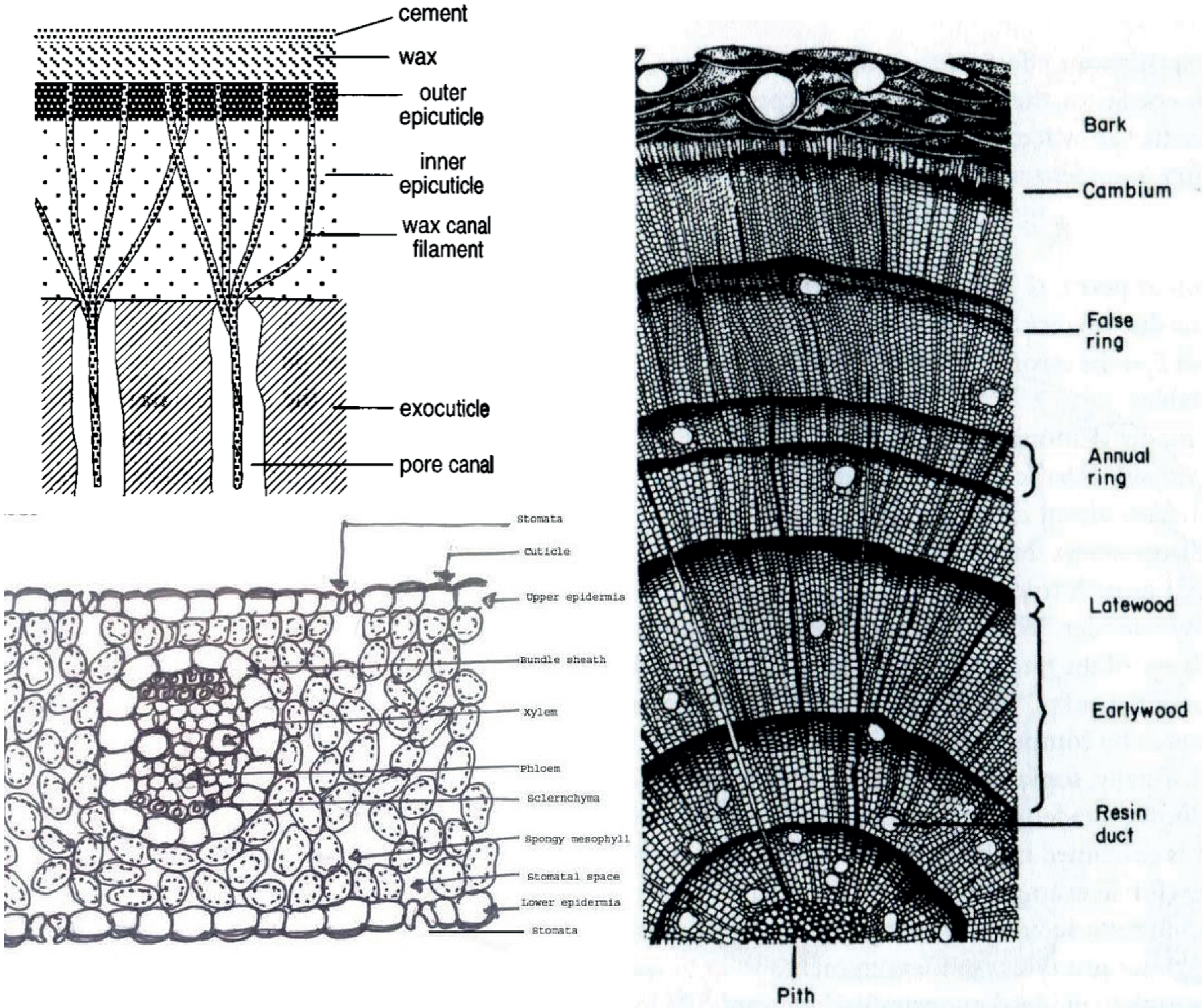

Figure 4.3. Cross-sections of some of the ten types of biological envelopes studies in this chapter.

4.4.3. Composition

As presented in chapter 3, biological material result from hierarchization of a narrow range of elements (C, N, O, H, Ca, P, S, Si …). Biologists count a wide range of biological materials with different functions (self-repair, adaptation, self-assembly) [24], [25]. The high diversity of functions and properties arise from multi-scale hierarchical structuring. Biological materials count two main families: organic and inorganic material which constitute the biological envelopes. They are classified in 4 groups of molecules: proteins, polysaccharides, lipids and polyphenols; and inorganic material into mineral. In order to compare the composition of biological envelopes, **Table 4.3** outlines the main organic and inorganic molecules which compose the envelope.

Material	Chemical family	Molecule	vascular plants' cuticle	vascular plants' bark	Fungi ' cuticle	arthropods cuticle	skin + feather	skin + hair	skin + spine	skin + scale	skin + mucus	skin + mucus + shell
Organic	Proteins	keratin					+	+	+	+	+	+
		collagen					+	+	+	+	+	+
		elastin					+	+	+	+	+	+
	Polysaccharide	chitin			+	+						
		cellulose	+	+								
	Lipids	phoslolipids	+	+								
		wax		+			+	+				
	Polyphénole	linin		+								
Inorganic	Mineral	Calcium ca				+						+
		silica										

Table 4.2. Overview of the main components of the ten biological envelopes.

4.4.4. Colour

This section compares the spectral qualities of the light emitted, reflected, absorbed, and transmitted by biological envelopes. As outlined in Chapter 3, the colours are formed in two different ways, from either pigment (chemical composition) or from light interaction caused by the structure of the surface (matter organisation at the nanometre scale) [26], [27]. If a surface reflects all wavelengths of light, it is perceived as white, in reverse it is perceived as black. In between situation, while the surface absorbs and reflects some wavelengths, the surface has a colour.

These ten envelopes exhibit a large range of colours perceived by human's vision from violet to red among the visible spectrum. But their distribution seems to be heterogeneous according to type of envelope and within the number of estimated species. The curves of skin, feathers, cuticles, setae, and skin, mucus (**c**) almost cover the whole visible spectrum. Indeed, these envelopes can both produce pigment and structural colorations. Conversely, hairs, fungus' cuticles, and thorns are distributed over a narrow range of visible colours from 575 nm to 800 since their coloration result from pigments (carotenoid, melamine, etc) [29], [30]. Plants' cuticles absorb most of the wavelength in order to transmit light radiation to the epidermis [28]. This property results of a translucid material.

Further researches will have to quantify the colours distribution per type of envelope since some are dominant. For instance, feathers' coloration covers the whole visible spectrum (see **Fig.4.5**). However, brown seems to be the most represented colour among birds. Likewise, **Figure 4.4** shows that the colours of frogs' skins (Anura) covers the whole visible spectrum, however only two species have blue colorations among the 3 500 described species: the blue poison dart frog (*Dendrobates azureus*), and the dyeing dart frog (*Dendrobates tinctorius*).

Further research must build reflectance spectra based on quantitative data and not estimations as undertaken in this section [31]The lack of quantitative data remains the main difficulty of such a review. Indeed, most colorimetric studies focus on a small group of taxa biological such as morpho butterflies (*Morpho)* [32]–[34], or hummingbirds (*Trochilidae*) [35].

4.5. Function of regulation

The six following sections compare the ten envelopes and their regulation capabilities for each environmental aspect: heat, light, water, air, noise and mechanical stress. Using comparative tables and radar charts these sections help to compare the envelopes in order to select the most adapted biological model for a specific challenge. Each section first reminds the building envelope requirements, introduces the physical properties of the environmental aspect to regulate, and then compare the living envelopes.

4.5.1. Light

This section compares the regulation of light by the ten biological envelopes. The BioMatrix helps to gather and link the data.

Light management in buildings. Buildings must provide a constant amount of light despite the multiple timescales lighting environmental fluctuations. This requirement is measured with the Daylight Factor[11] in percentage (2 < DF < 5%), or by Illuminance in Lux 300 < I < 750 lx[12]. Occupied building spaces must maintain lighting between a narrow range which also varies according to type of spaces [36]. During the day, the façade mostly acts as a filter to limit the excess of light. Its porosity varies depending on the environment fluctuations and the users' needs. At night, artificial light compensates the lack of natural light by illuminates the occupied spaces. In both situations, the challenge is to provide a constant visual light comfort with little amount of energy for façade adaptation and artificial light production (see **Fig. 2.3** chapter 2).

Physical properties of light. The light is modelled differently according to the field of physics – geometrical optic, wave optics, or quantum optics - but this work refers mainly to the first two. Light management depends on the source and the medium. As outlined in chapter 2, the sun is the main source of light. The solar spectrum is continuous but it can be divided into 3 main wavelength bands for fluency: ultraviolet (UV = 100-400 nm), visible light (400-700 nm), and infrared (IR > 700 nm) [37], [38, pp. 3–28]. A medium can regulate incident ray of light by three main functions: *blocking*, *filtering*, or *pass*. The description of regulatory functions is informed by our understanding of processes involved within the light regulation: *transmission, reflection, scattering, refraction, absorption,* and *energy conversion*[13] according to [39], [40, Ch. 7]. **Figure 4.6** resumes the functions and processes involved in light regulation.

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[11] The Daylight Factor (DF) is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies [130, p. 40].

[12] Daylighting legislations and illuminance-based standards vary according country. In France, Daylight levels are not described as being mandatory but preferred or recommended [36].

[13] Energy conversion refers to both fluorescence and phosphorescence. To comparative analysis, this work makes no distinction between the two physical phenomena.

Biological functions of light. As buildings, light management is a constant balance between the needs of living organisms and the available amount of light found within their surroundings. Indeed, the impact of light on certain living surfaces enable a variety of biological functions. Over the visible light spectrum, it generates colours which act as inter/intra species communication devices serving as a mating signal, a warning signal, or for startling prey [29], [41]. The colours of living organisms are produced by the differential absorption of light by pigments (e.g. carotenoids, melanins) and/or by the physical interactions of light with biological nanostructures, referred to as structural colours [42]. Light also supports biological functions such as the synthesis of some vitamins, e.g. vitamin D for humans absorbing UV [43]. But the excess of light – especially in the UV - can damage inner tissues or can be lethal for species within all kingdoms [44]. Thus, both buildings and living organisms must reduce or increase the difference between their needs and the environment when ambiance light is excessive or insufficient.

Envelopes' light regulation. The comparative analysis of light management allows us to place the ten biological envelopes in several categories which block, filter, or let in incidental solar radiation. The whole solar spectrum is considered without difference between wavelengths such as ultraviolet, visible, and infrared. The main trends of light regulation are outlined in **Table 4.5** The plus symbols (+) represent the functions carried out by the multi-layer envelope as obtained from scientific literature. The minus symbols (-) denote that the function is not, or little involved within the regulation for this type of envelope. The mention n/a points that no indication was found within the literature; the function is deduced from geometrical properties and composition of the envelope.

Biological envelopes	**Ref.**	block	filter	let in
Bark (vascular plants)	[45], [46]	+	-	-
Skin + feather (birds)	[30], [47], [48]	+	-	-
Skin + spine (echidna)	n/a	+	-	-
Skin + hair (mammals)	[49], [50]	+	+	+
Cuticle + trichome (vascular plants)	[51]–[55]	-	+	+
Cuticle + seta (arthropods)	[56], [57]	+	-	-
Skin + scale (reptiles)	[58], [59]	+	-	-
Fungi fruit cuticle (of fungi)	n/a	-	+	+
Skin + mucous + shell (gastropods)	[60]	+	-	-
Skin + mucous (nematodes, amphibians)	[61]	-	+	+

Table 4.5. Qualitative overview of the main functions involved in light regulation of incident wavelength per type of envelope. Table nomenclature adapted from [3], [40, Ch. 8], [62].

Block / Filter. Most of the ten envelopes block and/or filter a large part of solar radiation (*bark, skin + feather, skin + spine, skin + mucous + shell, cuticle + seta, skin + scale*). Indeed, the biological functions provided by most of the outmost envelopes of living organisms do not vary across climates; they protect deep tissues from ultraviolet-induced skin damage whatever the species which features this type of envelope, regardless of its environment [63].

Filter / Let in. However, some envelopes must filter and let the light in such as vascular plants (*cuticle + trichome*) for photosynthesis. They have developed highly efficient adaptations to regulate the wavelength they are subject to since they are rooted in the ground. The envelopes *skin + mucous* and *fungi fruit cuticle* are also placed in the same category; however, they mostly live in environments where they are not exposed to the solar spectrum as plants are. For instance, fungi fruits mostly grow under humid environments, and protected from direct exposure to sunlight. Likewise, amphibians and nematodes (*skin + mucous*) live under micro-climates where their close environment filter the amount of light they are exposed to (leaves, mud, soil, etc).

Block / Filter / Pass. The envelope type described as fur (*skin + hair*) has a wider operating range compared to envelopes in the previous category block / filter. Indeed, furs include species living under varied environments – with a high or low UV index - which have developed wavelength-specific absorptions [56]. Physical properties of hair (density, length, colours) vary widely to provide different functions of regulation. Mammal with brown dense coat of hair block the solar spectrum absorbing the incident wavelength, whereas some mammals with white dense coat filter then transmit the light beam to the deep tissues by scattering, e.g. polar bear (*Ursus maritimus*, **Figure 4.9**) [49].

Envelopes patterns for light regulation. As previously outlined with fur, inter-specie variety occurs for some biological envelopes. This variety can result in a wide range of light regulations, and/or in a large diversity of processes involved in. As an illustration, **Figure 4.7** compares the main processes that block light beams for five different barks. They provide the same function of regulation through different geometries, colours, and processes.

In the perspective of design application, **Figure 4.8** represents non-exhaustive biological patterns found within the different types of biological envelopes for light regulation. They are grouped according to their composition, geometry and the regulation processes involved in. However, they are mentioned to illustrate the biological patterns. Biological envelopes result in a mix of these patterns, where each layer can provide a different function of regulation through different processes.

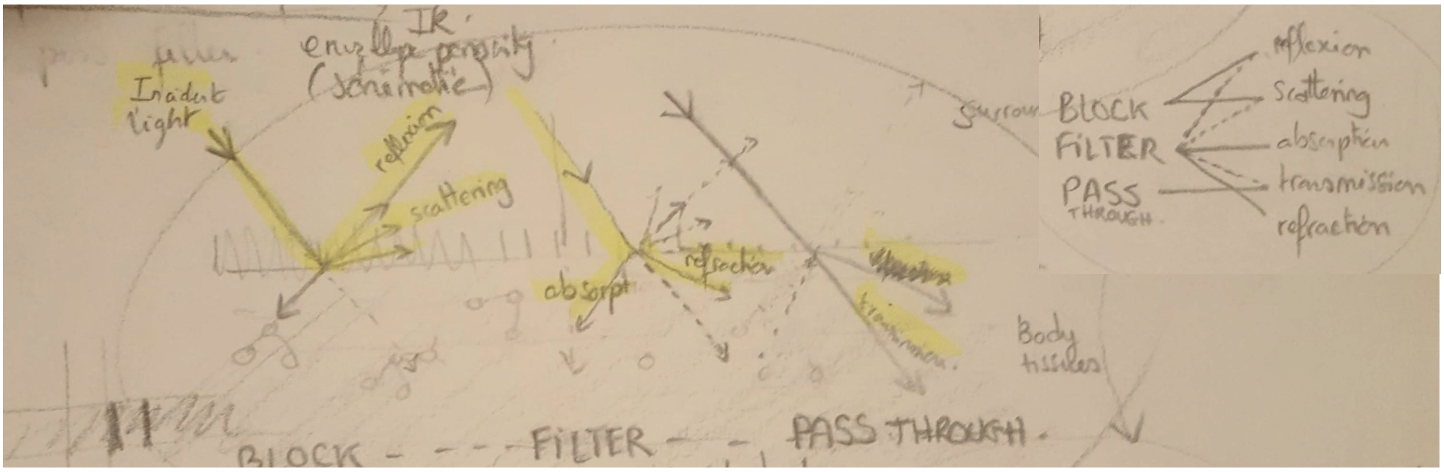

Figure 4.6. Functions and processes of light when interacting with a medium. (a) Three mainfunctions and the identify processes for light regulation, adapted from (Ref Lopez), (Ref Lidia). (b) Main processes involved within the light regulation for each function, diagram under Licence Creative Commons BY SA 4.0. E. Cruz, G. Chancoco.

Figure 4.7. Morphological inter-specie variety of the bark of vascular plants (Tracheophytes). Barks block the light through their colorimetric and morphological characteristics. *Sapindus marginatus (a), Araucaria araucana (b), Pandanus Furcatus (c), Pristinera Paniculata (d), Pachira Aquatica (e), Podocarpus Totara (f).* Pictures under Creative Commons Licence CC BY 4.0 Christian Arlet.

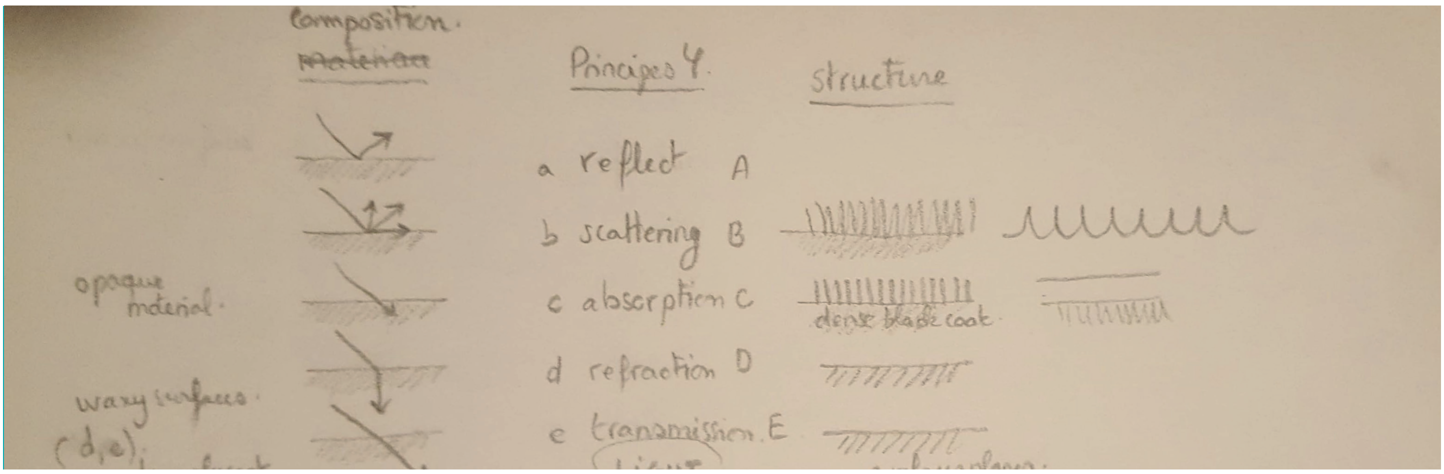

Figure 4.8. Biological patterns for light regulation (non-exhaustive). Nomemclature adapted from (Gorb 2008).

Relevant biological models. For the design of facades, the three biological envelopes *skin* + *mucous*, *fungi fruit cuticle, cuticle* + *trichome* and some *skin* + *hair* envelopes seems to be interesting models. They filter and let in the light during the day whereas other envelopes mostly block light beams. However, this overview calls for some nuance since the envelopes *skin* + *mucous* and *fungi fruit cuticle* are not exposed to the same solar radiation as most vascular plants (Tracheophytes). Indeed, the survival of Tracheophytes heavily depend on the amount of light perceived by leaves for photosynthesis.

In addition, Table 4.5 does not take in account envelopes that go against the general trend. The aim is only to only reflect major trends within these groups to guid the designers among the 1.2 million of species already described. But some living systems with specific adaptations remain relevant. As a counterexample, the wings of the glasswing butterfly *Greta oto* (**Figure 4.10**) transmit the whole solar spectrum whereas most of the envelopes of arthropods block or filter light in Table 4.5 [64]–[66].

Further research must investigate analogy of biological functions to complete the morphological analogy between outer most layers of buildings and organisms carried out in this work. Designers with the help of biologists should also identify living systems that provide the same biological functions as looked for buildings. In this case, biological systems need both to be exposed to the same lighting environments and to provide the same biological functions of light transmission. All eyes of animals may be as interesting for light filtration and transmission as the surface of leaves [67].

Towards combination of biological patterns. Figure 4.11 presents biological patterns that can be adapted for light regulation by the building envelope. Architects and designers have now access to biological patterns that can be combined. Living organisms cannot free from evolution process combining novel living adaptations, whereas human design can. But without being exhaustive, this review of biological patterns will help the designer to select the most adapted strategies to combine.

However, these patterns simplify the processes and physical principles involved in light regulation by the envelope. Further research will have to detail them as illustrate by **Figure 4.8** light transmission within the fur of the polar bear [49]. This kind of detailed diagram will help both architects and civil engineers to understand biological process, then to develop new solutions for building facades.

Data availability. These qualitative results lead to the topics of data availability. Very few systematic reviews of many living organisms can be found for light application. Existing are qualitative reviews and carried out by researchers in biomimetics looking for relevant models for the design of facades such as [3], [39], [62]. Some quantitative reviews can be found in the literature; however, they screen a narrow range of hummingbird's species evenly distributed across the phylogeny[14]. Assuming that intra-individual and interspecific diversity in colour have been poorly explored, they discovered an unsuspected diversity of structures producing iridescence [35]. Likewise, S. Cassey, S. Portugal, G. Maurer et *Al.,* determined the eggshell change in reflectance from a taxonomically representative

[14] The family of Hummingbirds (Trochilidae) counts 336 taxa described. Gruson et *Al.* characterized iridescent properties of 10% of existing taxa during a 3-years PhD [35].

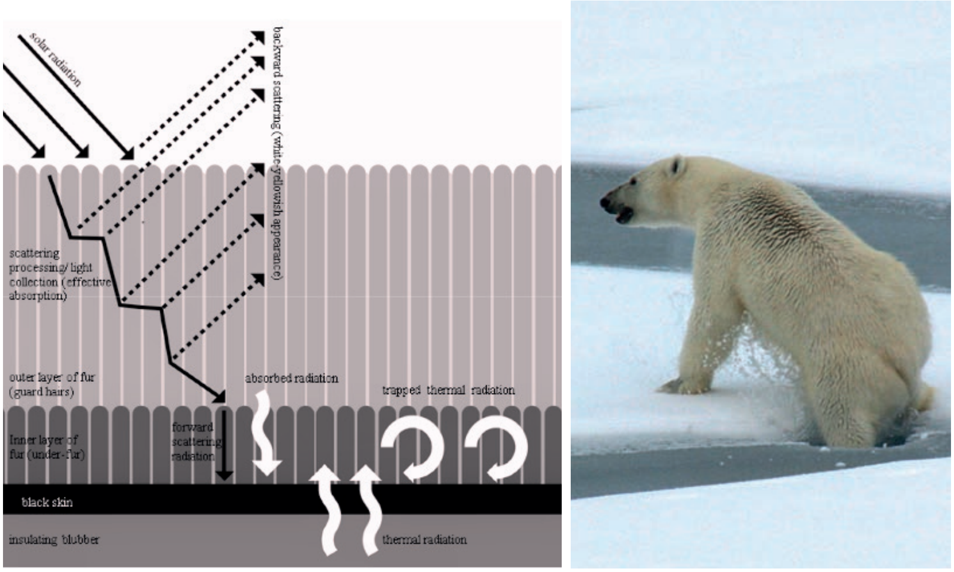

Figure 4.9 (a) Diagram explaining the energetic function of the polar bear`s pelt. The processes involved in the direction of the light beam are presented. Diagram reused with permission from (Ref Kasim 2016). (b) Polar bear (Ursus maritimus),
Picture under Pixabay Licence.

Figure 4.10. Counterexamples of Table 1. the wings of the glasswing butterfly *Greta oto* transmit the whole solar spectrum whereas most envelopes of arthropods block or filter the light. Pixabay Licence.

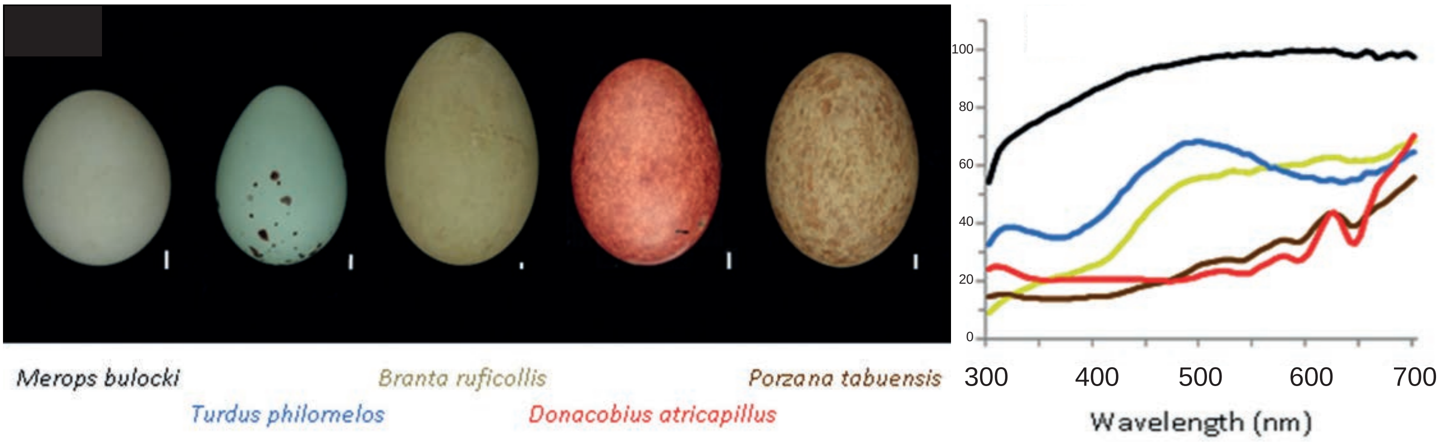

Figure 4.11. Varability in Avian Eggsheel. (a) The eggs of the five representative avian species as photographed courtesy of the Natural History Museum, Tring, United Kingdom. (b) Average reflectance spectra for the five representative eggs showing different reflectance spectra. Colours of the lines in (b) correspond to the text colours of the species labels in (a), permission of reuse from R. Cassey

4.5.2. Heat

The current section presents a mapping of thermal properties of the ten biological envelopes for implementation in buildings, based on the BioMatrix tool presented in chapter 3. This section aims to highlight biological principles, patterns and systems that may be relevant for the temperature control of buildings with the façade. Heat exchanges are considered in both directions' contrary to the previous section 'Light' where only solar incident light beams were considered. The following section gives a brief background on the main thermal transfers that occur in physics and their application in biology.

Thermal regulation in buildings. Considered as the third humans' skin[16], buildings must provide constant thermal comfort over days and seasons, despite thermal environmental fluctuations. The term "thermal comfort" sums up to a set of internal climatic conditions that can be measured by four quantitative variables according to [69, p. 23]:

- temperature of interior air (from 19 to 21°C),
- relative humidity of interior air (from 30 to 70%),
- airflow across the body (from 0 to 0.2 m/s),
- surface temperature of building components (equal temperatures of 19.5 to 23°C for all surfaces enclosing the room)

There are no fixed target values for these variables since requirements varies according to countries, but there is general agreement on that operating ranges [70], [71]. To maintain constant comfort conditions, the building façade acts as a filter to thermal transfers. For convenience, we consider that buildings internal temperature is maintained between 19 to 21°C by an environment independent heating or cooling system, and the facade regulates the thermal exchanges according to environments fluctuations.

As described in chapter 2; building thermal issues can be break down into three thermal situations. Depending on the thermal difference between the building (T_{int}) and its surroundings (T_{ext}), the facade acts in three different ways to contribute to maintain a constant internal temperature:

(a) $T_{ext} < T_{int\,(20°C)}$: the façade limits the thermal transfer from the inside to the outside
(b) $T_{ext} \approx T_{int\,(20°C)}$: the façade filters thermal transfer
(c) $T_{ext} > T_{int\,(20°C)}$: the façade limits excess of heat by blocking thermal transfer from the surroundings

Thermal transfers always flows from the hotter to the colder side [69, p. 23]. When outside temperature is lower than the required indoor building temperature ($T_{ext} < T_{int\,(20°C)}$), the façade acts as a barrier by blocking the thermal flow from the inside to the outside. These climate situations mostly arise in cold seasons or at night. Likewise, when the inside temperature is lower than the outside temperature ($T_{ext} > T_{int\,(20°C)}$), the façade blocks the thermal flow from the outside to the inside. The façade can allow thermal exchanges when the inside temperature is approximately equal to the outside temperature

[16] *Envelope* is a widely used concept in architecture to qualify the roof and the façades considered as the *humans' third skin* or the *extended organism* [15], [16]. See Chapter 1.

($T_{ext} \approx T_{int\ (20°C)}$). Thus, the thermal porosity of the façade little vary despite thermal environment fluctuations. In all three situations, the challenge is to maintain a constant thermal comfort with little amount of energy for façade adaptation and internal heat production. Indeed, the building sector of many developed countries account for about 40% of the global energy consumption and contribute over 30% of the CO_2 emissions. A large proportion of this energy is used for thermal comfort in buildings [70].

Heat transfer. To understand thermal transfers within buildings and biological envelopes, some thermodynamics principles and heat transfer fundamentals are first presented.

Thermal transfers always flows from the hotter to the colder side through four basic thermal transport processes: conduction, convection, radiation and phase-change [69, p. 23]. Conduction refers to the process by which heat diffuses through a solid or a stationary fluid. Convection is the transfer of heat by the movement of molecules within in fluids (gases and liquids). Thermal heat radiation occurs through the exchange of heat between surfaces, or between a surface and a surrounding fluid, by long-wavelength electromagnetic radiation. Heat transfer with phase-change refers to substance change of state at constant temperature. Melting (solid to liquid), evaporation (liquid to vapor) and condensation (vapor to liquid) are three of the most important phase change processes[17] [72, Ch. 1, p13]. As a result, a medium can block, filter or pass heat exchanges according to the processes involved and its thermal conductivity[18].

Thermoregulation in nature. Thermal regulation have widely been reviewed by both biologists and also researchers in biomimetics. This section introduces basic knowledge of thermoregulation in nature mostly synthetized from research in biomimetics [40], [73]–[75], thermal reviews [76]–[80], and handbooks in biology [81, Ch. 48]. The two main sources of heat for organisms are both based on solar energy: first, indirectly through metabolising food and, second, through direct solar gain. As a result, living systems combine morphological, physiological, and behavioural adaptations in order to manipulate temperature gradients.

Zoologists distinguished two types of organisms that respond to fluctuating ambient temperatures: thermo-regulators and thermo-conformers. Thermo-conformers are referred as ectotherms[19] and poikilotherms, i.e. they obtain their heat from external sources; their body temperature adapt to thermal fluctuations [73], [81]. Ectothermy is the prevailing thermoregulation system in invertebrates, and in some classes of vertebrates such fish, amphibians, and reptiles [78], [82]. By extension, plants and fungi

[17] crystallization, or freezing (liquid changing to a solid), sublimation (solid changing to a vapor) and deposition (vapor changing to a solid deposition) are less frequent, and therefore not detailed in this research [72, Ch. 1, p13].

[18] Thermal conductivity: refers to the intrinsic ability of a material to transfer or conduct heat (denoted by λ in W/m.K)

Definitions from [73], [132] :

[19] Ectotherm: organism with body temperature that depends on external sources of heat, directly or indirectly from the sun.

can belong to this category since they do not produce heat, have low core temperature which follows thermal environments fluctuations, and can be regulated through physiological adaptations. In contrast, thermo-regulators are referred as endotherms[20], homeotherms[21] and heterotherms[22], i.e. they are able to generate their heat internally through their metabolism and maintain a high body temperature [73], [81]. Depending on species, normal core temperature is maintained between a narrow thermal range for mammals 36°C to 38°C, in birds (Aves) from 36°C to 42°C [73], [81]. Some groups within mammals have low core temperature such as echidnas (30-32°C) [83].

Both thermo-conformers and thermo-regulators manipulate the temperature gradient between their core and the environment. The environment is considered in the physical sense: it can be a fluid (air, water in liquid or gaseous form) or a solid (soil, water in the form of ice). As detailed in the previous section Heat transfer, heat exchange encompasses conductive, convective, radiative, and phase-change heat transfer within the body of the organism, and between living system and its environment. Within the core, heat transfer mostly occurs by conduction through internal tissues. Then, the direction of heat transfer between organisms and their environment depend on the temperature difference between the surface of the organism and the environment, while the rate of heat transfer depends on the thermal conductivity of the outmost organism layers. For terrestrial organisms, heat exchange at the outer surface of the animal occurs largely by radiation and convection with the surrounding environment. Direct contact with solid surfaces (soils, rocks, vegetation, ice) increase thermal exchange through conduction [73]. The conduction rate depends on the ratio between the total surface area of the organism and its surface in contact with the solid. For instance, thermal conduction plays a significant role in thermal exchanges for amphibians, reptiles, gastropods, insects, and small mammals, whereas most of mammals, vascular plants, fungi, and birds. Indeed, their small size, short legs and locomotion induce a large surface contact between their body and the surface on which they move. They can behaviourally manipulate the temperature gradient for conductive heat transfer by selecting the surface with which they are in contact [73]. The type of thermal exchanges varies according to their behaviour (mobile or immobile), morphology (exchange surface, colour) and physiology (thermo-regulators or thermo-conformers).

Envelopes' thermal regulation. The comparative analysis of thermal regulation allows us to place the ten biological envelopes in several categories which block, filter, or pass thermal exchanges through four difference processes: conduction, convection, radiation, and thermal conversion. **Table 4.2.** outlines the main trends of thermal exchanges. The plus symbols (+) represent the functions and processes carried out by the multi-layer envelopes as obtained from scientific literature. The minus symbols (-) denote that the functions or processes is not involved within the regulation for this type of

[20] Endotherm: organism with body temperature that mainly depends on internal metabolic heat generation.

[21] Homeotherm: animal with relatively constant body temperature, often but not exclusively associated with stable relatively high body temperature.

[22] Heterotherm: organism displaying phases of endothermy alternating with periods of lower ectothermic metabolism.

envelope. The plus/minus symbols (±) is used when the processes is little found within the type of envelope to regulate thermal exchanges.

Biological envelopes	**References**	**Functions**			**Processes**			
		block	filter	pass	conduction	convection	radiation	phase-change
Skin + feather	[84]–[87]	+	+	-	-	+	+	-
Skin + spine	[88]–[92]	+	+	-	+	+	+	-
Skin + hair	[84]	+	+	-	±	+	+	±
Bark (of vascular plants)	[93]–[96]	+	+	-	-	+	+	-
Cuticle + trichome	[97], [98]	+	+	+	+	+	+	+
Skin + scale	[79], [99], [100]	-	+	+	+	+	+	-
Cuticle + seta	[101]–[105]	-	+	+	+	+	+	?
Fungi fruit cuticle	[106]	-	+	+	-	+	-	+
Skin + mucous	[107]–[112]	-	+	+	+	+	-	-
Skin + mucous + shell	n/a	-	-	+	+	+	+	-

Table 2. Qualitative overview of the main functions and processes involved in thermal exchanges between envelope of organisms and their environment. Table nomenclature adapted from [3], [40, Ch. 8, 5], [62].

This review outlines two main types of envelopes which mostly correspond to the categories thermo-regulators and thermo-conformers presented in section Thermoregulation in nature.

Block / Filter. Most of the envelopes which both block and filter thermal transfer are featured by thermo-regulator organisms (*skin + feather, skin + spine, skin + hair*) and bark of vascular plants. Regardless of their thermal environment, they maintain their internal temperature within narrow thermal ranges producing heat and blocking thermal exchanges through a well-insulated envelope. Their appendages - such as feather, spine and hair - are hierarchical material that traps still air in order to reduce thermal convection between the body and its surroundings [1, Ch. 40]. Quantitative studies have measured that the thermal conductivity of feather, and fur is close to the thermal conductivity of glass wool [73]. Their low thermal conductivity also results from the thermal properties of the biomaterial keratin which feather, hair, and spine are mostly made of [113], [114]. Thus, the structure and composition of their outmost layer do not transmit heat towards the inner tissues since the air-keratin matrix blocks thermal transfer.

When $T_{env} > T_{core}$, these envelopes block thermal exchanges from the surroundings by reducing conduction and convection to avoid overheating. Within thermo-conformer, some of their envelopes can evacuate heat through phase-change (sweating) noted with the symbol (±) in Table 2. Indeed, very few mammals sweat profusely for thermoregulation as reviewed by [73], e.g. humans, horses, patas monkeys (*Erythrocebus patas*). When $T_{env} < T_{core}$, the envelope also blocks heat from the body to the surroundings. Different geometries can reduce the thermal exchanges such as multi-layered structures with low thermal conductivity (air-keratin matrix, blubber or adipose tissue[23], etc).

Likewise, barks of vascular plants (Tracheophyta) act as thermal barrier protecting the trunk from overheating (to avoid vapour bubbles in the vessels conducting sap to the leave) or freezing (formation of ice within the tissues) [115]. Geometrical features, thermal conductivity of wood, or the combination of both regulate thermal transmission. Bark are composite material mostly made of linin, and cellulose which have low thermal conductivity [96].

Block / Filter / Pass. The envelope type described as leaf (*cuticle* + *trichrome*) has a wider thermal range compared to the other ten. Indeed, terrestrial plants (Tracheophyta) occur worldwide from the hottest to the coldest regions. Where thermo-conformers organisms mostly block thermal exchanges through their envelope to maintain constant internal temperature regardless to their environment; leaves provide different thermal adaptations depending on the thermal environment. This group has a wider thermal range where leaves' lethal/damage temperature is between 0 to 40-45°C [115].

Filter / Pass. Most of the envelopes which both filter and pass thermal transfer are featured by thermo-conformers organisms (skin + scale, skin + mucous, cuticle + seta, skin + mucous + shell) and fungi fruit cuticle. Thermo-conformers allow thermal transfer through their envelope since their internal heat production is negligible for thermoregulation. Due to their small size, short legs and locomotion inducing ground proximity, thermal exchanges mostly occur by both conduction and radiation for these envelopes.

The envelope of reptiles (*skin* + *scale*) and insects (*cuticle* + *seta*) mostly capture heat by direct exposure to solar radiation, and with conduction between the ground and their body. Their envelope have high thermal conductivity which conduct heat through the inner tissues by conduction. According to their colours, they can regulate the rate of solar radiation absorbed since dark colours mostly produced absorption of short wavelength by pigments (carotenoids, melanin, etc) absorb more radiation than bright colours.

The envelopes of land gastropods and amphibians such as *skin* + *mucous* and *skin* + *mucous* + *shell*, are wet skins featured by living systems than live under moist environments [117]. These living organisms highly have heat and water permeable skin that can reduce body temperatures below air temperatures through rapid evaporative cooling (phase change). However, they quickly risk dehydration if they are exposed to direct solar radiation, and without being in contact with water [118].

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[23] Adipose tissue: animal tissue composed of lipid (fat) filled cells (lipocytes/adipocytes) that store energy and also provide insulation and mechanical support [73], [132].

Envelopes patterns for thermal regulation

As previously outlined with the wide thermal range of leave in Table 2, thermal inter-specie variety occurs for some biological envelopes. This variety can result in a wide range of thermal regulations, and/or in a large diversity of processes involved.

In the perspective of design application, further developments must present non-exhaustive biological patterns found for thermal exchanges that can be adapted for building facades and illustrated by biological envelopes.

Concluding remarks to design building skins. This section provided qualitative classifications of the ten types of biological envelopes regarding to their thermal performances.

Relevant biological models. Aligned with [73], the biological envelopes of thermo-regulators such as *skin + feather, skin + peak* and *skin + hair* may be interesting for building applications since birds and mammals have comparable features to temperature control and energy use in buildings. As many buildings, these animals regulate their temperature within narrow thermal ranges regardless to the thermal fluctuations, by generating internal metabolic heat and with a good insulation. In both situations ($T_{ext} > T_{int}$ and $T_{ext} < T_{int}$), their envelope plays a key role by blocking thermal exchanges. Thus, their insulation properties due to their multi-layers structures and highly adaptive make them relevant biological models for building facades.

Since advanced knowledge in civil engineering allows to build façade with good insulation, their performances can significantly be improved by daily and seasonal adaptations as thermo-regulators do. Indeed, these three biological envelopes are continually adapted in order to control the thermal exchanges between the body of the organism and its surroundings. Nowadays, most of the buildings' insulation do not adapt across thermal fluctuations. Thus, there is no single biological system which simultaneously maintain a narrow internal thermal range over days and seasons despite thermal environmental fluctuations, and without moving.

Towards combination of biological patterns. Since there is no single relevant biological systems which both have the same physical and thermal constraints as buildings, designers have to combine relevant biological strategies. As outlined by biological patterns for thermal. These results are aligned with [40], where the concept of "imaginary pinnacle" was introduced in order to combine relevant biological strategies.

Data availability. Results from qualitative analysis must be completed by quantitative data. Indeed, the concept of operating range does not consider the thermal variety per type of envelopes which depends on climates, the age of the biological organism, its physiological and morphological adaptations, etc. These first qualitative classification needs to be completed with quantitative data to provide an accurate classification per type of envelopes. However, literature counts very few comparative investigations of thermal performances all domains of living organisms. McCafferty et *Al.* is the only study that has nowadays reviewed and compared quantified thermal performances of biological tissues with building materials. This study provides a comparative analysis of some animals' behaviour, physiology, and morphology for thermal regulation focusing on thermal conductivity of mammals' coats, and birds' feathers. However other kingdoms (Plantae, Fungi), domains (Archae, Bacteria), and other animals such as arthropods (Arthropoda) or nematods (Nematoda) within eukaryotes are not considered in that thermal review. Thus, there is a need for thermal characterisation of living envelopes beyond these qualitative thermal reviews for biomimetic applications.

4.5.3. Noise

This section compares the acoustic qualities of the ten biological envelopes. As outlined in Chapter 3, sound is a vibration that propagates through the material such as gas, liquid or solid. Acoustic waves can be blocked, filtered or can pass through the biological envelopes. The processes involved in the regulation of these functions are as follows: reflection, absorption, diffraction, and transition. **Table 4.2** gives an overview of the functions and processes involved for the sound wave regulation per type of envelope. As a reminder, biological envelopes are considered under ambient temperature (20°C) and normal pressure at 1 atm (1,013 bar). This work considers only the acoustic waves produced outside the body of the living organisms and regulated by its biological envelope. This analysis is based on qualitative data deduced from the physical properties of biological materials: composition and architecture.

Biological envelopes	**Physical properties (composition)**	**Geometry**	**Functions**			**Processes**			
			block	filter	pass	absorption	transmission	diffusion	reflection
Vascular plants' cuticle	Mainly water, organic fibres	thin, smooth surface			+	+	+		
Vascular plants' bark	Fibrous composite	smooth and/or textured surface		+			+		+
Fungi cuticle	Porous	smooth and/or textured surface	+			+			
Arthropods cuticle + seta	Ductile material (chitin)	Smooth surface		+			+		+
Skin + feather	Flexible + ductile material (keratin)	multi-layer with air layer, surface multiplied by the feathers	+			+		+	+
Skin + hair	Flexible + ductile material (keratin)	multi-layer with air layer, surface multiplied by the fur	+			+		+	+
Skin + spine	Flexible + ductile material (keratin)	multi-layer with air layer, surface multiplied by the spine	+			+		+	+
Skin + scale	Flexible + ductile material (keratin)	multi-layer		+			+		+
Skin with mucous	Flexible (collagen, xxx)	thin surface		+		+	+		
Skin, mucous + shell	Flexible + ductile material	multi-layer with mineral layer		+		+	+		+

Table 4.4. Overview of the functions and processes involved for sound wave regulation per type of envelope.

The composition and architecture of biological materials influence the regulation of acoustic waves. Soft biological materials absorb the acoustic wave and then reduce its propagation within the material. Soft materials dissipate acoustic wave through the material. The layer “tissue” or “skin” of the biological envelopes with hair, scale, feather, spine, mucous, and shell absorb has these acoustic characteristics. This layer is made up of collagen, which guarantee the elasticity of the material. Conversely, hard biological materials mostly reflect the incident wave (chitin, keratin, minerals, lignin). Unlike soft material, a small part is absorbed and then transmitted within the material. The speed wave is faster than within soft biological material.

As soft biological material, porous structures absorb then dissipate sound waves by friction with the air (e.g. cap of the fungi fruit). Two main layers compose the biological envelopes skin+hair, skin+feathers and skin+spine: the appendages and the tissues. The outmost layer blocks the acoustic wave through several processes: reflection by the appendage layer made of keratin (hard material), absorption by the large contact surface offered by the appendage. Un-reflected or absorbed acoustic waves are transmitted to the soft tissue and dissipated.

These first results need to be verified through quantitative analysis. Applying the concept of Emerging Properties presented in Chapter 1, acoustic performances of biological material cannot be understood as a sum of properties. However, very few experiments have assessed sound wave regulation by biological envelopes as outlined by the lack of literature. Indeed, most of the terrestrial living organisms have specialized organs for sounds perceptions such as ears. The available literature points that only arthropods (*Arthropoda*) perceive sound wave through their envelope. Their setae – which are hair-like structures located on the arthropods’ exoskeleton – help to perceived the mechanical wave variations of their surroundings. Likewise, few literatures assess acoustic performances of plant communities excepted in order to evaluate their sound attenuation abilities [119]–[122].

4.6. Multi-regulation

Table 4.4. synthetizes the main regulation functions of each type of envelope per abiotic factors. As a reminder, the behaviour of the envelopes is studied in the context where the living organism is active, during the day and at the adult stage of development. The symbols (+) denote the main function of regulation per abiotic factor per biological envelope. For instance, vascular plants’ cuticle (*Tracheophytes*) mostly block air and water since the gas exchanges occur through specialized organs which pierce the cuticle - the stomata. Very little gas exchanges occur with cuticular transpiration, botanists consider minor this contribution behind the stomata’. For this purpose, Table xx outlines that vascular plants’ cuticle block air infiltration rather that filter. In addition, the table only assesses the regulation of abiotic factors from the environment to the body of the living organism. Regulation from inside the organism to the outside is not included in this table.

Further investigations must compare results presented in table 4.4.

Regulation of environmental stresses	Heat			Light			Air			Water			Noise			Mechanical		
Biological envelopes and example	block	filter	pass	block	filter	pass	block	filter	pass	block	filter	pass	block	filter	pass	block	filter	pass
Vascular plants’ cuticle			+			+	+			+					+			+
Vascular plants’ bark		+		+			+			+						+		
Fungi cuticle		+			+			+			+			+			+	
Arthropods cuticle			+	+				+		+						+		
Skin + feather		+		+				+		+				+				+
Skin + hair				+				+				+		+				+
Skin + spine				+				+		+								
Skin + scale						+	+			+							+	
Skin with mucous						+			+		+							+
Skin with mucous and shell			+	+			+			+								

Table 4.5. Overview of multi-regulation properties of living envelopes. Synthesis of tables 4.2 and 4.3.

5. Conclusion

This section brings together the topics of living envelopes, multi-regulation, and classification. Ten biological envelopes are compared, and clustered using several variables of the BioMatrix. Chapter 4 addresses the three following sub-questions. Their answers are presented as follow.

- **What are the main types of Eucaryotes' living envelopes in terrestrial ecosystems?**

Biological envelopes can be found all hierarchical levels of organization, all climates and all kingdoms. This work only selects the outmost layers of eucaryotes (Eucaryota) living under all terrestrial environments in order to limit the field of exploration. The non-exhaustive list of biological envelopes goes as follow: cuticle+trichomes, bark, cuticle+seta, skin+feather, skin+spine, skin+scale, skin+mucus, skin+spine.

The geometries' comparison outlines one common pattern that adapt according to its body location, to the species, and to the environment. Biological envelopes are multi-layers systems made of two layers: the deep tissues such as the dermis, epidermis hypodermis which produce the appendages such as trichomes, feathers, hairs, spine.

- **How to select the 'right' biological model?**

There is no "right" biological model, but several biological systems to combine to provide a systemic design. These results are aligned with the first conclusions of L. Badarnah [40, Ch. 8] and A. [123]Some living organisms are relevant since they maintain the same operating ranges within their body and are subject to the same abiotic factor(s) as buildings. However, none of them is simultaneously subject to the same six environmental constrains, with the same frequency and intensity as buildings.

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Key concepts

Architectural practice,
Education, Research, Politics

Taxonomic bias,
Qualitative, quantitative
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Ethic
Sustainability
Ecosystemic services

Discussion & Conclusion

The main developments and highlights of this PhD thesis – the BioMatrix, comparative tables and patterns - are concluded and discussed in chapter 5. These contributions have provided several tools to help designers in the initial building design phases during which investigation is undertaken to find relevant biological systems

Biomimetic approach can be integrated all design steps of a building, from programming to construction administration, however, the approach is not widespread yet, especially over architectural practice. A discussion on the educational, research, design practices and politics brakes that can limit its integration within architectural practice is provided. This section presents a non-exhaustive overview of opportunities to enhance biomimetic illustrated with existing biomimetic buildings, research, and educational programs.

The access to biological data was also found as one of the major challenges to enhance the development of biomimetic. This section discusses the strong taxonomic bias found throughout the research, and outlined in chapter 2 and 4. Likewise, a discussion on the lack of both qualitative and qualitative data is provided.

Finally, the last section of the chapter discusses ethical aspects since biological data acquisition and biomimetics developments raise ethical question. These questions are discussed in the light biomimicry's original philosophy, the current context of sustainability in architecture, and ecosystemic services.

5.

Table of content

5.1. Conclusion

As outlined in chapter 2, the design of buildings can be divided into the six following steps: *(i) programming, (ii) schematic design, (iii) design development, (iv) construction documents, (v) tender documents*, then *(vi) construction administration* [1]. Biomimetic approach can be integrated at all steps; however, this research focuses on its integration within the steps i*i* (**Fig. 5.1**, top in green).

Within that step *ii* and aligned with current research efforts, this work has focused on the facilitation of the 'technology pull' biomimetic approach, based on the 8 steps of the unified problem-driven biomimetic design processes [2], and for the design of building envelopes (**Fig. 5.1**, middle).

Figure 5.1 illustrates the main developments of this work (bottom), within the eight steps of the unified problem-driven biomimetic design processes (middle), and among the six conventional building design phases (top). In the building design phases, this research only focuses on the step *ii* - *schematic design*. Within the 8 steps of the 'technology pull' biomimetic design process, the development of this research primarily focuses on the biological aspects which will inform the biomimetic design process (steps 4 to 6, in green). The first steps were briefly carried out in order to provide context for the study, i.e. the design of a multi-functional building envelopes (steps 1 to 3). The last steps of both biomimetic design processes are beyond the scope of this work since this is currently being investigated within the framework of another PhD thesis across research and practice, and in collaboration with the author[1] (steps 7 and 8).

Biomimetic contributions of this work have been developed to help both architects and engineers to select the biological systems best adapted for the design of multi-criteria systems – in this case building envelopes.

The tools subsequently developed in chapter 4 – radars charts, comparative table and patterns of organisation - provide guidance for the selection and then the combination of biological systems strategies when designing a biomimetic building envelope. Since architecture is both a creative and technical domain, these biomimetic tools aim to provide a structured approach whilst allowing creativity. Their description, purpose, and application is as follows and illustrated in the bottom section of **Figure 5.1.**

[1] PhD research (2020-2023) of Tessa Hubert carried out at the MECADEV, I2M and Nobatek/$INEF_4$ (Bordeaux, France) in collaboration with the CEEBIOS (see the Foreword and Chapter 1, section 'Collaborations').

- **The multi-criteria Bio-Matrix** is a descriptive tool which helps designers to structure mapped biological knowledge in step 4 – *Identify potential biological models* – in the unified problem-driven biomimetic design processes [2]. The BioMatrix provides a general and comprehensive understanding of living organisms with the aim of solving multi-criteria design challenges related to building envelopes. The matrix is comprised of four main categories and sub-categories - matter, functions, environment, time – that designers can complete themselves or with the help of biologists. The circular matrix encourages lateral thinking through the use of visual connexions between the different categories (see **Fig. 5.1.A)**. Referring to the ISO standard 18458:2015, 'Biomimetics – Terminology, concepts and methodology' [3], it should be noted that the BioMatrix can be also used in the step 4 – *Identifying potential biological models* – of a 'biology push' biomimetic design process.

- **Comparative tables, radar charts, MCA**[2] are descriptive tools based on the categories described by the BioMatrix. Following the selection of different biological systems designers can then qualitatively compare and choose the most relevant models in step 5 – *Selecting biological model(s) of interest*. Indeed, none of the biological models simultaneously meet the different requirements for a building envelope. These tools allow a multi-criteria comparative analysis of the biological functions and processes involved in the regulation of the environmental factors which confront them, i.e. heat, light, water, mechanical stress, noise, air. (see **Fig. 5.1.B)**.

- **Patterns of organization** is a tool to use in step 6 – *Abstracting* - to abstract the observed recurrent geometries, material properties and physical processes among selected living systems. These schematic cross-sectional views facilitate the technological transfer from the biological envelope to the building façade. This design step no longer refers to biological systems, focusing rather on physical principles. Designers can choose to combine several patterns according to their specific design challenge and technology available for transfer while biological systems cannot (see **Fig. 5.1.C)**.

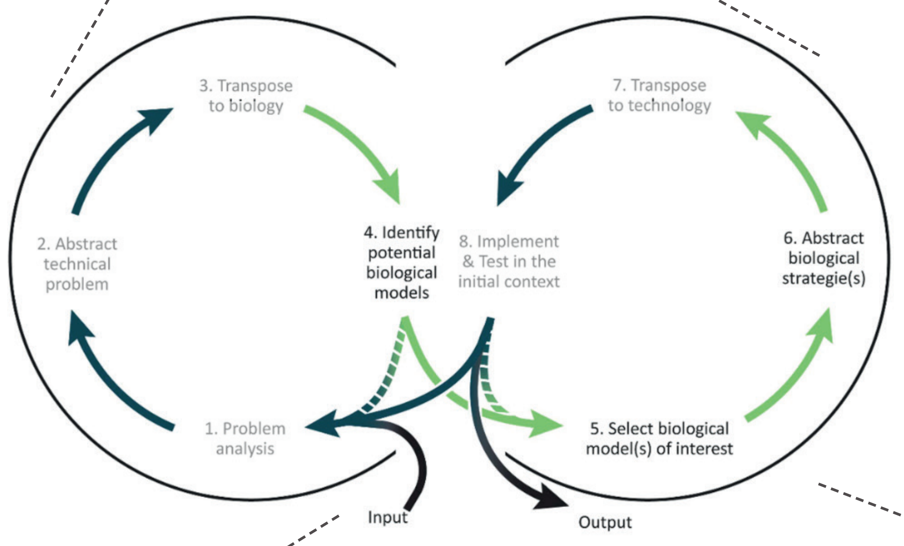
Although these tools result from both literature analysis and observation of current practices within the author's professional environment, they have not been implemented within architectural practice yet. There is a need to test, and then improve that tools in order to suit best to designers' practice. It is planned to test them via the BCL - Biomim' City Lab – French collective, which gather together a group of building practitioners (architecture studios, engineering consultants, property developers and local authorities) [4], [5].

[2] MCA: Multiple Component Analysis (see chapter 4, multoi-regulation).

Building design steps

i. programming	ii. schematic design	iii. design development	iv. construction documents	v. tender documents	vi. construction administration
The client establish the program of requirements (programmi-	Architects provide sketches that illustrate the basic concepts of the design. They research of local compliance and	Architects and civil engineers provide the final design. They deliver detailled floor plans, elevations and building cross-sec-	They provide construction drawings/ blueprints, notes, and technical specifications necessary for bidding, construction, and	Architects select a builder or a group of builders with a com-	Architects monitor the verify the concordance with the construction documents. competitive

Biomimetic design process



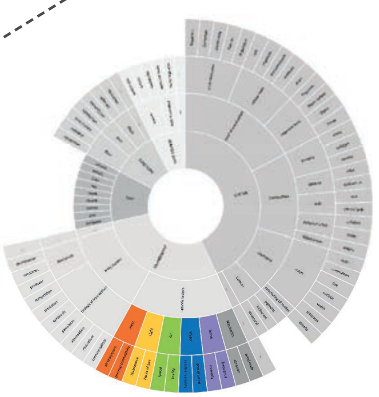
The unified problem-driven biomimetic design processes, with permission from P. Fayemi [2].

4. Identify potential biological models
Identify biological models that correspond to the technical problem

5. Select biological model(s) of interest
Identify relevant biological strategies among the previous selection

6. Abstract biological strategie(s)
Abstract biological principles into concepts to facilitate transposition

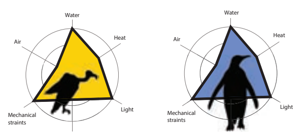
Main research contributions



A.

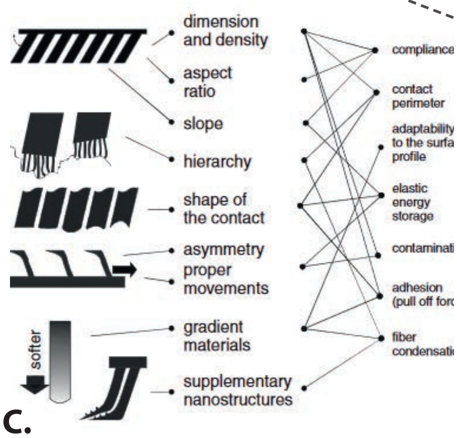
Multi-criteria BioMatrix (for step 4) structures mapped knowledge in biology. This tool provides a general and comprehensive understanding of living organisms with the aim of solving multi-criteria design challenges.

Biological envelopes	block	filter	let in
Bark (vascular plants)	+	-	-
Skin + feather (birds)	+	-	-
Skin + spine (of xxx)	+	-	-
Skin + hair (of mammals)	+	+	+
Cuticle + trichome (vascular plants)	-	+	+
Cuticle + seta (of arthropods)	+	-	-
Skin + scale (of reptiles)	+	-	-
Fungi fruit cuticle (of fungi)	-	+	+
Skin + mucous + shell (xxx)	+	-	-
Skin + mucous (of nematodes, amphibian	-	+	+



B.

Comparative table, radar charts, MCA (for step 5) are descriptive tools based on the categories described by the BioMatrix. They allow a multi-criteria comparative analysis of the biological functions and processes involved in the regulation of the environmental factors.



C.

Biological patterns (for step 6) abstract the observed recurrent geometries, material properties and physical processes among selected living systems. These schematic cross-sectional views facilitate the technological transfer from the biological envelope to the building façade.

Figure 5.1 Mapping of the main developments for the design of multi-functional envelopes. The six conventional building design steps adapted from [1] (top). The eight steps of the unified problem-driven biomimetic design processes with permission from [2] (middle). Main contributions (bottom).

5.2. Discussion

Many biomimetic tools, methods and frameworks have been designed over the last decade as review by [2], [6]. However, their use is not widespread yet, especially over architectural practice [7]. The author assumes that the lack of a clear methodology and suitable tools is not the only challenge. This section discusses the brake that can hinder integration of biomimetic in design practice.

5.2.1. Biology as a new domain among several others

Architects plan, develop and implement building designs. They compile feasibility reports, determine environmental impact, create project proposals, estimate costs, determine timelines and oversee construction processes. This multi-disciplinary profession must find a balance between artistic, economic, technological and more recently, ecological knowledge.

In theory, Architects know enough about other disciplines to ask the right questions without being experts in any of those domains. However, the explosion of knowledge due to technological advances – 3D modelling, numerical simulations, thermal imaging – as well as discoveries in material science – adaptive and PCMs[3] materials - has increased the complexity of architectural practice over the last years. Indeed, applying biology within architectural practice further increases complexity.

Applying biomimetic approaches requires interdisciplinary knowledge as underlined by different research in [8, Ch. 9], [9, p. 144], [10], [11]. This key aspect is outlined throughout this research, and especially in chapter 4 which refers to some five different fields of physics from geometrical optics and wave optics (6.1. Light), to thermodynamics (6.2. Heat), fluid mechanics (6.3. Water and 6.4. Air), and solid mechanics (6.5. Noise and 6.6. Mechanical stress). This section was only made possible through the author's background in civil engineering, not in architecture.

While the title 'Architect' is protected in most countries its current professional, social and economic standing varies from one country to another [12, p. 6]. In France, basic training in architecture does not provide the level of knowledge of physics, civil engineering and Life Sciences required for the integration of biomimetics as developed within this research[4].

[3] PCM: Phase Change Material

[4] In the 19th century the French system became marginalized with most of the countries by splitting up architecture and civil engineering training. Until 1968, architecture was taught by the School of Fine Arts. Architecture was considered as one of the four disciplines of the fine arts, along with engraving, sculpture and painting. As a result, French schools of Architecture are public institutions accredited both by the Ministry of Culture and Ministry of National Education [116].

5.2.2. Opportunities to integrate biomimetics in architecture

Applying system thinking as introduced in chapter 1, leads towards a broad analysis of the building sectors for integration of biomimetics. Beyond the scope of architectural practice, biomimetics can also be embodied within education, research, building industry and politics.

Based on author's observations within its professional environment and in collaboration with Tessa Hubert[5], this section lists and then discusses the opportunities of integration of biomimetics within different domains (education, research, building industry and politics). They can involve little behaviour modifications to in-depth transformations. Building examples illustrates these opportunities throughout the discussion, and **Figure 5.2** summarizes these non-exhaustive opportunities to enhance integration of biomimetic.

Education. The degree programme in architecture is a five-year undergraduate programme. The training is divided into two parts: the teaching of architectural design which is profession-oriented, and theoretical courses that underpin the architectural practice in the form of lectures, tutorials or seminars. These courses enrich the practice considered as the core of the teaching [12, p. 6].

Biomimetics has mostly been integrated within theoretical courses through introductive lectures i.e. few hours of teaching, or through seminars i.e. 20 to 50 hours [13]. These short-term courses explore biomimetic architecture through a narrow-defined scope such as envelopes [14]–[16], compliant mechanisms [17], [18]. Students are then free to integrate biomimetic principles within their architectural practice. The most advanced courses in biomimetics remain the 2-semesters ITECH programme offered at the University of Stuttgart, and which integrate a biomimetic seminar at the beginning of the semester with departments in biology at the University of Tübingen [17], [18]. Similarly, the One Studio programme offers a one-year post-professional Master's training for the development of bio-inspired construction at University of California [19]. However, none of the worldwide under-graduated architecture programmes have placed biomimetics as a central topic within the architectural practice. The master programme NID – Nature Inspired Design - of the design school of ENSCI in Paris, is the only comparable example since biomimetic is the core of this programme and embodied throughout all training [20], (**Fig. 5.2**, Education).

Research. Short-term research has always been part of architectural practice. Architects carry out literature, on-site analysis, interviews or drawing research for each single project as each differ from the previous one. Then, the design team draw building proposal(s) to address the multi-criteria requirements the building must meet. However, very few architecture studios have been associated or have carried out research in the academic sense.

Time seems to be the first limiting factor to combine architectural practice and academic research. Indeed, the building design timescale vary from weeks to months whereas academic research spread over years. As a result, architects promote the use of mature building systems and technology while

[5] PhD research (2020-2023) of Tessa Hubert carried out at the MECADEV, I2M and Nobatek/INEF4 (Bordeaux, France) in collaboration with the CEEBIOS (see the Foreword and Chapter 1 section 'Collaborations').

producing construction documents in the design step *iv* outlined in Figure 5.1. Using non-mature building systems will require additional assessment steps regarding to building code requirements.

In this context, very few architecture studios have initiated, and then carried out long-term, and applied biomimetic research beyond the construction of a single building. But some research studies remain the exception such as SymBio2 programme manage by the French architecture Studio XTU which has developed a photobioreactors façade system[6] inspired by an autotroph[7] marine slug (*Elysia chlorotica*) [21], [22]. This bio-façade is currently built in Paris within the Algo House [23]. Likewise, Tangram Architecture Studio develops bioluminescent[8] facades systems in partnership with the Mediterranean Institute of Oceanography [24], [25], the international studio Art & Build has developed adaptive shading systems that mimic passive mechanisms observed in plants which is currently test within the building façade of the CIRC in Lyon in France [26], [27]. These breakthrough systems are being developed alongside the main activities of architecture studios, from the concept to the building construction. The business risk is high for architecture studios having regard to their size[9].

Beyond these examples, research in biomimetic architecture has mostly been carried out by academics rather than architecture studios. The worldwide most advanced research have been carried out by the labs ICD and ITKE at the University of Stuttgart within the funding programs of the Collaborative Research Centre SFB-TRR 141 in Germany (Stuttgart – Tübingen – Freiburg Universities) [28]. They have focused on lightening the structure to reduce material consumption by developing annual research pavilions [17]. One of their four research topics - Fibrous morphologies - have trigger the creation of the FibR company to upgrade research technology to the building sector. This example illustrates a soft transition whereby links between academic institution and a start-up fabrication company have been maintained for mutual benefit [29], [30]. Strengthening the link between applied research and architectural practice is essential to facilitate the integration of biomimetic (**Fig. 5.2**, Research).

Politics. In addition to the development of technical solutions by academics and spontaneous integration within design practice by some architects, a politic recognition is essential to enhance the development of biomimetics. Beyond supporting research, public institutions can enhance the development of biomimetic at the programming stage. The architectural design competition for the marine biomimetic centre of Biarritz has integrated biomimetic with the building requirements. This ambition was driven by local authorities including the Biarritz Town Hall [31] (**Fig. 5.2**, Politics).

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[6] Biological solar panels - thin glass panel of microalgae culture placed in the configuration of a double skin façade. This configuration both increases building performance – for heating and cooling - and optimizes the microalgae production.

[7] An organism capable of synthesizing its own food from inorganic substances using light or chemical energy. *Elysia chlorotica* remains an exception since only green plants, algae, and certain bacteria are autotrophs.

[8] Bioluminescence is the production and emission of light by a living organism. This chemical reaction occurs in marine vertebrates and invertebrates, as well as in some fungi, microorganisms including some bioluminescent bacteria, and terrestrial arthropods such as some fireflies [117].

[9] In France, only 12% of architecture studios have a turnover in excess of 500,000 euros. More than 70% of architects worked alone or with a salaried employee [118]

Implementation. Based on previous sections of this chapter, this section presents non-exhaustive opportunities to enhance biomimetic within architectural practice for the steps *ii* and *iii.* The building design step iii – design development – refers to the step 7 and 8 of the biomimetic design processes (see **Fig. 5.1**). This analysis focuses on designers' opportunities. Examples of existing buildings – mostly biomimetic building envelopes presented in chapter 2 - illustrate the listed opportunities within the table. Depending on the project context and actors involved, biomimetic can be undertaken in many ways, and at different design stages (see **Table 5.1**).

Opportunities are compared with four categories - technical risk, cost benefit, design time, level of innovation - and ranked with the three qualitative variables: low, medium and high. This preliminary analysis aims to provide guidance for designers. The aim is to use these preliminary results to build the foundation for further quantitative investigations.

Id.	**Opportunities to apply biomimetic in design practice**	**Design time**	**Level of innovation**	**Technical risk**	**Cost benefit**
	ii. Schematic design (identify, select, abstract biological strategies)				
	Ideal situation, e.g. n/a	low	high	n/a	n/a
1	'technology pull' biomimetic approach to search for relevant biological models, all domains. *e.g.* Biomimetic office building [9]	high	high	n/a	n/a
2	'technology pull' biomimetic approach to search for relevant biological models within a narrow range of organisms, e.g. ITECH Programme	med.	high	n/a	n/a
3	'biology push' biomimetic approach to emulate an observed strategy of a living organism. e.g. Flectofin [32], Breathing Skin [33], Eastgate [ref]	med.	med.	n/a	n/a
	iii. Design development (transpose to technology)				
	Ideal situation, e.g. n/a	**low**	**high.**	**low**	**high**
4	Upgrade a mature and existing biomimetic solution with high TRL e.g. Nianing church [34], [35] and Davies Alpine House [36], [37]	low	low	low	high
5	Novel combination of exiting and well-known building systems. e.g. Eastgate Building [38]–[40]	med.	med.	med.	med.
6	Upgrade a non-mature biomimetic solution with low TRL by integrating in a building the technical solution. e.g. n/a	med.	med.	med.	med.
7	Develop a novel breakthrough building systems. e.g. Art & Build [27], [41], XTU Paris [21], [22]	high	high	high	low

Table 5.1. Overview of opportunities to apply biomimetic in design practice. Colour coding reuse from Fig. 5.1

Figure 5.2. Non-exhaustive opportunities in architecture to enhance integration of biomimetic in education, politics, research and architectural practice. **Pictures credits:** E. Cruz, T. Hubert CC0 BY-SA-NC 4.0 (a), © Geneviève Sengissen (b), © ICD/ITKE University of Stuttgart (c,d), © Art and Build (e), © Arotcharen Architecte (f), © Atelier One (g), © Tobias Becker (h), © Exploration architecture (i).

5.2.3. Overcoming taxonomic biases

Taxonomic bias[10] – also referred to as taxonomic chauvinism [42] – was highlighted throughout this research. Chapter 2 outlined a strong bias among the thirty existing biomimetic building envelopes: more than half of them are inspired by the kingdoms Animalia (57%), and then Plantae (36%) (see **Fig. 5.3.A** and **5.3.B** adapted from [7], [43], [44]). Likewise, most of the living systems studied in chapter 4 also belong to these two kingdoms despite the kingdom Fungi was partly studied (see **Fig. 5.3.A** and **5.3.C** adapted from [7], [43], [44]). This distribution does not reflect the diversity of both estimated and described species on Earth.

These preliminary outcomes are aligned with the general trends in biology. Within the domain of Eucaryotes, many studies have showed that some organisms – mostly plants and vertebrates (birds and mammals) – are over-represented within research in Life Science while some are under-represented such as Arthropods (Insecta, Arachnida, Malacostraca and Maxillopoda), and Mollusca (Gastropoda and Bivalvia) [42], [45], [46]. The taxonomic bias is especially blatant for insects. Studying a sample of peer reviewed papers published over a 15 year period, Clark et al. showed that only 11% of them focused on Insecta, while they represent 79% of the global biodiversity [46], [47]. Similarly, Troudet et al. have quantified taxonomic bias in biodiversity data by considering 626 million of GBIF[11] occurrences which covered 24 classes of organisms. Their results shown that societal preferences, rather than research activity, strongly correlate with taxonomic bias. The most popular species on the web are also the species with the most records in GBIF [45] (see **Fig. 5.4**). Likewise, the French botanist and philosopher Francis Hallé assumes that plants are less studied than animals since they attract little public interest [48, Sec. Contemplating our navel].

The observed bias in the selection of the biological models in biomimetic research may arise from the existing taxonomic bias in Life Science. As outlined in chapter 4, most of the selected living systems belong the kingdoms Animalia and Plantae, despite the author's efforts[12] to balance the sample of studied organisms. Efforts were carried out in order to reduce the taxonomic bias – especially in chapter 4 - but the lack of biological data for some groups limits the exploration for biomimetic applications.

Cruz, Hubert *et Al* (2020), have assumed that the selection of biological models is mostly oriented by research opportunities and social preference since very few designers have a sufficient background in biology [7]. As outlined in section 5.1 of this chapter, integrating biological knowledge within architectural practice is not yet systematic, and may turn out to be challenging with regards to technical risk, cost/benefit tensions, design time, and level of innovation. As a result, designers refer to their own knowledge in biology – which might follow societal preferences – or can access to knowledge by

[10] Taxonomic bias: the fact that some taxa are more investigated than others.

[11] GIBIF – the Global Biodiversity Information Facility - is an international network and data infrastructure funded by the world's governments and aimed at providing anyone, anywhere, open access to data about all types of life on Earth [119].

[12] See chapter 4, The selected envelopes tried to cover the Life on Earth diversity.

collaboration with biologists rather than integrating biologist in the design process [7]. However, the current organisation of research in Life Science does not help to overcome this bias since most labs are specialized in some taxonomic groups or in some biomes. Indeed, biology is a vast field of study that need to be considered separately and resulting of highly specialized labs. Very few research labs both cover a wide range of taxa.

In addition to design effective man-made systems, the biomimetic approach must overcome some prejudices on living organisms inherited by a limited knowledge in biology. Overcoming this taxonomic bias will help increase the ecological awareness of designers, public and politics beyond the well-known living species [49]. For instance, the advertisement of under-represented organisms such as spiders (Araneae) to the general public and enhanced by a biomimetic approach can help increase ecological awareness. The good news is that many biomimetic researches have studied insects – which is the most under-represented group in biodiversity data (see **Fig. 5.4**) - such as the funding program of the Collaborative Research Centre SFB-TRR 141 (Stuttgart – Tübingen – Freiburg Universities) [28], the team of Stanislav Gorb at the Zoological Institute of the University of Kiel [50], and the research lab of Ecology of Multitrophic interactions & Biomimetism of the University of Tours in France [51]. Likewise, architectural designs emerge from an assumed and explain choice by the architects in terms of environmental, social and programmatic requirements. Since architects are expected to explain the ‘building design concept’, they may arise general public interest, and democratize biodiversity knowledge [52]. Biomimetic developments can therefore play a key role in the overcoming of taxonomic bias in the Life Sciences, and in the opening of new research fields of interests.

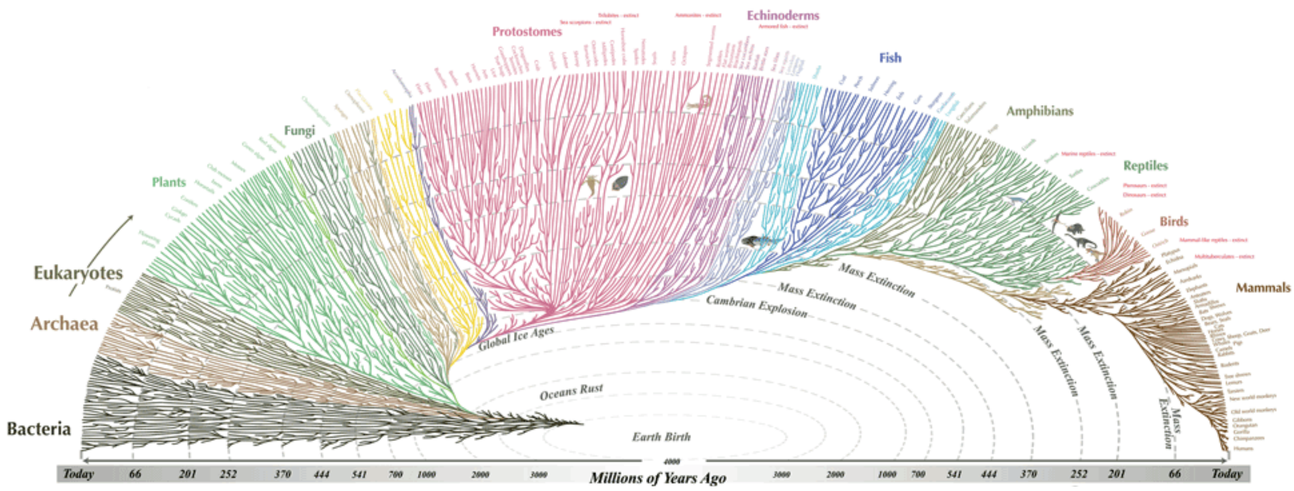

Figure 5.3.A. The Tree of Life, permission of reuse from © evogeneao.com.

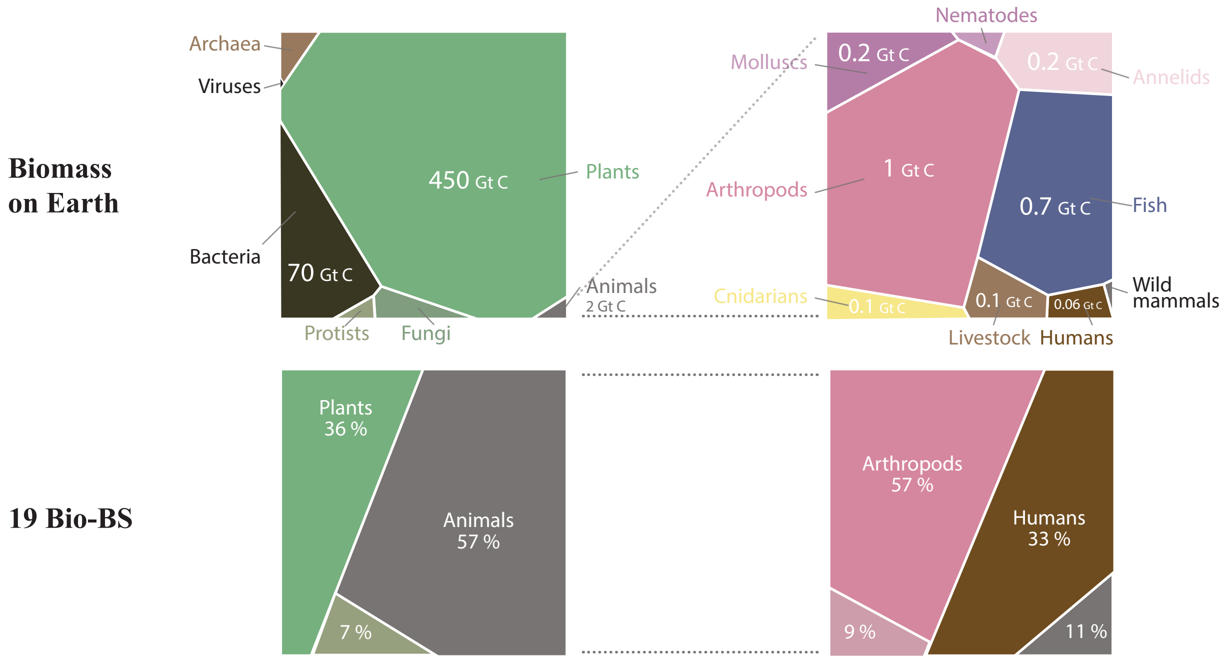

Figure 5.3.B. Comparaison of the 19 Bio-BS with biomass distribution. Distribution of the estimated biomass on earth in gigatons of carbon (GT C) (top), and distribution in percentage of the biological models which inspired the 19 Bio-BS (bottom). (see chapter 2, figure 2.7)

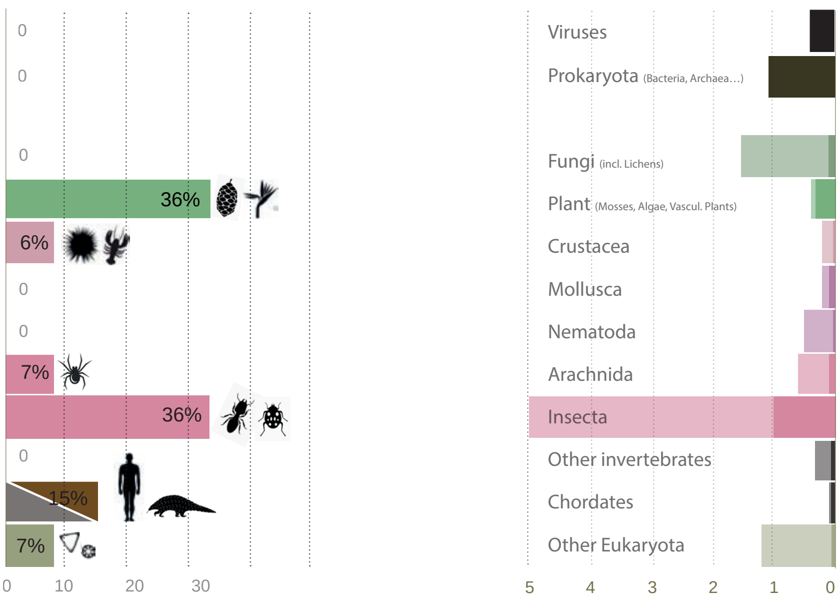

Figure 5.3.C. Comparaison of the 19 Bio-BS with distribution of estimated species on earth. Distribution of the major groups of biological models which inspired the 19 Bio-BS (left) according to the distribution of estimated species on earth (right). (see chapter 2, figure 2.7)

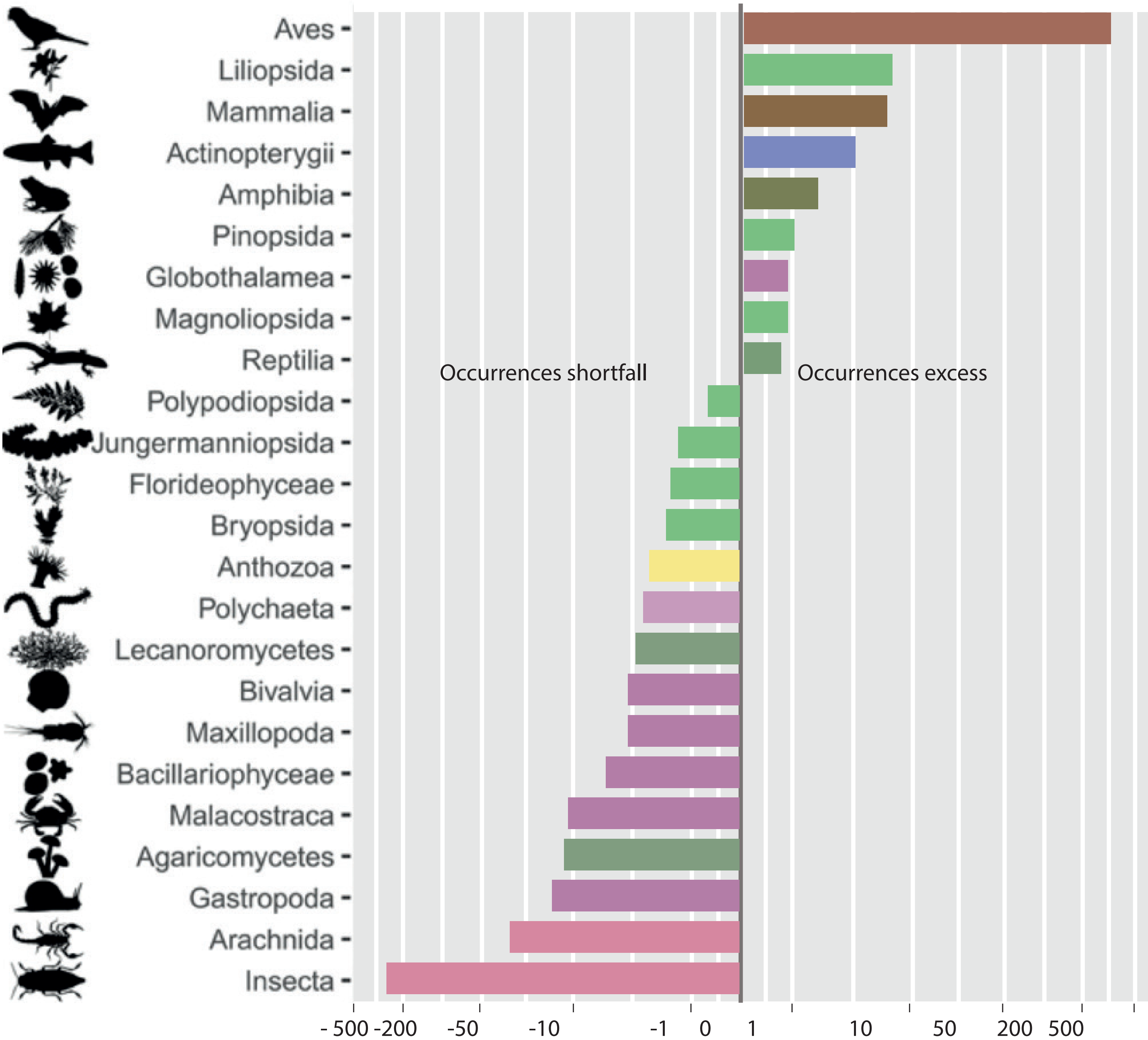

Figure 5.4. Taxonomic bias in biodiversity occurrence data. Taxonomic bias in biodiversity occurrence data. The vertical line at x = 0 depicts the 'ideal' number of occurrences per class, where each class is sampled proportionally to its number of known species. Right and left bars show the classes that are over- and under-represented in the GBIF mediated database compared to this 'ideal' sampling, respectively. Insects lack >200 millions occurrences and birds have an excess of >200 millions occurrences compared to an unbiased taxonomic sampling. Credits: reuse and adpated with permission from [45].

5.2.3. Available knowledge limitation

The interplay of biology and technology. The previous section discussed the unbalanced characterization between most of the multicellular and unicellular organisms due to societal preferences. However, technology advances have also played a central role in the distribution and description of living systems.

For instance, the recent development of modern imaging technologies has the biggest impact on the field of cell biology [53]. These technology advances have increased the description of unicellular organisms e.g. Eubacteria, Archaebacteria, some unicellular organisms within Eucaryotes (diatoms within the kingdom Protista, yeast[13] within the kingdom Fungi, etc). Living systems can now be understood at various level of time – from populations evolution over ages to chemical reactions within cells occurring in a few microseconds - and at different level of space – from population migration to cell division - since the development of modern imaging and satellite technology. These technologies have certainly changed the speed of scientific progress since dissection methods in the 14 centuries[14]. This interplay between biology and technology is expected to continue to do so since the world' body of knowledge increase exponentially [54], [55].

Since biomimetic developments depend on the available knowledge in biology, there is a need to keep the ongoing discussion between the fields of Life Sciences and Design Sciences. The Eastgate Centre is a good example since the architect drew his inspiration from the mound-building of the termites *Odontotermes transvaalensis* [38], [56]. But studying the structure and function of this specie, biologists demonstrated in 2001 that the building is modelled on an erroneous conception of how termite mounds actually work [57], [58] (see chapter 3).

Enhancing both qualitative and quantitative studies. Among the available knowledge in biology, chapter 4 outlined the lack of studies that both qualify and quantify the thermal, acoustic, optic, mechanical, air and water regulation behaviours of living envelopes. In addition, none of them simultaneously assess these behaviours.

Most of these existing studies are qualitative reviews, and carried out in the frame of biomimetic research looking for relevant models for the design of facades [59]–[62]. A taxonomic bias was also observed since they mostly focus on the kingdoms Plantae and Animalia, where flowering plants (Angiospermae) and vertebrates (within the phylum Chordata) are found in largest proportion (see chapter 2). Indeed, for biomimetic applications, there is a need to pursue review of qualitative performances of living envelopes beyond the domain of Eucaryotes.

[13] yeast is one of the few unicellular organisms into the kingdom Fungi. There are different types of yeast, and many are used to make bread, beer, and wine.

[14] the first human dissection took place in 1302 in Bologna (Italia).

Studies have barely quantified biological envelopes' performances, despite the intra-individual and interspecific diversity currently assumed across taxa. Indeed, cross-kingdoms systematic characterization is a huge effort which will need long term research beyond short-term grants. These little amounts of studies have focused on several species distributed within a narrow range in the phylogeny such as eggshell change in reflectance [63], or hummingbird's iridescent' colors [64] (see chapter 4, all sections data availability). Indeed, little basic research has been conducted with an objective of systematic characterization.

Towards the Life's Big Data. Beyond the lack of quantitative studies, chapter 4 has outlined that the data is scattered all research fields. For instance, the few studies that have quantified performances of living systems can also be found from outside of traditional biological research areas. They are applied research targeting human applications in agriculture (e.g. insects' cuticles and fungi response to UV irradiation for pest control [65], [66]), in building materials (e.g. wood photodegradation to predict wooden cladding evolution, or wood thermal conductivity for insulation material [67], [68]), or even medicine (e.g. mammals' UV responses for applications for human' skins cancer [69]).

Complexity of accessing, gathering, and then sorting that data increases since the amount of data produced by research increase every year in both Life Sciences and biomimetic [70]. In addition, the use of biological knowledge contained in databases remains a complex process, due to the data dispersion, its variety (images, texts, sound recordings, GPS coordinates, genomes, chemical characterizations, herbarium, etc), and its terminology differences between the Life Sciences and Design sciences [71].

The GIBIF - the Global Biodiversity Information Facility – remains one of the biggest databases in biology that gather more than 6.5 million species. However, the data is not sorted and adapted yet as needed for biomimetic design application (see Chapter 3). As most of the existing biodiversity databases, the GIBIF can only be queried using a biologist's terminology [72], [73]. The online database - AskNature™ [74]. However, the database has contained 2000 entries, while about 8.7 million[15] of eucaryotes species on Earth have been estimated with 6.5 million species on land and 2.2 million in oceans. Indeed, gathering, sorting and accessing biological knowledge remain to main challenges to enhance the development of biomimetic while overcoming taxonomic bias rather than creating new databasis.

For this purpose, several research institutions such as the Museum of Natural History of Paris, INRIA, in partnership with industrials and the Ceebios, has started in mid-2020 collaborative research in order to initiate a knowledge browser infrastructure, and aligned with current research in ontology as developed by [73], [75].

[15] There is a scientific consensus around that number (give or take 1.3 million), see chapter 4.

5.2.4. Ethics and biomimicry

As introduced in chapter 1, biomimicry refers to a 'philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development', while biomimetics refers to an 'interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution' according to ISO 2015:18458 [76].

Biomimicry's original idea was to "*understand how life works and create designs that continuously support and create conditions conducive to life*". Protecting, preserving and restoring the natural world while designing efficient and sustainable nature-inspired designs has been the main motivation of the approach [77], [78]. Indeed, technical innovations resulting from biomimetic approach must be inextricably linked to ecological considerations. However, at its present stage of development the notion of biomimicry is still relatively ad hoc for the benefit of biomimetic approach [80], [81]. In short *Homo sapiens,* its artifacts[16] and current worldwide lifestyle are not integrated within the earth' ecosystems yet. A deeper philosophy of biomimicry is currently needed as undertaken by O. Speck et al. [82]–[84].

This section discusses the steps towards providing a better ethos in architecture in the light of the main development undertook by this research.

5.2.5. Is biomimetic architecture sustainable?

'All natural-material designs based are sustainable' remains a popular myth. Smartphones, packaging, electrical household appliances are, for instance, made of 'natural material' since all components of man-made designs were once extracted from our natural environment. But all of us know that dropping them in the countryside will take years to breakdown while polluting the natural environment.

Biomimetics ≠ sustainable. Biomimetic – nature-based design – can follow the same logic. According to [81], [85], biomimetic approach does not systematically ensure more sustainable designs compared to a conventional when analysing from a life cycle perspective. Several novel biomimetic building systems as based on advanced technology that requires high carbon footprint material - e.g. alloy, streel, concrete - instead of low transformed material – e.g. straw, raw earth, wood. Within the thirty biomimetic building envelopes analysed in chapter 2, the homeostatic façade, the breathing skin envelope and the ICD/ITKE compliant mechanisms research pavilions, for instance use materials with a higher carbon footprint compared to ICD/ITKE hygroscopic research pavilions mostly made of plywood. Indeed, the rawer materials are transformed, the more they have an environmental footprint [78]. Despite no study have been conducted to assess their life cycle, these materials raise question about the environmental impact of these novel biomimetic systems [7]. In addition, none of the thirty biomimetic envelopes were designed for the renovation of an existing building, while building

[16] Artifact: object made by a human being, typically one of cultural or historical interest.

renovation is considered as the main challenge over the coming years regarding environmental needs [86]. Further research must quantify environmental footprint of biomimetic buildings in order to enhance the sustainability of future developments.

Seen beyond living systems' performances. Several tools have been developed over the past decade in order to de assess the environmental impact of a building or a building system. They have emerged at the interface of different scientific disciplines such as ecology and climatology. They help the designers to evaluate the impact of a novel system from local, regional to global scale. At global scale, the 17 SDGs - Sustainable Development Goals - developed by the UNESCO [87], the Planetary boundaries [88], and the Millennium Ecosystems Assessment [89] are, for instance, good frameworks to evaluate environmental impacts. Recent research have discussed the opportunity of biomimicry to achieve the SDGs [90], [91].

Ecosystem services for the built environment/biomimetic envelopes. At regional scale, current developments that link biomimetic and the built environment, have focused on the application of ecosystemic service [92]–[94]. Ecosystem service can be described as the benefits that people obtain from ecosystems. These services can be divided into four types of services: provisioning such as food and medicines, regulation services such as pollination and climate regulation, supporting services such as soil formation and fixation of solar energy, and life-fulfilling services such as artistic and spiritual inspiration' [89], [95] (see **Fig. 5.6**). Despite the concept is benefit human-centred, the services are both fundamental for humans' survival and maintaining healthy eco-systems.

Applied to the built environment and in our case, biomimetic envelopes should provide ecosystemic service in addition to their performances. This tool can be integrated in the design steps ii and iii – *Schematic design*, and *Design development* in addition to the 'unified problem-driven biomimetic design processes' (**Fig. 5.1**, top). The ecosystem based biomimetic design approach widely differs from the 'unified problem-driven' since the approach provides principles abstracted from ecosystems rather than principles emulated from one or several living system(s) [81].

Based imitation of ecosystemic services for the built environment outlined by [96], **Table 5.2** presents non-exhaustive building solutions to support ecosystemic services by the building envelope. Examples of existing buildings or mature building systems identified as regenerative[17] or biomimetics within the literature illustrate the listed opportunities within the table. The aim is to use these preliminary results to build foundations for further investigations. Further research should assess the adaptation to the building skin regarding to the ecological significance and applicability.

[17] Regenerative buildings – that enable social and ecological systems to maintain a healthy state - serve as contributors to and enhancers of place, its land, history, culture, stories and resources. They are no longer simply a consumer of resources [120, pp. 8–13].

5.2.6. Do we need to acquire more (quantitative) data?

Chapter 4 and 5 have outlined the lack of quantitative data due to taxonomic bias and inter-specie variety. Further research must logically undertake quantitative studies in order to provide the 'missing' data. Beyond the technical challenge to gather and then sort this huge amount of data, this novel direction in research raise ethical questioning. These questioning largely join ethics in biology since biomimetic developments rely on biological knowledge. This section presents ethical issues in the light of the conclusions of this research. They are discussed in both legal and philosophical terms.

Living organisms testing. Research studies a wide range of species – animals, plants, fungi, bacteria - using different techniques, and in a wide variety of contexts - both in situ and ex situ. Any form of intervention on a living organism will have some impact on that individual, directly or indirectly.

In order to set welfare and ethics standards for research involving living organisms, the European Directive 86/609/EEC was created in 1986. This common legislation has introduced restrictions on the use of living animals in scientific experiments to provide protection and welfare. This framework is limited to the mammals within the kingdom Animalia[18] [97]. Research projects must request institutions' permissions when the animal testing is estimated 'to exceed more stress than a punctual injection' (for sampling or injection). As a result, animal testing that involve non-invasive methods such as camera trapping or passive monitoring are not subject to European Directive. Likewise, any level of testing – from little to lethal - on invertebrates such as arthropods, molluscs, roundworms, sponges, echinoderms (starfish, sea urchins, sea cucumbers) and vertebrates such as fish and amphibians are, for instance, not subject to regulation yet.

In this vein, the 3Rs - Reduce, Refine, Replace – framework was defined at the end of the fifteens to increase animals' welfare [98]. The Three Rs - as originally proposed by the Universities Federation for Animal Welfare - has been widely used and little improved over the past decades [99].

Application to biomimetics. Biomimetics research involving testing on living animals will follow the same legislation, i.e. permission requestion when animals' testing exceed a stress cause by a punctual injection. As discussed in chapter 5, the lack of qualitative and quantitative evaluation of thermal, acoustic, optic, mechanical, air and water regulation behaviours of living envelopes, lead towards the development of new study to acquire novel data. This research direction mostly raises ethical questioning since the main motivation of biomimicry has been to protect the whole natural world while designing nature-suitable man-made systems [77], [78].

[18] From January 2013 scientific projects involving cephalopods (class Cephalopoda) became regulated by Directive 2010/63/EU, which regulates - in Member States of the European Union - the use of animals for scientific research and educational purposes [121].

The 3Rs can be applied to discuss future potential biomimetic developments outlined by this research. Within the domain of Eucaryotes, this section does not differentiate the class Mammalia to other kingdoms.

- ‘Replace’ aims to use non-living models instead of living organisms. The existing collections of Museums’ of Natural History allows testing on existing specimens rather than acquisition of new one.
- ‘Refine’ consists of limiting the impact on the living systems. Many characterizations tests can be implemented without causing damages to living organisms. Indeed, technological advances have allowed to carry out non-invasive testing in both in situ and ex situ (Refine). Thermal imaging, [ref]
- ‘Reduce’ aims to minimize the number of animals used. However, several mechanical characterisations must require the organism alive since its properties depends on the hydration rate of the tissues, e.g. insects’ cuticles, deer’ hoofs (see chapter 4, section 6.6. Mechanics). Likewise, coloration of some living materials are due behaviour adaptation such as the structural colour in cephalopods or the thermochromic colours of the blue Australian grasshopper *Kosiuscola tristisin* [100], [101]. While structural colours can be studies using Museums’ of Natural History existing collections, the blue coloration due to light absorption by pigment of the large blue butterfly (*Phengaris arion*) or the Gooty sapphire ornamental spider (*Poecilotheria metallica*) need for instance alive animal testing [102].

Beyond legal considerations, further research must discuss that points to position novel biomimetic research in the light of the initial development of biomimicry as defined by Janine Benyus [78], and then adapted by Gauthier Chapelle for the Francophone community [103].

5.3. References

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Deliverables

Publications

Journal article

E. Cruz, T. Hubert *et al.*, "Design processes and multi-regulation of biomimetic building skins: A comparative analysis," *Energy Build.*, vol. 246, p. 111034, Sep. 2021, doi: 10.1016/J.ENBUILD.2021.111034,
https://www.sciencedirect.com/science/article/abs/pii/S0378778821003182#!
Supplementary data (30 Bio-BS), available on demand.

- 'Multi-regulation within biological envelopes : a comparative review'(in preparation)
  E. Cruz, F. Aujard, K. Raskin (in preparation)

- 'Methods and tools in biomimetics to meet multi-criteria challenges: the case of envelopes'
  E. Cruz, F. Aujard, K. Raskin (in preparation)

Conference papers

- Cruz, E., Raskin, K. and Aujard, F. (2018) 'Biological adaptations for multi-regulation of the building skin', COST Façade TU 1403 –

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Contribution to press articles by proofreading and interview.

- ‘Architecture bio-inspirée : vers une conception régénérative’, E. Cruz, K. Raskin, Pierre d’Angle, (juillet 2017). Avaliable at : https://anabf.org/pierredangle/magazine/architecture-bio-inspiree-vers-la-conception-dhabitats-r-g-n-ratifs
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- ‘A Stuttgart architectes et urbanistes s’inspirent du vivant’, F. Rosier, Le Monde (2019). Avaliable at: https://www.lemonde.fr/sciences/article/2019/12/02/quand-la-nature-inspire-l-architecture_6021386_1650684.html
- ‘Architecture : comment la nature nous inspire,’ Géo Ado (avril 2019), avaliable at : https://www.geoado.com/sommaires/au-menu-de-geo-ado-avril-2019-n-195/
- ‘Le biomimétisme, une voie pour innover de façon durable’, F. Niedercorn, Les Echos (novembre 2020). Avaliable at: https://www.lesechos.fr/idees-debats/sciences-prospective/le-biomimetisme-une-voie-pour-innover-de-facon-durable-1261276
- ‘Envelopes bio-inspirées’. E. Cruz, C. Lequette, I. Darmon. Techniques de l’ingénieur (in preparation)

Grants

- **Transhumance** – 2k € (obtained September 2019) Research scholarship
- **AVIV** (MNHN) – 8k € (refused May 2018)
- **MITI** (CNRS) – 8k € (refused February 2018)

Lectures

Academic lectures without publication

- 13th and 14th ABS Conference – Advanced Building Skins, Bern, Switzerland. Chair and lecturer of the session 'Biomimetics for the building envelope' (2018 and 2019). Program available at: https://ams.abs.green/program-2019/biomimetics-for-the-building-envelope/
- E. Cruz, F. Aujard, K. Raskin (2019) 'A typological analysis of biological envelopes for architects and engineers', SEB, Seville – Society of Experimental Biology

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- Biomimétisme : l'architecture à l'école du vivant | Estelle Cruz | TEDxCannes - YouTube (2019). Available at: https://www.youtube.com/watch?v=_0UV2gaXDtY
- Biomimétisme en architecture : Vers une conception régénérative | Techniques de l'Ingénieur (2019). Available at: https://www.techniques-ingenieur.fr/actualite/conferences-en-ligne/biomimetisme-en-architecture-vers-une-conception-regenerative/
- Enveloppes bio-inspirées | Biomim'Expo 2019. Avaliable at: https://biomimexpo.com/2018/08/25/estelle-cruz/

Teaching

35 hours of teaching for the design of biomimetic building envelopes at ENSA PVS (Ecole Nationale Suppérieure d'Architecture de Paris Val de Seine) sponsored by ICADE.

"Icade - Résultats du Concours 'Enveloppes Bio-Inspirées' - YouTube." https://www.youtube.com/watch?v=3ozrB-m_Xvg (accessed Nov. 10, 2020).